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Frontiers in Artificial Intelligence and Applications

DIGITALIZATION AND MANAGEMENT INNOVATION IV

Proceedings of DMI 2025, Hong Kong, 7-9 July 2025

Edited by
Adela Lau
Antonio J. Tallón-Ballesteros

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DIGITALIZATION AND MANAGEMENT INNOVATION IV

Frontiers in Artificial Intelligence and Applications

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The University of Hong Kong, Hong Kong

and

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Preface

The 4th International Conference on Digitalization and Management Innovation (DMI 2025), which focused on the general theme of *digitalization and management innovation,* along with cutting-edge research topics, drew substantial participation from professors and postgraduate students – PhD scholars in particular – from universities worldwide, as well as technicians, policymakers, and senior executives from diverse industries and organizational sectors. The accepted papers primarily address the following key areas: novel e-supply chain, ESG, e-business and e-commerce, digital economy, digital marketing, green innovation, generative AI, computer vision, AI in chatbots, AI in healthcare, digital human, e-learning model, AI in the metaverse, naked-eye technology, lifelong education, and human resource management issues in innovation.

This volume of proceedings is organized in four parts:

- Part I: Digitalization and Management Innovation
- Part II: Track on Applied Education and Applied Research in AI, Data Science, and Web 6.0
- Part III: Special Session on "New Ecology of Lifelong Education"
- Part IV: Interdisciplinary Applications of Digitalization and Management Innovation

All submissions were subjected to rigorous and meticulous review by international Technical Program Committee (TPC) members and anonymous reviewers, ensuring alignment with DMI's research scope in terms of both thematic breadth and analytical depth. From 243 submissions, 73 high-impact contributions with strong relevance to the *Frontiers in Artificial Intelligence and Applications* (FAIA) series were selected for inclusion, representing the most promising advancements in the field.

We take this opportunity t extend our sincere gratitude to all keynote speakers, invited presenters, authors, TPC members, and anonymous reviewers, whose dedicated efforts were instrumental in ensuring the success of the conference. Finally, we would like to acknowledge the editorial team and colleagues at IOS Press for their collaborative work in publishing this volume as the fourth edition of the DMI conference series within the FAIA book series.

August 2025

Adela Lau, The University of Hong Kong, Hong Kong
Antonio J. Tallón-Ballesteros, University of Huelva, Spain

About the Conference

Co-organized by Beijing Wuzi University, Xiangnan University, and the HKU SAAS Data Science Lab of the University of Hong Kong, the 4th International Conference on Digitalization and Management Innovation (DMI 2025) took place from 7 to 9 July 2025, both on-site in Hong Kong and online. DMI 2025 aimed to provide a high-level platform for experts and scholars worldwide to share their latest ideas on digitalization and management innovation, and featured "New Ecology of Lifelong Education" which was supported by the Hunan Lifelong Education Research Base Xiangnan University, and "Track on Applied Education and Applied Research in AI, Data Science, and Web 6.0", proposed and chaired by Dr. Adela Lau from HKU SAAS Data Science Lab, School of Computing and Data Science, The University of Hong Kong with the aim of fostering and supporting the discipline. The agenda of the conference consisted of keynote speeches, invited speeches, oral presentations, and poster presentations.

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Section I

Digitalization and Management Innovation

Digitalization and Management Innovation IV
A. Lau and A.J. Tallón-Ballesteros (Eds.)
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The Influence of the Concept of 'Leadership Development and Civic Education' of the Federal Armed Forces on Corporate Success

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Abstract. The leadership principles of the 'federal armed forces' (Bundeswehr) provide its superiors with a framework for aligning their actions with the armed forces' interests, thereby contributing to the effective implementation of its mission. The leadership principles also include the concept of 'leadership development and civic education' (Innere Führung), which highlights approaches that can contribute to organisational success in a free market economy. This paper examines whether these approaches significantly influence organizations' social, innovative, and financial success. Therefore, this study adapted items from scales of the constructs of 'leadership' and 'justice' to capture the core content elements of 'human leadership' (Menschenführung) and 'law and military order' (Recht und soldatische Ordnung)—the two main aspects of 'leadership development and civic education' within the free market economy. Additionally, four hypotheses were formulated to examine the impact of 'human leadership' and 'law and military order' on various types of organisational success. These hypotheses were tested using a partial least square structural equation model based on data collected from 118 companies. The results revealed significant positive effects of 'human leadership' on the innovative and social success of organisations and significant positive effects of 'law and military order' on the financial and innovative success of organisations were uncovered.

Keywords. military leadership, organisational success, financial performance, innovation success, social performance

1. Introduction

Preliminary research indicates that companies led by Chief Executive Officers (CEOs) with military backgrounds demonstrate higher levels of performance than those led by CEOs without a military background [1]. This implies that skills acquired in the military can be advantageous in the civilian world [2]. However, there is a paucity of research

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investigating whether organisational principles of the military exert a similarly positive influence on corporate performance [3–5]. These studies identify central principles that are derived from personal experience, interviews, or observations of military principles, whose application in commercial enterprises is perceived as purposeful and successful in various specific cases. This study focuses on managers' personal competencies and empirically examines how the 'federal armed forces' (Bundeswehr) leadership framework, 'leadership development and civic education' (Innere Führung), positively influences business success.

2. Theory and Development of Hypotheses

The concept of 'leadership development and civic education' applies to all military personnel in the 'federal armed forces', particularly those in leadership roles. The concept of 'leadership development and civic education' is defined through its underlying principles, which form the basis for military service in the 'federal armed forces', shape the self-image of soldiers, and provide a guideline for leadership. These principles are based on military requirements and encompass ethical, legal, political, and social principles [6].The objectives of the 'leadership development and civic education' concept are to legitimise, integrate, motivate and shape the inner order (Innere Ordnung) of the 'federal armed forces'. The concept of 'inner order' refers to the leadership and organisational culture within the 'federal armed forces', based on the principles of the 'Basic Law for the Federal Republic of Germany' (Grundgesetz). 'Leadership development and civic education' aims to motivate soldiers, strengthen their sense of responsibility, and promote cooperation among them [6]. It establishes a fixed-value system for service in the 'federal armed forces' by encompassing 'human leadership' as well as 'law and military order', both of which significantly influence the leadership of soldiers and are particularly relevant for superiors [6].

2.1. Human Leadership

Within the 'federal armed forces', leadership is fundamentally determined by the values enshrined in the 'Basic Law for the Federal Republic of Germany' and constitutes a central task for all superiors. The ability to effectively lead individuals is a prerequisite for successful military leaders. Trust is identified as an essential characteristic of responsible leadership, as it serves as the fundamental basis for interpersonal interaction and comradeship. A deep understanding of human nature and the ability to empathise are important prerequisites for building trust. In addition, leaders must demonstrate self-control and predictability, as well as open-mindedness and positivity towards their colleagues. It is imperative to recognise that leadership should allow autonomy and foster shared responsibility and engagement [6].

In this section, the concept of 'human leadership' as a construct is applied to organisations operating within a market economy (i.e. profit-oriented companies), further explaining how it can contribute to organisational success. Leadership effectiveness in driving innovation is significantly influenced by a leader's ability to communicate appropriately and motivate others [7]. A true leader fosters an environment characterised by openness, fairness, and trust. Employees feel safe contributing ideas without fear of criticism

or failure [8]. Those who use this basis to share their skills and experience—in addition to receiving recognition for their commitment—exhibit increased motivation [9]. Motivated employees are inclined to actively think and seek improvement, which is a prerequisite for innovation. Teamwork and interdisciplinary dialogue also positively affect innovation [10]. Innovation is typically the result of the exchange of different perspectives. Managers who actively promote collaboration, learning, and experimentation play a pivotal role in overcoming departmental egotism and fear of negative consequences, thereby strengthening the willingness to take risks to realise one's own ideas. Consequently, this fosters the emergence of structures conducive to innovation. Organisations with effective leadership, as exemplified by 'leadership development and civic education', can consistently implement innovative ideas, thereby becoming market leaders and achieving long-term success. This suggests that effective 'human leadership' can positively influence an organisation's innovative success:

H1: 'Human leadership' positively influences the innovation success of organisations.

Ethical leadership is vital for building trust and positive reputation. It involves demonstrating integrity and social responsibility, which can lead to a long-term competitive advantage for the company [11]. Value-based leadership is predicated on the alignment of corporate decisions and managerial behaviour with ethical principles, moral values, and long-term social responsibility. These values are anchored in the principles of 'leadership development and civic education'. Managers who consistently act in accordance with these values establish clear standards and expectations for their employees. This fosters the development of a corporate culture in which integrity is not merely a promise but rather an active practice. Employees are guided by the behaviour of their superiors, who serve as role models, and thus adopt ethical behaviours. A company characterised by value-based management often builds trust among its employees, customers, investors, and society [12]. Trust is cultivated through a transparent decision-making process and the discernible integration of moral principles. Consequently, social responsibility has become an inherent aspect of such enterprises, extending beyond the confines of their immediate economic interests. It is committed to social and ecological issues, as it considers the long-term effects of its actions on society.
This commitment is reflected in a range of measures, including sustainable production methods, fair working conditions, and social commitment to community benefits. This commitment leads to several positive effects for the company, including enhanced reputation, increased attractiveness for talented and committed employees, and the potential to distinguish the company from its competitors. Consequently, it can be posited that effective people management can exert a favourable influence on an organisation's societal contribution and success in this domain.

H2: 'Human leadership' positively influences the social success of organisations.

2.2. Law and Military Order

The principles of 'law and military order' constitute a pivotal domain in 'leadership development and civic education'. Disciplinary superiors must recognise the profound impact of their disciplinary powers on the justice-related perceptions of subordinate

soldiers. Adherence to the law is the cornerstone of trust and mutual respect. The principle of 'law and military order' constitutes the foundational principle for the functioning of the military community and serves as a guideline for the behaviour and actions of soldiers [6].

In this section, the concept of 'law and military order' is applied to organisations operating within a free market economy (i.e. profit-oriented companies), exploring how this can positively contribute to organisational success. Different dimensions of organisational justice, including distributive, procedural, interpersonal, and interactional justice, have been found to positively correlate with organisational citizenship behaviour [13]. Distributive and interpersonal justice particularly enhance behaviours beneficial to supervisors [14, 15], whereas procedural and interpersonal justice [13, 16] boost behaviours beneficial to the entire organisation [14]. Employees who perceive the organisation's rules and implementation as equitable exhibit reduced apprehension of adverse outcomes, consequently expressing their objective perspectives. The incorporation of a more comprehensive array of information in decision-making processes within an organisation has been shown to reduce the occurrence of misjudgements, establishing a solid foundation for decision-making. When the rules and processes associated with decision-making are perceived as sound, managers and teams are more likely to make decisions that are comprehensible and less influenced by personal interests or biases. Transparent communication regarding the decision-making process strengthens acceptance and implementation of measures, which in turn fosters greater support for these measures and mitigates potential resistance to change. The utilisation of resources in the decision-making process is optimised, and risks are identified and mitigated at an early stage by incorporating diverse perspectives. Consequently, the implementation process accelerates, and the number of erroneous decisions decreases. This leads to increased productivity, reduced costs, and enhanced long-term financial performance. Therefore, it can be concluded that the perception of the 'law and military order' enhances the quality of decisions and improves their implementation, thereby positively influencing a company's financial performance.

H3: 'Law and military order' positively influences the financial success of organisations.

Organisational justice promotes knowledge sharing, which in turn fosters innovative behaviour [17, 18]. This suggests that a fair environment encourages employees to share ideas, which is crucial for innovation [17, 18]. Justice influences innovative work behaviours through affective commitment and organisational citizenship behaviour, suggesting that employees who are committed and work beyond their formal roles are more likely to engage in innovation [19] It also impacts innovative behaviour through perceived organisational support, highlighting that when employees feel supported by their organisation, they are more likely to engage in innovation [20]. This finding suggests a correlation between the perception of 'law and military order' and enhanced innovation outcomes.

H4: 'Law and military order' positively influence the innovation success of organisations.

3. Method

3.1. Procedure

To statistically examine the research model, data were collected from 19th October 2024 to 18th December 2024. A total of 206 organisations were informed of the research objectives associated with the survey and invited to participate in the data collection via an online link. No financial compensation was provided for participating in the survey. After the data collection, 118 completed questionnaires were obtained. Respondents represented a cross-industry sample, spanning all hierarchical levels and covering all major organizational sectors. Because a maximum of two paths are directed at individual endogenous constructs in the research model (see Figure 1), a sample size of at least $10 \times 2 = 20$ elements is necessary to evaluate the partial least squares (PLS) structural equation model in accordance with the application of the rule of 10 [21, 22]. We conducted a 'full collinearity test', as recommended by Kock [23]. None of the variance inflation factors exceeded the value of 3.3. This suggests that the data is not influenced by a common method bias.

3.2. Research Instrument

A PLS structural equation model was created and calculated using the 'Smart PLS 4' software. Figure 1 shows the internal structural equation model. The assumed cause-effect relationships between the constructs can be obtained from the model. The items used were reflective; therefore, the evaluation criteria for reflective measurement models were applied. A maximum number of 3000 iterations, a termination criterion of 10^{-7} and the path weighting scheme were selected as settings in 'Smart PLS 4'.

3.3. Measures

Items from Oliveira and Roth [24] were adapted for the construct of leadership, and those from Niehoff and Moorman [25] were adapted for the construct of 'law and military order'. For the dependent variables *financial success*, *innovative success* and *social success of organisations*, the items were adapted from Avlonitis and Gounaris [26]. All items were translated into German and measured using an anchored 7-point Likert scale with equidistant intervals.

4. Results

4.1. Assessment of Reliability and Validity of the Reflective Measurement Models

The composite reliability values of all constructs in the model were greater than 0.7. The Cronbach's alpha values of almost all constructs in the model were also greater than 0.7, with one exception: the construct *social success of organisation,* which had a Cronbach's alpha value of 0.667, was slightly below 0.7. Overall, this indicated that internal consistency reliability was established. Except for items *SocOrgSucc_2* and *SocOrgSucc_3*, all items met the threshold value of 0.7 for external loadings required for compliance with indicator reliability. *SocOrgSucc_2* had a value of 0.589, and *SocOrgSucc_3* had a

value of 0.698. Both items fell below the threshold value of 0.7 but were not excluded owing to content validity and because they exceeded the lower threshold value of 0.4, as recommended by Hair et al. [22]. All the average variance extracted (AVE) values of the constructs were above 0.5; thus, convergent validity was achieved for all constructs. The results also showed that the square root of the AVE value for all constructs was greater than the correlation of the respective constructs with other constructs. This implies that the Fornell-Larcker criterion is fulfilled, indicating that discriminant validity was fulfilled for all constructs.

4.2. Assessment of the Inner Model

The internal model was verified for possible collinearity. The variance inflation factors were not greater than 5 for all path connections from exogenous constructs, indicating no collinearity problems. Figure 1 shows the calculated path coefficients and calculated coefficients of determination.

5. Discussion

Calculation of the structural equation model yielded the following results: 'Human leadership' had a significant positive effect of +0.260 ($p < 0.01$) on the *innovation success of organisations*. Therefore, H1 was supported. 'Human leadership' had a positive effect of +0.460 ($p < 0.001$) and a high level of significance for the *social success of organisations*. Therefore, H2 was supported. Additionally, a positive effect of +0.343 ($p < 0.001$) of 'law and military order' on the *financial success of organisations* was calculated with a high level of significance, thereby supporting H3. A positive effect of +0.253 ($p < 0.05$) was calculated for the effect of 'law and military order' on the *innovation success of organisations*, thereby supporting H4. Therefore, the results of the structural equation model support all four hypotheses, and in some cases, at high significance levels ($p < 0.001$). This, in turn, confirms that the assumptions made in the Hypotheses section regarding the causal relationships between the dependent and independent variables are valid.

The coefficients of determination for the dependent variables lead to the following results: 'Law and military order' explain 11.7% of the variance in the construct of *financial success of organisations* ($p < 0.05$). This is a considerable proportion given that 'law and military order' are the only constructs in the research model that show a path link to the *financial success of organisations*. The coefficient of determination for the construct *innovation success of organisations* explains 20.6% by the two constructs: 'human leadership' and 'law and military order' ($p < 0.05$). This proportion is also significant because only two-path connections are directed towards the *innovation success of organisations*. Additionally, 'human leadership' explains 21.1% of the variance in *social success of organisations* ($p < 0.05$), which is considerable, considering that only one path link is directed towards *social success of organisations*. Therefore, it can be observed that although only one or two links are directed at the individual dependent variables of the research model, the variance of all these dependent variables can be explained to a considerable extent by the respective independent variables.

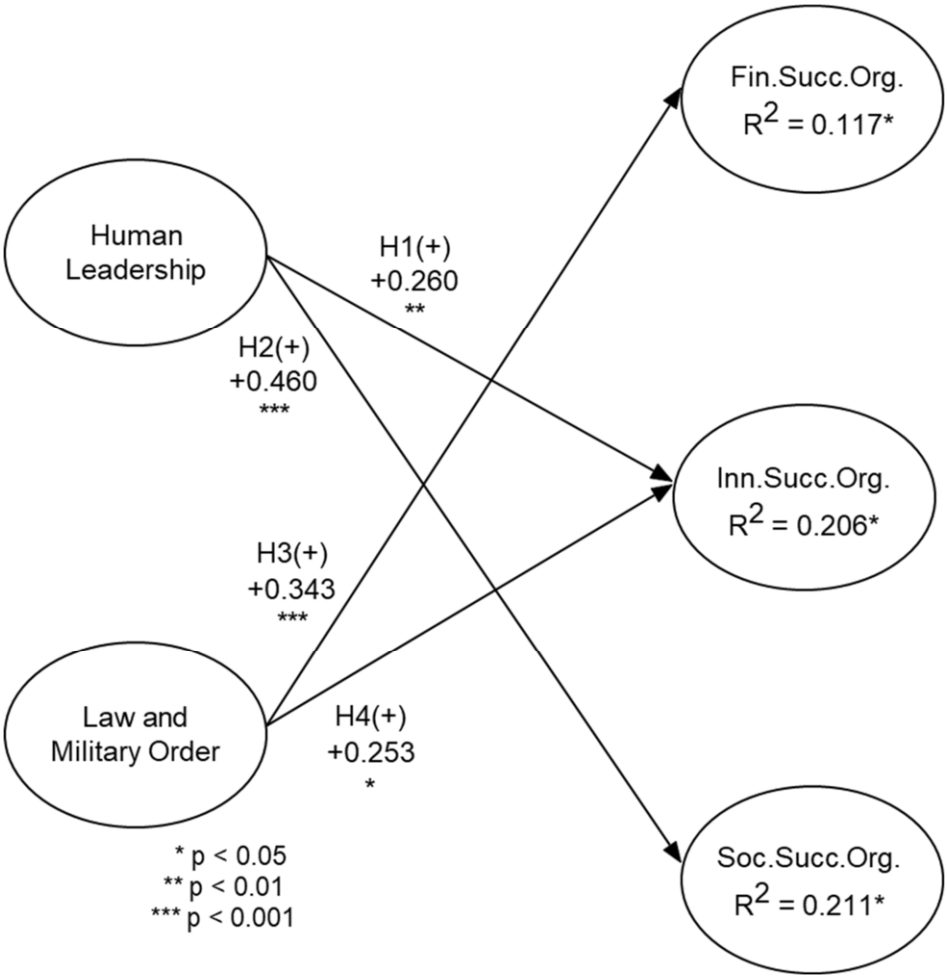


Figure 1. Path coefficients and associated significance levels of the research model.

6. Conclusion

The results of the structural equation model showed significant positive effects of the constructs of 'human leadership' and 'law and military order' on various forms of organisational success. These results confirmed the hypotheses proposed in this study. The two design fields, 'human leadership' and 'law and military order', characterise the concept of 'leadership development and civic education', suggesting that the aspects of this concept captured by the question items and applicable to private sector organisations positively influence their social, innovative, and financial success.

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Improving Tertiary Students' Mental Health via Gamified Extensible E-Commerce-Well-Being Minigames (Eco) Systems: A Preliminary Case Study

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Abstract. Good mental health among tertiary students influences productivity and well-being. However, sometimes, due to lack of planning/time management and communication skills, students' stress, anxiety and depression (SAD) have increasingly worsened. This study integrates e-commerce-mental health/well-being mini-games with gamification as the connector, contextualized within goal-based scenarios and rule-based personalized recommendations for different market segments in a mobile app, Mindful Quest. Requirements Engineering, User Experience pragmatic-hedonistic qualities, Technology Acceptance Models, and the integrated drivers of online shopping model are applied as frameworks, design and assessment guides. Mini games include self-care activities and adventure/time management (analogically reflective), communication/caring activities (outward/societal outlook), and self-paced educational library (enrichment). Preliminary survey findings from purposive sampling indicate congruence is reflected in value (and price) consciousness, technological factors, and browsing enjoyment. Analogical to weights, the average for the importance of clarity (ease of use) is 89%, for mental health/well-being activities (usefulness) 88%, and productivity (the most important value) 91%. The most important strengths are gamification (47%) and enjoyment from mixed content (e.g. education/personal growth and entertainment; work and self-care; productivity and mental health/well-being goals; self-care and rewards) with gamification for 2some (17%). These findings contrast with two related literature which weigh hedonistic higher than pragmatic qualities, congruence as different from value consciousness, and demographics/society over individuality in decision making; highlighting age, income and gender as moderating factors. Due to Mindful Quests' object-orientation, it is possible to instantiate/adapt/abstract/link to external stacks/(eco) systems. Limitations are small sample size, purposive sampling and subjectivity in perceptions.

Keywords: Design thinking, requirements engineering, metaverse, gamified e-commerce-mental health/well-being, self-care, adventure, analogically reflective, outlook, User Experience, Technology Acceptance, flow

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1. Introduction

Good mental health/well-being holds both intrinsic and instrumental value. However, according to the World Health Organization (WHO), mental health/well-being is a worrying global concern, as it will affect the individuals' ability to handle life's stresses, to learn effectively, to work productively, and to contribute to his/her local and global communities.

Increasingly, this problem includes teenagers. In Malaysia, the 2022 National Health and Morbidity's (NHMS) Adolescent Health Survey [1] reveals that 26.9% of Malaysian adolescents experience depression, 13.1% have the intention to commit suicide, and 9.5% have tried to commit suicide. Subsequently, a 2023 NHMS survey [2] on non-communicable diseases and healthcare demand finds that 1,000,000 people in Malaysia aged 16 years old and above experience depression. Hence, this serious issue demands a user-centred design approach.

1.1 Problems to be addressed and objectives

Many researchers, e.g. [3] suggest that mental health should be viewed from different perspectives. The first perspective for this study is mental health/well-being. Among factors contributing to mental health/well-being issues are loneliness, negative self-image and family issues [3], time [4, 5], possible stigma and students' lifestyle [6, 7].

Since our scope of research involves only Malaysian tertiary students, the aim is to develop a system to enhance university students' time management skills and to help them better manage stress and anxiety. As university students love to play games, and students need to de-stress socially, the game application needs to improve time management skills and provide avenues to engage and think outwards to develop different perspectives, improve problem-solving skills, and subsequently, well-being.

The second perspective is from e-commerce and gamification. Gamification is included because it bridges the mental health/well-being system components with the e-commerce platform. Our gamified e-commerce-mental health/well-being mobile app, *Mindful Quest*, enables students to earn rewards similar to *Shopee*, Asia's most successful e-commerce portal. In contrast to *Shopee*, our mini games directly address mental health/well-being issues.

The objectives for this study are:

1) a) to elicit key factors contributing to and impacts from poor mental health among university students from related literature,
   b) to elicit the benefits of games/gamification to e-commerce from literature,
   c) to determine functions which may be attractive to university students from the top 10 mental health websites via Google search,
   d) from 1 a), b) and c), to determine relevant functions, which will be attractive to the targeted Malaysian university students, as guided by TAM 1, 2, 3 (Figure 1a) [8-10] and defined by [11] in Figure 2,
2) from 1d), to design and develop a gamified e-commerce-self-care-adventure mini games mobile application *Mindful Quest,*
3) to test/evaluate *Mindful Quest* based on Technology Acceptance Models (TAM) 1, 2, 3 [8-10], and [11]'s user experience,
4) to discuss findings in relation to [11]'s user experience, [12]'s habitual drivers, and [13]'s online shopping drivers (Figure 1b).

1.2 Hypotheses

Corresponding hypotheses (Figure 1c) are:

1) TAM 1's [8] perceived ease of use and perceived usefulness and TAM 3's [10] anchors and adjustment factors will be more dominant than TAM 2 [9] factors, in relation to technology acceptance of *Mindful Quest,*
2) [12]'s findings indicate price value, and hedonic qualities are likely to influence habitual use more. Our findings will be similar for price value, but due to the age group, pragmatic qualities will be more important than hedonic qualities,
3) [13]'s drivers for online shopping finds congruence followed by value (and price) consciousness as the most important. This study's findings will concur on congruence, but equate congruence with value (and price) consciousness,
4) Based on hypothesis 3, objective consumption can be influenced by personalized engagement, pivoting around anchor (computer playfulness) and adjustment factors (perceived enjoyment and especially, objective usability) *and also, vice versa*.

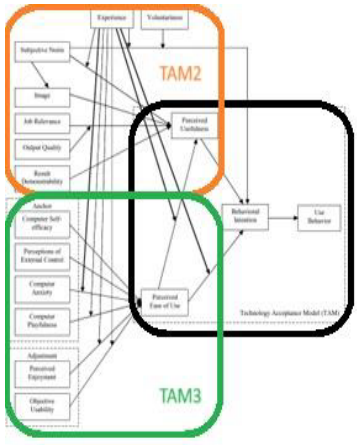


Figure 1a. TAM 1, 2, 3 [8-10]

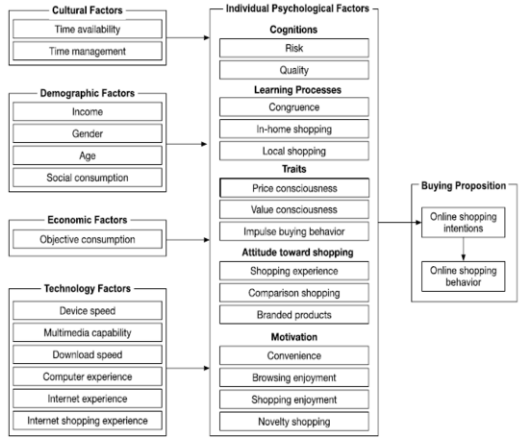
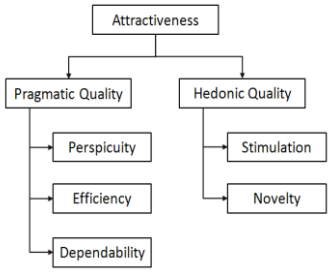


Figure 1b. [13]'s integrated online shopping drivers



Figure 1c. Hypotheses for this study



Attractiveness: Extent users like the app?
Perspicuity: Ease of use/learnability?
Efficiency: Productivity, fast response time?
Dependability: User control/reliability, security, predictability?
Stimulation: Exciting/motivating/fun?
Novelty: Creative/interesting?

Figure 2. [11]'s User experience constructs

2. Related work

2.1 Academic stress and time management

Academic stress is a persistent concern for tertiary students. High stress levels among tertiary students often come from academic commitments, poor study habits, and ineffective time management skills [4]. [5]'s findings indicate that university students who have good time management skills are able to make use of time effectively, striking a proper balance between work and rest. As such, disposition, time management, and burnout require further attention.

[6, 7, 14, 15]'s studies in the Malaysian context concur with the above findings on the need for better time management. Findings confirm that the level of stress has an inverse relationship with academic performance. Proper time management and exercise are recommended alternatives.

2.2 Games and gamification

Shopee, a prominent online marketplace in Southeast Asia, utilizes games and gamification elements to enhance customer engagement, improve customer retention, and drive sales [16]. In terms of gamification elements, [17] confirm that the *Shopee* gamification strategy has increased customer loyalty by 77.8%. Similarly, [18, 19] find that *Shopee* gamification positively impacts buying impulsivity, customer engagement/ customer satisfaction. Furthermore, [20]'s study indicates that gamification elements e.g. challenges/levels enhances the shopping experience, encouraging repeat visits and increasing the time users spend on the platform in Indonesia. Hence, designing satisfying gameplay experiences is critical to customer retention/attraction.

2.3 Existing online games to stress, anxiety, time management, communication

SPARX (Smart, Positive, Active, Realistic, X-Factor thoughts). SPARX (Smart, Positive, Active, Realistic and X-Factor thoughts) applies cognitive-behavioural therapy (CBT) in an engaging and accessible manner. SPARX's key features include a fantasy-based gaming environment where users choose an avatar and embark on a journey to defeat Gloomy Negative Automatic Thoughts. The coverage of SPARX's 7 modules/ levels are in Table 1. [21]'s study reveals significant reduction in hopelessness, anxiety, depression, and improved quality of life. Hence, SPARX is a key reference for our e-commerce-mental health/ well-being game design and development.

Table 1. SPARX's provinces, themes and coverage

Level	Coverage
1	**Cave province: Finding hope** - Introduces cognitive behavioural therapy model, Gloomy **N**egative **A**utomatic **T**houghts (GNAT) - Introduces hope and relaxed controlled breathing
2	**Ice province: Being active** - Scheduling activities and behavioural activation, progressive muscle relaxation, - Interpersonal skills
3	**Volcano province: Dealing with emotions** - Dealing with anger and hurt, interpersonal skills: assertiveness and negotiation
4	**Mountain province: Overcoming problems** – - **S**ay the problem, **T**hink of the solution, **E**xamine pros and cons, **P**ick one and try, **S**ee what happens. - Cognitive restructuring with **S**mart, **P**ositive, **A**ctive, **R**ealistic, **X**-factors thots
5	**Swamp province: Recognizing unhelpful thots** - Cognitive restructuring: Recognizing different types of GNATs

6	**Bridge-land province: Challenging unhelpful thots** - Cognitive restructuring: Learning to challenge/switch negative for helpful thots, - Interpersonal skills: Negotiation
7	**Canyon province: Bringing it all together** - Recap of all skills, mindfulness (tolerate distress), preventing relapse

Overcooked 2!! [22] is a cooperative cooking simulation video game, which has gathered a large and dedicated player base. Besides allowing character customization, the game allows players to select the game mode (story, practice or survival). Moreover, players need to navigate the interactive world map to unlock new kitchens and challenges. This creates a sense of exploration and discovery. Changes in the dynamic kitchens during gameplay e.g. portals (via the interactive world map), moving platforms, and new elements, e.g. environmental hazards, require players to adapt their strategies on the fly. After choosing a role, players must coordinate their actions to efficiently prepare and serve dishes within a limited time frame in the game.

Sky: Children of the Light. With its beautiful graphics, unique social gameplay and emotional storytelling, the adventure game *Sky: Children of the Light*, includes beautifully crafted environments and realms that invite players to explore and discover secrets in the game [23]. Each realm offers a unique theme and challenges, encouraging players to immerse themselves in the magical kingdom. Character customization allows players to customise their characters through various outfits, hairstyles, and accessories, creating a personal connection to the game.

In addition, *Sky* promotes altruism and positivity through its gameplay mechanics. Players can help each other by sharing candles and hearts. These can be used to purchase cosmetics or unlock certain tasks to achieve progress. Consequently, the development of a supportive community encourages players to be kind and generous. *Sky* supports cross-platform play, allowing seamless interaction and play on iOS/Android/Nintendo Switch.

Comparison of 10 popular mental health games is presented in Table 2 below.

Table 2. Comparison of 10 popular mental health games' gamification mechanics

	Single Player / Multiplayer	Time Tracking	Badges & Rewards	Interactive challenges	Point System	Educational Knowledge	Others
Overcooked 2!	Both	✓	✓	✓	✓	N/A	World Map Character Customization
MonSTRESSity	Single					Anxiety Management	Character Customization
Squishem	Single	✓		✓		Stress Management	Audio Effect
SPARX (Smart,	Single		✓	✓		Mental health	Storyline,
Positive, Active, Realistic, and X-Factor thoughts)						and well-being	Character customization, Multiple-choice question
Rescue Dash	Single	✓	✓	✓	✓	N/A	Storyline Leaderboards Visual and audio effect
Sky: Children of the Light	Both		✓	✓		N/A	Seasonal Events Calming Visuals and Music Personal Emotes and Expression Character Customization Supportive Community Exploration and Adventurous Map
Boson X	Single	✓		✓	✓	N/A	N/A
Subway Surfers	Single		✓	✓	✓	N/A	Leaderboards and Rankings

2.4 Technology Acceptance Models

The Technology Acceptance Model (TAM) introduced by [8], aims to predict and explain users' acceptance of technology. The TAM 1 model emphasizes two constructs, i.e., perceived usefulness (PU) and perceived ease of use (PEoU). TAM 2 [9] extends from TAM 1 and covers extrinsic and social factors, while TAM 3 [10] highlights intrinsic human factors e.g. computer anxiety and its inverse, computer self-efficacy. These form part of the anchors to technology acceptance. Computer playfulness (another anchor) corresponds with perceived enjoyment to encourage adjustments. TAM 1, 2 and 3 are presented in Figure 1a. We are interested in these anchors and adjustment constructs.

Next, [12] have extended the Unified Theory of Acceptance (UTAUT) to UTAUT2. The latter emphasizes the importance of hedonic motivation, price value as well as habit. They discover that age, gender and experience, moderate behavioral intentions and technology use. Findings from online consumer tests indicate that UTAUT2 better explains behavioral intentions by 18%, technology use by 12%.

Ten years later, attempting to better understand the key drivers influencing customer segments, and relevant stakeholders, [13] have integrated existing literature on online shopping (Figure 1b). The integrated model enables instantiation to different contexts, to discover the relative correlative importance of modelled variables.

3 Methodology

3.1 Research framework: [8-10]'s TAM 1, 2, 3, [11]'s UX, [12 (and 13)]'s drivers

[24] find that by tracking behaviours and incorporating a therapeutic approach, i.e., behavioural suggestions (BSs), and a supportive community, the mobile game app can encourage patients to engage in positive and meaningful activities to improve their mood. Thereafter, a recommender system can support personalized mental health/well-being.

The success factors from Section 2.3, have formed the main inspiration/bases in terms of game mechanics, for the design and development of this study's e-commerce-mental health/well-being game. TAM 1, 2 and 3 [8-10], [11]'s User Experience constructs, and [12]'s drivers are applied to guide the design, development, and formulation of the alpha and beta testing questionnaires. TAM 1, 2, 3 and [12]'s constructs map well with [11]'s UX qualities (Figure 2). [13]'s online shopping drivers model frames the bigger picture.

Some examples of mappings are:

a) since age moderates technology adoption [12], and the sampled respondents for this study are young, *Mindful Quest* needs to be *attractive* as defined by [11],
b) as hedonic quality [12] involves novelty and stimulation [11], the mini games should identify what constitutes novelty/stimulation and how important these are.

3.2 Agile methodology

SCRUM vision. Continuing from prior studies [25, 26], two ecosystems (e-commerce + mental health/well-being mini games) are integrated (loosely coupled) to emulate the metaverse in one mobile application.

Design: Game model and components. The project scope includes the development of a mobile game application designed to feature self-care (analogically reflective) [27]

activities, adventure/time management activities/tools, communication skill-building exercises (caring for others, outlook development), and educational content on mental health/well-being. Gamification elements involve various levels or challenges, that players must complete by effectively managing their time. To enhance interaction and to determine rewards, the mini games provide feedback on players' task completion, tracks their progress throughout the game, highlights areas for improvement and celebrates achievements when players complete the games on time.

Development: Programming Environment. Android Studio with Flutter provides a powerful and flexible development environment for creating cross-platform applications. Flutter enables the development of natively compiled applications for mobile, web and desktop from a single codebase while Android Studio supports Flutter through the Flutter and Dart plugins. The IDE and its emulator enables designing, previewing UI and testing.

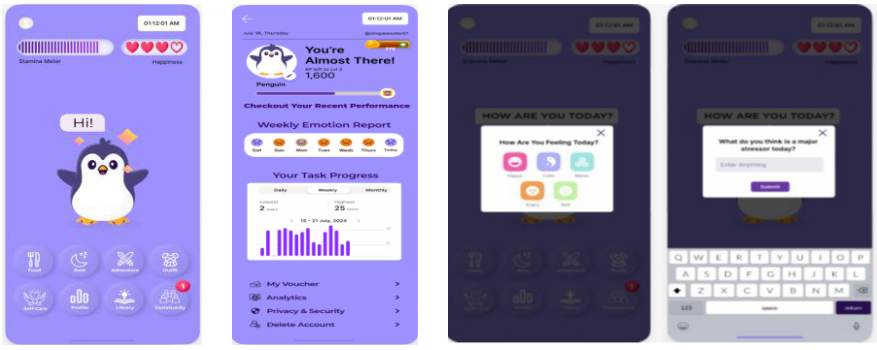
Firebase is utilised as the database. It is a real-time synchronised cloud-hosted database that stores data in Javascript Object Notation (JSON) format. Firebase also ensures authentication by tracking and identifying user logins, in Google, Facebook etc.

Evaluation. TAM 1, 2 and 3 [8-10], [11]'s UX are guiding frameworks for both design and evaluation. The Google survey form is distributed online. A Likert scale of 1 to 7 is applied for the alpha survey questions. For the beta survey questions, a Likert scale from 1 to 5 is utilized. There is a change from a Likert scale of 1 to 7 for the alpha user testing to 1 to 5 for the beta user testing, as Malaysian surveys usually apply a Likert scale of 5 and we hope to get more or similar number of respondents at the end of the semester, when every student is busy with his/her own assignments/capstone projects. Due to the difference in Likert scales, the averages' ranking are utilized to identify the relative importance of each construct in the User Experience questionnaire and the TAM 1, 2 and 3 questionnaires. The limitation of the study lies in the small sample size, the purposive sampling and the subjectivity of self-reported perceptions.

4 Findings and discussion (alpha prototyping and testing)

4.1 Screenshot of Figma prototype

Figures 3a, b, 4a, b, 5, 6 present sample screenshots of the developed e-commerce-mental health/well-being game prototype in this study. The support community page (not shown), awards users for helping their friends.



Figures. 3a, b. Daily login page, progress/achievement page, **4a, b.** Emotions monitoring

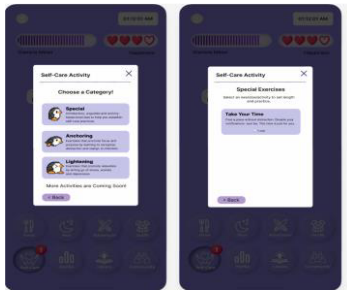


Figure 5. Self-care activities pages

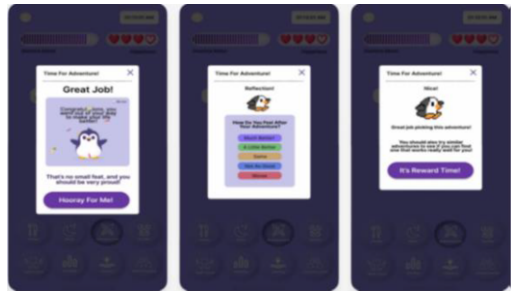


Figure 6. Adventure Pages

4.2 Alpha testing TAM-based findings

Findings indicate that majority of the respondents are aged between 18-21 and the number of female respondents double that of male. Demographic distributions are presented in Table 3a and outcomes for each survey section in Tables 3b-j. Perceived usefulness questions are highlighted in yellow, perceived ease of use in green.

Table 3a. Demographic distribution

Age (%)			Gender (%)			Current time management skills (%)					
<18	18-21	22-25	F	M		2	3	4	5	6	7
	65.0	27.5	60.0	37.5		10.0	10.0	27.5	30.0	12.5	10.0
Knowledge about mental health & self-care (%)						Current communication skills (%)					
2	3	4	5	6	7	2	3	4	5	6	7
5.0	17.5	15 .0	42.5	15.0	5.0	7.5	2.5	30.0	32.5	17.5	10.0
Use of Shopee/Lazada (%)											
2	3	4	5	6	7						
7.5	7.5	17.5	12.5	25	27.5						

Table 3b. Results for Section 2: Daily login experience and emotion reflection

Extent that daily login prompt on feelings for the day is useful to reflect on their emotional state						Extent that the daily prompt on major stressor for the day is useful in understanding and managing their stres					
2	3	4	5	6	7	2	3	4	5	6	7
Re0	10.0	10.0	25.0	22.5	32.5	2.5	2.5	27.5	17.5	27.5	22.5
Extent that easy to set Penguin's name and gender						Extent easy to complete daily logins, reporting feelings, stressors, and energy levels					
2	3	4	5	6	7	2	3	4	5	6	7
	12.5	12.5	17.5	12.5	45.0		7.5	17.5	20.0	20.0	35.0

Table 3c. Results for Section 3: User experience with the "food & beverage" function

Extent satisfied with the variety of food and beverage						Extent the variety remind them to choose healthier options					
2	3	4	5	6	7	2	3	4	5	6	7
	2.5	12.5	30	32.5	22.5		7.5	12.5	17.5	42.5	20.0
Extent easy to navigate & use the FeedMe function											
2	3	4	5	6	7						
	7.5	10.0	7.5	32.5	42.5						

Table 3d. Results for Section 4: Avatar's sleeping schedule

Extent sleep schedule is useful to maintain healthy sleep routine						Extent enjoy managing Penguin's sleeping schedule					
2	3	4	5	6	7	2	3	4	5	6	7
2.5	7.5	5.0	32.5	25.0	27.5	2.5	7.5	7.5	17.5	30.0	35.0
Extent that easy to set and follow sleeping schedule											
2	3	4	5	6	7						
5.0	5.0	12.5	22.5	25.0	30.0						

Table 3e. Results for Section 5: Task challenge effectiveness and usability

Extent challenges are useful to complete tasks faster						Extent easy to understand & complete challenges					
2	3	4	5	6	7	2	3	4	5	6	7
	7.5	17.5	15.0	40.0	20.0		5.0	7.5	15.0	32.5	40.0
Extent that easy to understand and complete the challenges											
2	3	4	5	6	7						
	5.0	7.5	15.0	32.5	40.0						

Table 3f. Results for Section 7: Self-care activities user experience

Extent self-care activities are useful to reduce stress, depression, anxiety						Extent enjoy the self-care activities					
2	3	4	5	6	7	2	3	4	5	6	7
2.5	2.5	15.0	27.5	30.0	22.5		5	5	17.5	42.5	30
Extent easy to follow & complete self-care activities in the game											
2	3	4	5	6	7						
	2.5	12.5	12.5	47.5	25.0						

Table 3g. Results for Section 8: Dashboard /profile feature

Extent dashboard/profile useful to track progress/ achievements						Extent easy to navigate and use the dashboard/ profile					
2	3	4	5	6	7	2	3	4	5	6	7
		15.0	22.5	35.0	27.5			15.0	12.5	35.0	37.5
Extent easy to navigate and use dashboard/profile											
2	3	4	5	6	7						
		15.0	12.5	35.0	37.5						

Table 3h. Results for Section 9: Library/Knowledge center user experience

Extent the library/knowledge center is useful for learning about different self-care activities?						Extent that content in the library/KCentre is relevant/ applicable to daily life					
2	3	4	5	6	7	2	3	4	5	6	7
2.5		12.5	17.5	35	32.5		5.0	7.5	22.5	30	35
Extent easy to navigate & find information in the library/ Kcentre											
2	3	4	5	6	7						
	7.5	5.0	22.5	30.0	35.0						

Table 3i. Results for Section 10: Social interaction and community feature

Extent the community features (adding friends, visiting kingdoms) enhance user experience						Extent enjoy social interactions and community features in the game					
2	3	4	5	6	7	2	3	4	5	6	7
	5.0	7.5	25.0	32.5	30.0			15.0	30.0	22.5	32.5
Extent easy to add friends and complete tasks on time											
2	3	4	5	6	7						
		10.0	22.5	35.0	32.5						

Table 3j. Results for Section 11: Overall experience and feedback

Overall experience with Mindful Quest						Extent likely to recommend to others					
2	3	4	5	6	7	2	3	4	5	6	7
	2.5	15.0	7.5	32.5	42.5			15.0	22.5	30.0	32.5

4.3 Alpha testing user experience findings

The user experience findings (Table 4) indicates very positive outcomes. Clarity/ease of use questions are highlighted in green, productivity in purple, hedonic quality in yellow. Recommending to others ranks the highest in average, at 5.8/7. The next top 4 are pragmatics, i.e., clear (5.71), easy (5.63), supportive (5.58), efficient (5.49). The lower averages for hedonic qualities indicate the need to integrate the mental health/well-being components with e-commerce components and gamification, to increase adoption.

Table 4. User experience questionnaire's ranked averages

Q. no.	Question	Avg.	%
9	**To what extent are you likely to recommend *Mindful Quest*?**	5.80	83%
4	How would you describe your experience with the game? [Confusing - Clear]	5.71	82%
2	How would you describe your experience with the game? [Complicated - Easy]	5.63	80%
1	How would you describe your experience with the game? [Obstructive - Supportive]	5.58	80%
3	How would you describe your experience with the game? [Inefficient - Efficient]	5.49	78%
5	How would you describe your experience with the game? [Boring - Exciting]	5.46	78%
6	How would you describe your experience with the game? [Not interesting - Interesting]	5.41	77%
7	How would you describe your experience with the game? [Conventional - Inventive]	5.39	77%
8	How would you describe your experience with the game? [Usual - Leading edge]	5.29	76%

4.4 Improvements made to beta prototype

Certain features from the alpha prototype are removed to better align the user journey and prioritize core functionalities, while evolving with user needs. The game login page is replaced with an e-commerce login which is associated with the user's e-commerce accounts. The daily login page which prompts users to share their feelings and thoughts is also removed in beta to simplify the user experience. Removing this feature allows resources to be reallocated to more impactful areas, e.g. task scheduling systems and self-care activities. Similarly, the sleep quality page is removed, as its utility is limited in the context of the platform's primary objectives.

5 Findings and discussion (beta prototype and testing)

Some sample screenshots are presented in Figures 7a, b, c and d.



Figure 7a. Game homepage

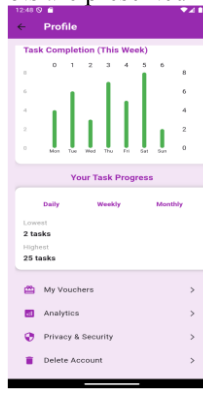


Figure 7b. Game profile page

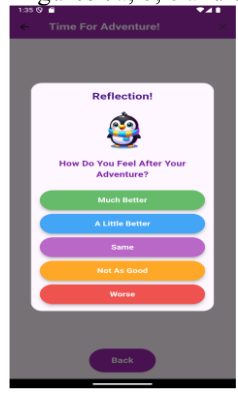


Figure 7c. Self-care activities

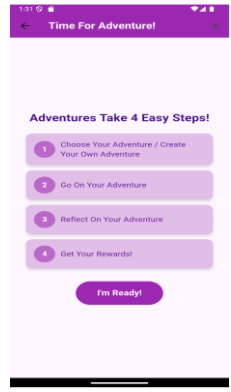


Figure 7d. Adventure/ time management page

6. Discussion

6.1 TAM 1 and TAM 3's dominance over TAM 2

Hypothesis 1: TAM 1's perceived ease of use and perceived usefulness and TAM 3's anchors and adjustment factors will be more dominant than TAM 2 factors, in relation to technology acceptance of *Mindful Quest*

The averages for each question from the survey formulated based on TAM 1, 2 and 3 [8-

10], are ranked in descending order in Table 5. From Table 5, there are three key categories, i.e., clarity/ease of use (green), which strongly influences productivity (purple), and use of mental health/well-being (adventure/time management-self-care)/usefulness (yellow). That Q1 and Q2's averages are higher than Q3's, is very encouraging of possible adoption. The top 3 factors are productivity (anchor/adjustment)-related. From a decision tree perspective, productivity is the root (highest information gain).

Table 5. Ranked averages in descending order and identification of three key constructs contributing to technology recommendation (Q3) from the TAM-based beta testing

No.	Question	Avg.	No.	Question	Avg.
Q1	I feel more *motivated* to complete my tasks with this game.	4.67	Q9	I found it *easy to learn* how to play the game and understand its features.	4.47
Q2	The game helps me stay *focused* and *motivated* to complete tasks efficiently.	4.63	Q10	The game provided *clear feedback* about errors or next steps.	4.47
Q3	**I would recommend this game to others**	**4.60**	Q11	I did *not encounter any unnecessary challenges* when using the features.	4.43
Q4	The game will enable me to accomplish my tasks *quickly and effectively*.	4.53	Q12	Playing the game made me feel more productive/in control of my *emotions*.	4.40
Q5	The instructions provided were *clear and sufficient*.	4.53	Q13	The buttons, icons, and menus in the game are *intuitive and easy to use*.	4.40
Q6	The adventure and self-care features are useful for improving my mental health and time management.	4.50	Q14	The game helps me manage my stress and time more effectively.	4.37
Q7	This game as a tool I can use regularly to enhance my time management skill/learn more about self-care.	4.50	Q15	The self-care activities, library motivate me to prioritize my mental well-being.	4.23
Q8	I was able to navigate through the game *without confusion*.	4.50	Q16	The game improves my understanding of mental health strategies.	4.20

6.2 Contrast with [12]'s findings

Hypothesis 2: [12]'s findings indicate price value, and hedonic qualities are likely to influence habitual use more than pragmatic qualities. Our findings will be similar for price value, but due to the age group, pragmatic qualities will be more important than hedonic qualities.

From Table 6, the highest overall mean among the three key constructs is productivity at 4.56 (91%), followed by clarity (ease of use) at 4.47 (89%), mental health, i.e., time management/adventure-self-care (usefulness) at 4.40 (88%). The three factors are almost equally important, indicating good systemic balance.

However, there is an age (and thus income) difference compared to [12]'s study. From Tables 4, 5, 6, [11]'s pragmatic qualities are more important than hedonic qualities.

Table 6. Identification of three key constructs from the TAM-based beta testing questionnaire contributing to technology adoption/recommendation (Q3)

Clarity (ease of use)		**Productivity (ease of use)**		**Mental health/time management/ self-care (usefulness)**	
Q no.	**Avg.**	**Q no.**	**Avg.**	**Q no.**	**Avg.**
5	4.53	1	4.67	6	4.50
8	4.50	2	4.63	7	4.50
9	4.47	4	4.53	12	4.40
10	4.47	12	4.40	14	4.37
11	4.43			15	4.23
13	4.40			16	4.20
Overall mean 4.47 (89%)		**Overall mean 4.56 (91%)**		**Overall mean 4.40 (88%)**	

6.3 Most impactful factors perceived by users and [13]'s drivers

Hypothesis 3: [13]'s drivers for online shopping places congruence as most important, followed by value consciousness. This study's findings will concur on congruence but equate congruence with value (and price) consciousness.

[13]'s drivers shaping consumer purchasing behaviour are congruence followed by value consciousness, risk, local shopping, shopping enjoyment, and browsing enjoyment. The verbatim feedback to Mindful Quest which respondents find most impactful/essential (strengths), are presented in Table 7. Fourteen respondents (47%) choose gamification. Gamification thus forms the centre of the must-have Gaussian curve.

Five of the respondents (17%) have chosen mixed balance (i.e., education/ personal growth and entertainment, work and self-care, productivity and mental health goals, self-care and rewards), followed by customization of personal tasks and character, helpfulness, variety of features and the cute character. This group may be those aged 22-25. This Gaussian curve overlaps with the gamification Gaussian curve, as some respondents in the second Gaussian curve, are motivated by achievements and rewards. This suggests Gaussian Mixture Models (GMM), which enrich [28]'s evolution of joint entropy between the dynamic e-commerce+mental health and interlinked (sub) systems.

Both gamification and mixed balance contribute to 64% of the sampled respondents and as such, are regarded as the two most significant, useful for Pareto Charts and/or Kano models. The tail of the Gaussian curve are customization (of the cute character and inputting one's own task) and other attractors e.g. easy to follow and genuinely helpful, lots of features) with each at 1%.

Table 7. Most impactful functions/features of *Mindful Quest* for 30 sampled respondents

Gamification (14/30) [47%] Pragmatic quality	Mixed balance (5/30) [17%] Hedonic quality	Customization (2/30) [1%]	Other attractors (2/30) [1%]
• Gamification of tasks to make time management enjoyable. • Gamifying productivity makes managing my schedule feel like a fun challenge	• The combination of education/personal growth via the library, self-care and entertainment	• To be able to input personal tasks and see tangible rewards upon completion	• The self-care challenges are easy to follow and genuinely helpful
• The ability to input personal tasks and see tangible rewards for completion	• Different task category & self-care technique	• Cute character	• A lot of features
• Reward, Being rewarded for task completion, Timer & reward, Reward system • Earn vouchers after complete task, The vouchers and coins earned, Earn vouchers, I love the vouchers	• The game introduces a balance of work and self-care, which feels refreshing.		
• Self-care activities + rewards • The reward system and self-care techniques	• I love how the game makes me feel I'm accomplishing my tasks & mental health goals.		
• Task customization & reward system	• Self-care activities and rewards		

6.4 Multi-channel persuasive reflection and self-refinement

Hypothesis 4: Based on hypothesis 3, objective consumption can be influenced by personalized engagement, pivoting around anchor (computer playfulness) and adjustment factors (perceived enjoyment and especially, objective usability), *and also vice versa*.

Given that community-based (eco)systems develop and evolve over time, based on pattern recognition, decomposition, logic and abstraction (computational thinking components), there are shared possibilities between intertwining strands of [27]'s analogical creativity and *Scratch* fractals [29] to enhance [28]'s evolution of joint entropy in dynamic systems (e-commerce + mental health), especially within a Gaussian Mixture Model (GMM) sample/population. When abstracted, data can provide higher levels of insights, to enhance personalized navigation, recommendations and reflection.

Based on the key factors identified in this study, the following are sample rules for a goal-based scenario, but for an inverse student segment, i.e., those with high SAD.

Scenario 1: Encouraging more communication/outward outlook with users/players of similar interests

Rule 1	**Rule 2**
IF the student's history indicates high occurrences of SAD, AND social consumption is low, AND time management skills are self-rated low, AND communication skills are self-rated moderate, THEN suggest connecting to others in the system who have similar purchased items AND recommend adventure challenges which are moderately playful, AND include tool tips to improve clarity, AND encouraging visual on current productivity/ gamification status.	IF the student's history indicates high occurrences of SAD, AND social consumption is moderate, AND time management skills are self-rated low, AND communication skills are self-rated moderate, THEN suggest connecting to others in the system who have purchased similar and related purchased items, AND recommend adventure challenges which involve connecting with others who have time management skills self-rated moderate, AND include tool tips to improve clarity, AND encouraging visual on current productivity/ gamification status.

7. Conclusion

This project has designed and developed a fully functioning e-commerce application, with gamification rewards from mini games designed to improve mental health, time management skills and productivity among university students. Alpha beta testing results based on TAM 1, 2, and 3 [8-10], [11]'s UX, [12, 13]'s drivers are very promising.

The mental health/well-being mobile components can also be adapted to help autistic children and seniors with dementia. Loose coupling between e-commerce-mental health/ well-being mini games enables extensions to any ecosystem as well as improves scalability/reconfiguration, to enhance hedonic (stimulating, novelty) qualities. Improvements can be made to the mini games, e.g. to gather and analyze user data related to self-care activities and task management skills, to enhance personalized recommendations in self-care and time management.

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A Study on the Correlation Between the Allocation of Scientific and Technological Resources and Regional Independent Innovation Capacity in China

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Abstract. This paper constructs a theoretical model for testing the relationship between China's regional scientific and technological resource allocation and regional independent innovation capability. Taking the 31 provinces and cities in China as the research object, for the systematic correlation between the three dimensions of S&T resource allocation and the three dimensions of regional independent innovation capability, we break through the limitations of the existing uni-dimensional research, and innovatively constructed a typical correlation model of dual system. The empirical research shows that scientific and technological resource inputs have the strongest driving effect on innovation input capacity (coefficient of 9.564), followed by the environmental dimension (8.916), and there is a differentiation feature of the output dimension that the transformation of benefits is better than the transformation of talents. This paper reveals the three-dimensional law of "input-led-environmental synergy-output differentiation", which provides a quantitative basis for the formulation of regional innovation policies.

Keywords. Science and technology resource allocation, regional independent innovation capacity, typical relevance, resource allocation efficiency

1. Introduction

Against the backdrop of increasingly fierce global competition in science and technology, regional independent innovation capacity has become a key driving force in promoting economic growth, industrial upgrading and fostering core competitiveness. The report of the Twentieth National Congress of the Communist Party of China (CPC) clearly puts forward "accelerating the implementation of the innovation-driven development strategy" and emphasizes "optimizing the allocation of innovation resources and enhancing the overall effectiveness of the national innovation system". The core of implementing regional independent innovation is to enhance regional independent innovation capability, while the rational allocation of scientific and technological resources, as the basic support of regional independent innovation

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capability, directly affects the effectiveness of the regional innovation system [1][2]. Existing studies have shown that there is a close link between the allocation of scientific and technological resources (including the three dimensions of scientific and technological resource inputs, environment and outputs) and regional independent innovation capacity (covering input capacity, environmental capacity and output capacity) [3]. However, most of the existing studies focus on a single dimension (e.g., the relationship between R&D funding inputs and outcome outputs) and lack an in-depth exploration of the multidimensional correlation between the S&T resource allocation system and the regional capability of independent innovation [4]. Based on this, this paper aims to construct a systematic correlation framework between the allocation of scientific and technological resources and regional independent innovation capacity, and conduct a typical correlation analysis between the allocation of scientific and technological resources and regional independent innovation capacity, so as to provide theoretical basis and practical guidance for optimizing the regional innovation policy.

2. Indicator Construction

2.1 Construction of Evaluation Indicators for S&T Resource Allocation

In this paper, S&T resource allocation is taken as the target layer; S&T resource input B_1, S&T resource environment B_2, S&T resource output B_3 as the guideline layer; and other 8 specific evaluation indicators, including: S&T personnel input C_{11}, S&T funding C_{12}, S&T infrastructure input C_{13}, S&T awareness C_{21}, S&T industry development C_{22}, S&T informatization C_{23}, S&T output C_{31}, Economic Benefit Output C_{32} as the indicator layer to construct the evaluation index of S&T resource allocation.

2.2 Construction of Evaluation Indicators of Regional Independent Innovation Capacity

In this paper, regional independent innovation capability is taken as the target layer; regional independent innovation input capability D1, regional independent innovation environment capability D2, regional independent innovation output capability D3 are taken as the criterion layer; and other 9 specific evaluation indexes, including: talent input capability E11, funding input capability E12, public relations capability E21, innovation network capability E22, talent realization capability E31, technology realization capability E32, value realization ability E33, innovation radiation ability E34, and supporting development ability E35 as the index layer to construct the evaluation index of regional independent innovation capability.

Both the S&T resource allocation evaluation index model and the regional independent innovation capacity evaluation index can further refine the measurement indicators (see Table 1 for details).

Table 1. Refined measurements at the indicator level in the evaluation indicator model

Indicator Layer	Indicators for Measuring S&T Resourcing	Indicator Layer	Indicators for Measuring Regional Innovation Capacity
C_{11}	Full-time equivalent of R&D personnel C_{111} Number of technicians per 10,000 persons C_{112} Number of persons with tertiary education or above C_{113}	E_{11}	Full-time equivalent of R&D personnel in non-foreign-funded organizations E_{111} Participants in R&D projects from non-foreign-funded organizations E_{112}
C_{12}	R&D funding C_{121} R&D investment intensity C_{122} Local financial allocations for R&D expenditures C_{123}	E_{12}	R&D Expenditures Non-Foreign Costs E_{121} Technology acquisition and adaptation costs for non-foreign-funded institutions E_{122}
		E_{21}	Funding for the implementation of the National Industrialization Plan E_{211}
C_{13}	Fiber optic line length C_{131} Average number of computers per 100 households C_{132} New fixed assets in high-tech industries C_{133}	E_{22}	R&D Expenditures per Personnel E_{221} Value of technology market contracts per capita E_{222}
C_{21}	Patent applications for 10,000 employed persons C_{211} Coefficient of the ratio of the average wage in the scientific research sector to the average wage in society as a whole C_{212} Amount of technology results absorbed by 10,000 people C_{213}	E_{31}	Number of graduate students graduated E_{311} Growth rate of R&D personnel in non-foreign-funded organizations E_{312}
		E_{32}	Number of invention patents authorized by non-foreign-funded institutions E_{321} Contract value of technology market transactions E_{322}
C_{22}	Net exports of high-technology industries C_{221} funding for education C_{222} Urban workers in cultural industries C_{223} Urban employment in the scientific research industry C_{224}	E_{33}	Output Value of Enterprises Above Scale in High-Tech Industries E_{331} Output value of new products of non-foreign-funded enterprises E_{332}
		E_{34}	Output value of enterprises above large scale accounted for the proportion of the country E_{341} Share of high-tech industries E_{342}
C_{23}	Number of Internet users per 10,000 people C_{231}	E_{35}	R&D expenditure as % of GDP E_{351} Share of fiscal allocation to science and technology in total fiscal expenditure E_{352}
C_{31}	Coefficient of scientific and technological awards at the national level C_{311} Patent grants C_{312} Number of papers published C_{313}		
C_{32}	Gross output value of high-tech industries C_{321}		

2.3 Data Sources and Pre-processing

The data in this paper are mainly from official authoritative statistics, including publications such as China Statistical Yearbook, China Science and Technology Statistical Yearbook, China Education Statistical Yearbook, China Science and Technology Statistical Compendium, China High-Tech Industry Statistical Yearbook, as well as the official websites of the National Bureau of Statistics (NBS) and the Ministry of Science and Technology (MOST), and other governmental departments.

In terms of data processing, some of the indicators (e.g., R&D expenditures, etc.) can be obtained directly from the Statistical Yearbook as raw data, while some (e.g., full-time equivalents of R&D personnel in non-foreign-funded organizations, etc.) need to be integrated with multiple data sources and calculated. Since all indicators are positive, no normalization is required. However, considering the differences in the unit of measurement of each indicator, it is necessary to normalize the deviation of all indicator data to eliminate the influence of the unit of measurement and ensure the comparability of the data [5].

2.4 Weighting

In the evaluation indicators of S&T resource allocation and regional independent innovation capacity, each indicator contains 1-4 subdivided indicators, and the weights of the influence of the subdivided indicators on the allocation of S&T resources and the regional independent innovation capacity are different, so this paper chooses the hierarchical analysis method (AHP) combined with the expert survey data to determine the weights of each indicator[6].

First, this paper designs the questionnaire items according to the affiliation of indicators and variables. Then, 17 experts focusing on the research of scientific and technological resource allocation and independent innovation from the School of Management of Wuhan University of Technology were invited to participate in the questionnaire survey. Finally, the judgment matrix was constructed by calculating the average value of the experts' ratings, and the AHP method was used to calculate the parameters such as the weights of each indicator, the maximum eigenvalue and the consistency index (see Table 2 for details).

2.5 Calculation of Normative Level Indicators

The weights of the refined indicators were determined according to the hierarchical analysis method (AHP), and then the weighted average method was used to find the values of each measurement indicator in the guideline layer of regional scientific and technological resource allocation and regional independent innovation capacity (see Table 3 Table 4 for details).

Table 2. Results of weight calculation

Norm	Weights	Maximum Eigenvalue	C.I.	C.R.	Pass or Fail
C_{111}、C_{112}、C_{113}	0.656,0.232,0.112	3.055	0.028	0.048	yes
C_{121}、C_{122}、C_{123}	0.400,0.400,0.200	3.000	0.000	0.000	yes
C_{131}、C_{132}、C_{133}	0.125,0.301,0.573	3.023	0.012	0.020	yes
C_{211}、C_{212}、C_{213}	0.429,0.143,0.429	3.000	0.000	0.000	yes
C_{221}、C_{222}、C_{223}、C_{224}	0.333,0.167,0.167,0.333	4.000	0.000	0.000	yes
C_{231}	0.431	3.000	0.000	0.000	yes
C_{311}、C_{312}、C_{313}	0.571,0.286,0.143	3.000	0.000	0.000	yes
C_{321}	0.500	2.000	0.000	0.000	yes
E_{111}、E_{112}	0.667,0.333	2.000	0.000	0.000	yes
E_{121}、E_{122}	0.667,0.333	2.000	0.000	0.000	yes
E_{211}	0.333	2.000	0.000	0.000	yes
E_{221}、E_{222}	0.667,0.333	2.000	0.000	0.000	yes
E_{311}、E_{312}	0.333,0.667	2.000	0.000	0.000	yes
E_{321}、E_{322}	0.667,0.333	2.000	0.000	0.000	yes
E_{331}、E_{332}	0.500,0.500	2.000	0.000	0.000	yes
E_{341}、E_{342}	0.500,0.500	2.000	0.000	0.000	yes
E_{351}、E_{352}	0.667,0.333	2.000	0.000	0.000	yes

Table3. Scores of indicators on allocation of scientific and technological resources in 31 provinces and cities in China

Region	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}
Beijing	0.712	0.950	0.229	0.797	0.563	1.000	0.563	0.246
Tianjin	0.244	0.304	0.197	0.522	0.138	0.646	0.275	0.221
Hebei	0.151	0.131	0.208	0.077	0.250	0.232	0.073	0.086
……	……	……	……	……	……	……	……	……
Qinghai	0.063	0.038	0.044	0.121	0.070	0.263	0.126	0.003
Ningxia	0.077	0.036	0.062	0.050	0.067	0.156	0.114	0.006
Xinjiang	0.110	0.043	0.096	0.056	0.138	0.299	0.077	0.006

Table 4. Scores of independent innovation capacity indicators in 31 provinces and cities in China

Region	E_{11}	E_{12}	E_{21}	E_{22}	E_{31}	E_{32}	E_{33}	E_{34}	E_{35}
Beijing	0.417	0.686	0.682	1.000	0.428	0.879	0.213	0.173	0.912
Tianjin	0.154	0.248	0.060	0.577	0.232	0.122	0.200	0.116	0.387
Hebei	0.184	0.252	0.056	0.305	0.366	0.050	0.076	0.059	0.087
……	……	……	……	……	……	……	……	……	……
Qinghai	0.009	0.009	0.013	0.128	0.640	0.004	0.003	0.000	0.069
Ningxia	0.015	0.028	0.009	0.150	0.096	0.002	0.006	0.002	0.080
Xinjiang	0.037	0.029	0.017	0.116	0.142	0.009	0.008	0.002	0.055

3. Model Design

The interaction between the allocation of scientific and technological resources and regional independent innovation capacity constitutes an innovation ecology of "input - environment - output". In the input dimension (B_1-D_1), sustained investment in scientific

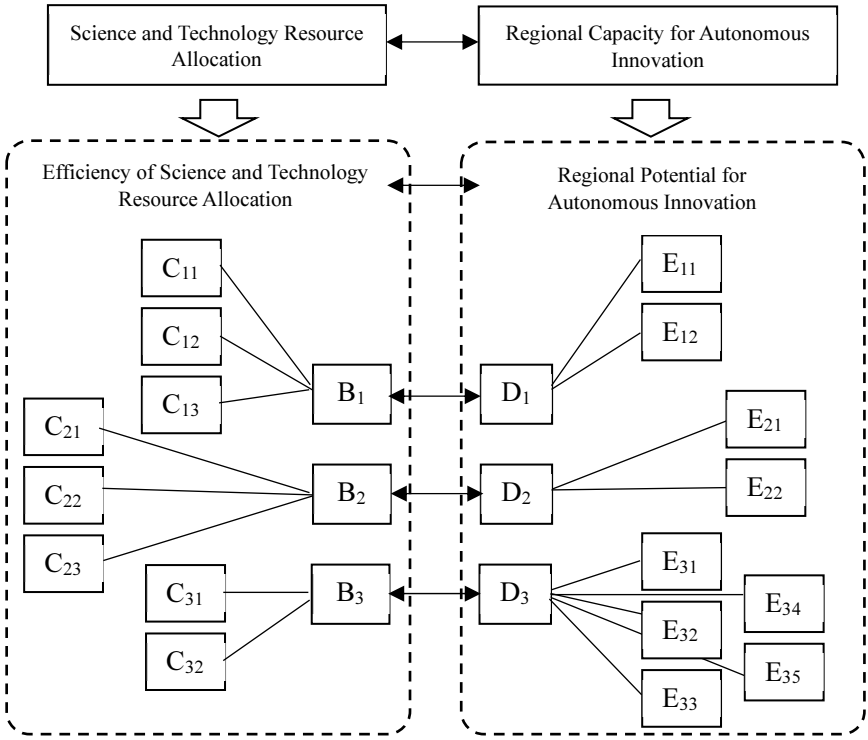


Figure 1 . Theoretical model for testing the relationship between S&T resource allocation and regional independent innovation capability

and technological personnel, funding and infrastructure creates a "fuel effect" and provides the original driving force for regional innovation. In the environment dimension (B_2-D_2), the catalytic effect generated by scientific and technological awareness, industrial foundation and informationization level promotes the cultivation of innovation ecology by optimizing external conditions. In the output dimension (B_3-D_3), scientific and technological achievements and economic benefits bring about "feedback effects". The results drive the innovation value cycle, validating the efficiency of resource allocation in the previous period and accumulating material and intellectual capital for a new round of innovation. Together, these three dimensions determine the sustainable evolutionary capacity of the regional innovation system.

3.1 Hypothesis Formulation

In accordance with the above analysis of the relationship between the allocation of scientific and technological resources and regional independent innovation capacity, this paper puts forward the following core hypotheses.

H1: There is a correlation between regional S&T resource inputs and regional capacity for autonomous innovation inputs;

H2: There is a correlation between regional S&T resource environment and regional independent innovation environment capacity;

H3: There is a correlation between regional S&T resource output and regional independent innovation output capacity;

H4: There is a correlation between regional S&T resource allocation efficiency (ratio of inputs, environment and outputs) and regional autonomous innovation potential capacity;

H5: There is a correlation between regional scientific and technological resource allocation and regional independent innovation capability [7] [8].

3.2 Correlation Analysis

(1) Relationship between regional scientific and technological resources investment and regional independent innovation investment capacity

This study adopts the typical correlation analysis method to analyze the correlation between the two sets of variables of regional scientific and technological resources input and independent innovation input capacity through SPSS software. The results show that the variance explained by the input of scientific and technological resources reaches 86.6%, while the capacity to invest in independent innovation reaches 95.8%. In terms of redundancy indicators, the overall redundancy of the two groups of variables is 1.7% and 4.2% respectively (see Table 5 for details). All the test indicators show that the correlation analysis between the two is significant.

Table 5. Typical correlation analysis statistics between regional scientific and technological resources input and regional independent innovation input capacity

Variant	Regional Inputs of Scientific and Technical Resources	Regional Capacity to Invest in Autonomous Innovation
Number of Variables	3	2
Typical Correlation Coefficient	0.977	0.803
Wilk's	0.016	0.355
Chi-SQ	110.869	27.983
Sig.	0.000	0.000
Extracting the Variance %	86.6	95.8
Overall Redundancy%	1.7	4.2

Based on the results of the variable loadings analysis shown in Table 6, it is found that there is a significant typical correlation between regional S&T resource inputs and independent innovation input capacity. In terms of scientific and technological resources input, the typical loadings of personnel input and financial input both exceed -0.9, while the loadings of infrastructure resources input are lower than -0.9, and the importance of the personnel factor is slightly higher than that of other factors. In terms of regional autonomous innovation input capacity, the loadings of personnel input capacity and financial input capacity also exceed -0.9, while financial input shows stronger explanatory power.

Table 6. Loadings of two sets of variables of regional scientific and technological resources input and regional independent innovation input capacity

Regional Inputs of Scientific and Technical Resources	Typical Loads	Regional Capacity to Invest in Autonomous Innovation	Typical Loads
Regional S&T Staff Input	-0.968	Regional Independent Innovation Talent Input Capacity	-0.958
Regional S&T Funding	-0.935	Regional Autonomous Innovation Investment Capacity	-0.999
Regional S&T Infrastructure Inputs	-0.887		

(2) Relationship between the regional scientific and technological resource environment and the regional capability of independent innovation environment

The variance explained by the scientific and technological resource environment reaches 74.2%, while the regional independent innovation environment capacity reaches 86.1%. In terms of redundancy indicators, the overall redundancy of the two groups of variables is 12.1% and 13.9% respectively. However, among the constituent dimensions of the regional independent innovation environment capability, the autocorrelation between the offensive capability and the network capability is weak (the correlation coefficient is only 0.494). This result shows that at the macro level, there is a significant correlation between the regional scientific and technological resource environment and

the independent innovation environmental capacity. However, at the micro level, there is insufficient coordination among the internal elements of innovation environmental capacity, and the low correlation among the elements of capacity makes the enhancement of environmental capacity lack of endogenous motivation, and fails to produce the synergistic effect of "1+1>2" [9] [10] [11].

Based on the results of variable loading analysis, it can be seen that high loading variables (>|-0.9|) include: scientific and technological awareness in the regional scientific and technological resource environment, and research and network capabilities in the capability of autonomous innovation environment. Low loading variables (<|-0.9|) include: the level of development of science and technology industry and the degree of informationization of science and technology. This suggests that there is a significant and typical correlation between the regional S&T resource environment and the capability of autonomous innovation environment. This correlation mainly drives the development of autonomous innovation environment capability through the enhancement of scientific and technological awareness. The second is the level of science and technology industry development and the degree of regional science and technology informatization.

(3) Relationship between regional S&T resource output and regional autonomous innovation output capacity

The variance explained by the output of scientific and technological resources reaches 67.6%, while the output of regional independent innovation capacity reaches 48.4%. The overall redundancy of the two sets of variables is 32.4% and 25.6% respectively.

As can be seen from the results of the load analysis of the two groups of variables, the output of regional scientific and technological resources is mainly driven by the enhancement of the output of economic benefits (load 1.000), which significantly drives the development of innovation value realization capacity, forming the core conduction path of "economic benefits-value realization". In contrast, the impact of scientific and technological talent output on the ability to realize innovative talent is relatively limited (low loadings), indicating that the enhancement of regional innovation output capacity relies mainly on the transformation of economic benefits rather than the accumulation of talent factors.

(4) Relationship between regional S&T resource allocation efficiency (inputs, environment and outputs) and regional potential capacity for independent innovation

The variance explained ratio of regional S&T resource allocation efficiency reaches 70.9%, the potential capacity for regional independent innovation is 67.9%, and the overall redundancy is 9.7% and 32.1% respectively.

As shown by the results of the loadings analysis, there is a significant typical correlation between the regional S&T resources allocation efficiency and the potential capacity for independent innovation, including S&T personnel inputs and funding inputs (loadings > -0.9). It shows that regional scientific and technological personnel input and scientific and technological funding are the most important factors in the enhancement of the potential capacity for regional independent innovation. The output of scientific and technological personnel and industrial development, on the other hand, have a secondary impact on the radiation capacity. This indicates that the enhancement of regional innovation capability mainly depends on the efficient allocation of scientific and technological human and financial resources, especially the cultivation of innovation development support capability.

4. Conclusion

Typical loadings of the two sets of variables of S&T resource allocation and autonomous innovation capacity are extracted through typical correlation analysis, and the typical loadings of the corresponding dimensions are multiplied to obtain the matrix of coefficients of action (e.g., S&T personnel input loadings × talent input capacity loadings), to quantify the strength of the correlation between the cross-system variables (see Table 7 for details). The strength of the association between the dimensions was judged according to the size and significance of the coefficients, and if the coefficient of action was significant and had a large value (e.g., >0.6), the corresponding hypothesis was supported.

Table 7. Coefficients on the role of regional S&T resource allocation in promoting regional independent innovation capacity

		D_1		D_2		D_3					Subtotal	Total
		E_{11}	E_{12}	E_{21}	E_{22}	E_{31}	E_{32}	E_{33}	E_{34}	E_{35}		
B_1	C_{11}	0.927	0.967						0.657	0.852	3.421	9.564
	C_{12}	0.896	0.934						0.698	0.880	3.408	
	C_{13}	0.850	0.886						0.442	0.557	2.735	
B_2	C_{21}			0.866	0.827				0.599	0.756	3.048	8.916
	C_{22}			0.822	0.785				0.623	0.785	3.015	
	C_{23}			0.761	0.727				0.604	0.761	2.853	
B_3	C_{31}					0.179	0.368	0.594	0.631	0.795	2.557	5.751
	C_{32}					0.302	0.602	1.000	0.571	0.719	3.194	

Based on the data shown in Table 13, the following main conclusions can be drawn:

(1) Inputs of scientific and technological resources have the strongest driving effect on innovation input capacity.

The coefficients of science and technology resources input dimension (B1) and independent innovation input capacity (D1) are generally higher than those of other dimensions, e.g., the coefficient of science and technology funding input on innovation funding capacity is as high as 0.934, and the coefficient of science and technology personnel input on talent input capacity reaches 0.927. This suggests that “hard inputs” of regional scientific and technological resources (human resources, capital and infrastructure) are the core driving force to enhance the capacity of independent innovation inputs, verifying the strong correlation of H1 and indicating that increasing R&D inputs can directly enhance the basic capacity of regional innovation.

(2) S&T environment is robustly associated with innovation environment capabilities, but slightly weaker than the input dimension.

In the environment dimension (B2-D2), the coefficients of science and technology awareness, industrial development and informatization level on innovation PR capability and network capability are all over 0.7, but the overall coefficient of effect in total (8.916)

is slightly lower than that of the input dimension (9.564). This suggests that a favorable S&T environment (policy support, industrial agglomeration, digitalization level) can effectively catalyze the formation of an innovation ecosystem (H2 holds), but its role is more dependent on the synergistic support of the input dimension.

(3) The correlation between scientific and technological output and innovation output capacity shows a divergence.

Significant differences emerge in the coefficients of action for the output dimensions (B3-D3). The coefficient of economic benefit output on value realization ability reaches 1.0, reflecting strong transformation efficiency. The coefficient of scientific and technological talent output on talent realization ability is only 0.179, indicating that there is a bottleneck in the transformation of talent achievements. This result partially supports H3, suggesting that the region needs to optimize the talent incentive mechanism to avoid the imbalance of "focusing on economic output but not talent retention".

(4) Allocative efficiency is significantly correlated with potential innovative capacity, but is constrained by output shortcomings.

Table 7 shows that the coefficient of the role of the efficiency of S&T resource allocation (comprehensive B1/B2/B3) on the potential capacity of innovation (radiation, support capacity) is generally above 0.6, which verifies H4. However, the coefficient of the role of S&T talent outputs on the radiation capacity (0.631) is significantly lower than the output of the economic benefits (0.719), which further corroborates the problem of the output polarization in the Conclusion 3, and indicates that the efficiency enhancement need to make up for the short board of talent results transformation.

(5) Strong correlation between the S&T resource allocation system and the overall independent innovation capability.

The total value of the coefficients of all dimensions is significant (9.564 for inputs, 8.916 for environment, 5.751 for outputs), and the system-wide correlation is verified by H5, but the contribution of all dimensions is in the order of inputs > environment > outputs, which suggests that the enhancement of the regional innovation capacity is still mainly resource-driven, and needs to be transformed to the higher-order stage of "environment optimization-output feedback" in the future [12][13]. This finding provides empirical evidence for the development of regionally differentiated innovation policies: the eastern region can strengthen environmental empowerment, while the central and western regions need to prioritize the strengthening of the input base [14].

This paper also has certain shortcomings. The data in this paper mainly rely on statistical yearbooks and official public data, and fail to include the latest S&T policy effects after the implementation of the 14th Five-Year Plan. Moreover, the data coverage is limited to the provincial macro level and lacks a finer-grained analysis of the core units of innovation such as key city clusters and high-tech zones, leading to limitations in the timeliness and spatial resolution of the study's conclusions, which makes it difficult to accurately capture the dynamic changes in the pattern of regional innovation in recent years and the differences in the allocation of resources at the micro level.

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Self-Evaluation of Mental Health in the Social Media Era: Insights from Youth in the Republic of North Macedonia

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Abstract. Social media are very important in the youth's daily life as they represent a way of communication and socialization among their peers. The impact of social media, whether positive or negative, deserves to be studied because it forms and shapes their world. The purpose of this study is to provide an overview of mental health among youth in North Macedonia. The research was conducted using a purposive sample of 107 students aged 18 and above from the final fourth year of two high schools in North Macedonia. The students were screened for usage of social media and only students who used 2 hours or more daily were included in the study. Self-evaluation of mental health was measured using the Mental Health Inventory-5 (MHI-5). The specific findings reflect the current situation regarding mental health among young people who use social media for 2 or more hours per day and conclude that young people have moderate mental health self-evaluation. The obtained results reflect the reality that exists among high school students in their final year and are a valuable source of information about their mental health. This study contributes to the ongoing discussion about fostering healthier digital environments for young people and enhancing their well-being.

Keywords. Well-being; Social Platforms, Adolescents; Digital Communication; MHI-5

1. Introduction

Lloyd [1] writes that social media is a powerful force in the lives of young people with a wide range of effects on their development. Furthermore, given the importance of adolescence in the genesis of mental illness, social media is a factor in young people's mental health. However, despite the role that social media clearly plays in the development of mental illness, the author concludes that little research has been done on the impact that social media has on young people's mental illness. Overall, the findings of current research suggest that social media has a major impact on young people in both

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positive and negative ways. In particular, some studies show a higher incidence and severity of bullying online compared to offline, which may contribute to the development of depression. This contrasts with the positive impact that social media appears to have on young people in minority groups (ethnic minorities and those with chronic illnesses or disabilities) by allowing them to connect with others who live similar lives despite geographical separation. Such a relationship acts as a positive influence in the lives of these people, although no direct link to mental illness has been shown.

Azagba et al. [2] investigated the association between social media use and mental health in a nationally representative sample of US middle and high school students (n = 23,366). Using the Patient Health Questionnaire - 4 to assess mental health, the study categorized social media use by frequency and identified two latent groups: a 'better' group with minimal poor mental health indicators and a 'worse' group with more indicators. Frequent social media use was associated with poorer mental health in both groups, although the association was stronger in the 'worse' group. The study conducted by Nazari et al. [3] investigated the relationship between social media use and mental health among 781 university students in Lorestan province, Iran. In this 2021 cross-sectional study, data were collected using questionnaires assessing demographic characteristics, social media use, problematic social media use, and mental health (DASS-21). The results showed that better mental health (lower DASS-21 scores) was significantly associated with being married, a student's major, and higher household income. Conversely, poorer mental health (higher DASS-21 scores) was significantly associated with problematic social media use and overall social media use. The authors concluded that social media use was directly related to mental health, and called for further research into its potential harms and safer usage. Barthorpe et al. [4] analyzed cross-sectional data from the Millennium Cohort Study to explore associations between social media screen-time as recorded in time use diaries (TUD) and key mental health outcomes - self-harm in the past year, depressive symptoms (Short Mood and Feelings Questionnaire), self-esteem (short Rosenberg scale). Social media TUD data were available for 4,032 adolescents. Results show that greater amount of time spent on social media was associated with an increased risk of self-harm and depression and lower levels of self-esteem in females.

Some of the negative aspects of social media is a special type of violence named "cyberbullying" [5]. This is defined as sending or posting cruel text or images that can hurt other people, and for which the primary channel is social media or other electronic means of communication. Most often, it is a violent peer behavior that manifests itself through a public compromising recording that is spread through social media. In addition, other methods have been observed, such as: sharing images of peers or other people in inappropriate situations, overweight people, a poll for the most unattractive classmate, and the like. The author concludes that with the increase in social media use, electronic violence among high school students is also increasing. Apart from this evidence, the negative influence of social media is demonstrated in the study of Beullens and Vandenbosch [6]. The study states that today's generation of adolescents, through the use of social networking sites, are provided with information about the perceptions, attitudes and behaviors of their peers, including information about alcohol consumption. The results of their study suggest that alcohol-related content creates positive norms for its use, which seems to be associated with increasing intentions to drink alcohol in the future. Additionally, Chern and Huang [7], in their study on Internet addic-

tion and health-related quality of life, demonstrate that Taiwanese students who are addicted to the Internet had significantly lower quality of health in physical, physiological, social and environmental domains.

Another study in the field conducted by Chambers et al., [8] points out that there is a persistent and growing tension between harmful online content and the potential for supporting vulnerable people online. Although their research identifies both negative and positive impacts of the internet on mental health, the authors conclude that there is a lack of policy frameworks to guide the development of health resources for online mental health care. The authors conducted research on the website ReachOut.com, which has been providing online services in Australia and Ireland for 20 years. Their study provides important insights into young people's online behavior and preferences for seeking help. One of the findings of the same study confirms that young people explicitly seek information about suicide online when they do not feel comfortable going elsewhere. The authors concluded that online services such as ReachOut.com have an important role in providing rapid relief to young people who are in a stressful situation and in facilitating their access to informal (family, friends) and formal (mental health professionals) sources of support.

The following part provides information about the context, more specifically about social media usage in North Macedonia. Micevska [9] notes that social media in North Macedonia has been gaining momentum since 2008. In her research, 87.6% of students from several universities had social media profiles, indicating that social media are part of the everyday lives of young people. The author states that respondents believe that social media is more accessible, i.e. it allows them to get information quickly, easily and in a timely manner from anywhere at any time. According to the author, technology is a means by which they maintain contacts and obtain information about their friends and acquaintances, but sometimes this is also the only means they use to get in touch with friends. The negative side is that they do not pay enough attention to the dangers that lurk in real life due to sharing too much personal information online, nor do they have reservations when sharing personal thoughts with people they do not know in person. Given the accessibility, young people are increasingly turning to online channels, as supported by a study from neighboring Kosovo where Efremov and Pruthi [10] found that manufacturers mainly use online communication strategies.

Regarding mental health, data provided by UNICEF [11] for North Macedonia shows that one in ten young people will experience some form of mental health problem. Additionally, the Institute of Public Health offers valuable information that is presented in the Annual Report of the Institute of Public Health (IPH) published on August 12, which is celebrated as International Youth Day. According to data from the Institute of Public Health [12], young people in North Macedonia visited a doctor more often in 2022 compared to the previous year 2021. In terms of reasons, these were mostly for respiratory diseases, but there was also a huge leap in visits to a psychologist. In terms of mental health, data show that the most common symptoms among young people are anxiety, depression, panic and phobic mood, self-harm and suicidality, coping with loss, identity crisis, displaced aggression, addictive behavior including internet addiction, domestic violence, relationship violence, inactivity and passivation, neglect of self, low self-esteem, hopelessness and despair, strong psych somatization, negative self-image, strong frustration and low tolerance. To overcome these situations, the Institute offers many recommendations that are reflected in: psychoeducation, indi-

vidual support for young people with previous mental health difficulties, youth support groups led by licensed psychologists and psychotherapists, support for marginalized groups, career and psychological counseling for young people. Official data show that the number of visits to a psychologist and speech therapist has increased from 1,871 in 2021 to 2,011 visits in 2022. The findings are especially important for the context of the study as they show the situation related to COVID-19 during which many adolescents increased usage of social media.

Building on insights from the aforementioned studies, it becomes evident that evaluating mental health among youth is crucial. Additionally, there is a lack of studies that provide valuable data on the state of mental health among adolescents in a non-Western context. Current study is particularly valuable because it highlights the effects of digital platforms on well-being in a specific national context, which is less frequently addressed in global literature. The abovementioned aspects lead to the research question: how do young individuals evaluate their own mental health? Addressing this question provides valuable insights into their mental well-being. Therefore, the aim of this study is to provide an overview of self-evaluation of mental health among youth who use social media for two or more hours per day.

2. Materials and Methods

The data were collected through an anonymous survey with secondary school students aged 18 and above. Google Forms was used for this purpose. Class teachers and parents who were given access to the survey were previously notified. Participants were screened for social media usage per day, with only those reporting two or more hours of daily use included in the study. A recent study by Mougharbel [13] points that heavy social media use (often defined as 3 hours or more per day) is associated with increased odds of psychological distress. In this case, 2 hours per day was chosen as a cut-off score as it represents a significant portion of the day (having in mind that students spend 8 hours on average in sleeping and minimum of 6 hours on average per day in school). The screening revealed a wide range of social media usage among the surveyed students. While 22.4% reported spending 120 minutes daily, and another 22.4% between 121-180 minutes, a significant portion reported much higher usage. Specifically, 14.0% spent 181-240 minutes, 15.0% spent 241-300 minutes, 10.3% spent 301-360 minutes (5-6 hours), and 15.9% reported an incredible 6 or more hours daily. Mental health was assessed via self-evaluation using the Mental Health Inventory-5 (MHI-5) [14]. The instrument is chosen as it provides a short overview of mental health. Mental Health Inventory-5 (MHI-5) consists of 5 questions. This self-report measure assesses mental well-being over the past four weeks using five questions related to nervousness, sadness, calmness, downhearted and blue and happiness. Each question utilizes a six-point Likert scale, ranging from 'All of the time' to 'None of the time. Questions addressing negative emotions are scored inversely to those addressing positive emotions. The final MHI-5 score was calculated using the standard instructions for this instrument. MHI-5 score ranges from 0 to 100 and is calculated by summing the individual question scores, subtracting five, and then multiplying the result by four. The results are presented in percentages for each question and chi-square goodness of fit test was performed on each question.

The study was conducted in December 2023. Regarding the sample for the needs of the research, 107 students from the final fourth year of two secondary schools in the capital Skopje were surveyed. The research included 57 students from vocational high school and 50 students from gymnasium. The sample consisted of 51 % female and 49% males. The sample included students from other cities but who decided to study in the capital because there is no available vocational school in their home city or decided to study in top-ranked gymnasium in the capital. A purposive sample was selected, including a vocational school with an emphasis on economics, and a gymnasium, to capture a broader range of student backgrounds and academic experiences. This selection was also based on the perception that these students, due to their specific educational paths, possess a higher level of awareness and engagement with social media. The selection of students was done according to predefined criteria such as students who are 18 years or above and students who use social media at least once a day for a minimum of 2 hours. The students did the self-evaluation of mental health regarding past month.

The research was carried out with prior notification of parents who were notified through the class teacher. The survey was set up as anonymous and confidential with an explanation that it would serve only the needs of this research. The instructions were provided in the questionnaire, along with information about the respondents' right to withdraw from the research at any time.

3. Results

The results of the empirical research, obtained from the MHI-5 scale are presented in the following part. The answers for each of the questions are presented in table 1. The results are presented in percentages according to answers of the questions.

Table 1. Summary of results regarding self-evaluation of mental health among youth

Questions MHI5	All of the time	Most of the time	A good bit of time	Some of the time	A little of the time	None of the time
Q1. Have you been a very nervous person?	7.5	16.8	15.0	20.6	36.4	3.7
Q2. Have you felt so down in the dumps that nothing could cheer you up?	6.5	12.1	8.4	18.7	28.0	26.2
Q3. Have you felt calm and peaceful?	10.3	36.4	22.4	18.7	9.3	2.8
Q4. Have you felt downhearted and blue?	7.5	11.2	10.3	15.9	29.0	26.2
Q5. Have you been a happy person?	21.5	34.6	19.6	14.0	8.4	1.9

The Chi-Square Goodness of Fit test revealed a significant deviation from a uniform distribution in responses to Q1, "Have you been a very nervous person?", χ^2 (5, N = 107) = 39.58, $p < .001$. The expected frequencies were calculated based on the assumption that responses would be equally distributed across all options. The data indicate that the observed frequencies of choosing different levels of nervousness (e.g., "All of the time," "A little of the time") differ significantly from what would be expected if all options were chosen with equal probability, suggesting that "A little of the time" has a much higher frequency (36.4) than expected (16.67), while "None of the time" has a much lower frequency (3.7) than expected. The same test (Chi-Square Goodness of Fit test) revealed a significant deviation from a uniform distribution in responses to Q2, "Have you felt so down in the dumps that nothing could cheer you up?", χ^2 (5, N = 107) = 23.80, $p < .001$. The expected frequencies were calculated based on the assumption that responses would be equally distributed across all options. The data indicate that the observed frequencies of choosing different levels of feeling down (e.g., "All of the time," "None of the time") differ significantly from what would be expected if all options were chosen with equal probability. The distribution of responses to Q3 about feeling calm and peaceful also shows a significant departure from a uniform pattern. A Chi-Square Goodness of Fit test (χ^2 (5, N = 107) = 45.85, $p < .001$) indicates that the observed frequencies of choosing different levels of feeling calm and peaceful (e.g., "All of the time", "Most of the time") differ significantly from what would be expected if all options were chosen with equal probability. Specifically, the response "Most of the time" was much more frequent (36.4) than expected (17.83), while the response "None of the time" was much less frequent (2.8) than expected (17.83), highlighting a non-uniform distribution in reported feelings of calmness and peace. The results revealed a significant deviation from a uniform distribution in responses to Q4, "Have you felt downhearted and blue?", χ^2 (5, N = 107) = 25.53, $p < .001$. The expected frequencies were calculated based on the assumption that responses would be equally distributed across all options. The data indicate that the observed frequencies of choosing different levels of feeling downhearted and blue differ significantly from what would be expected if all options were chosen with equal probability. For Q4, "A little of the time" was much higher (29.0) than expected (17.85), while "All of the time" was much lower (7.5) than expected (17.85). The Chi-Square Goodness of Fit test revealed a significant deviation from a uniform distribution in responses to Q5, "Have you been a happy person?", χ^2 (5, N = 107) = 41.54, $p < .001$. The expected frequencies were calculated based on the assumption that responses would be equally distributed across all options. The data indicate that the observed frequencies of choosing different levels of feeling happy differ significantly from what would be expected if all options were chosen with equal probability. For Q5, "Most of the time" was much higher (34.6) than expected (17.85), while "None of the time" was much lower (1.9) than expected (17.85).

Overall, the results suggest that most students experienced positive emotional states in the past month, with the majority feeling happy most of the time and reporting minimal nervousness or sadness. The calculated MHI-5 score for this group is 63.17. The interpretation of the score and comparison with other studies are provided in the next section.

4. Discussion

The results show the self-subjective assessment of students' emotional state in the past month. While many students reported experiencing positive emotional states, the distribution of responses across the range of possible feelings was not uniform. For nervousness (Q1), a significantly larger percentage of respondents reported feeling nervous only "a little of the time" or "none of the time," compared to feeling nervous "all the time" or "most of the time." Similarly, for feeling down (Q2) and downhearted/blue (Q4), a greater proportion of respondents indicated experiencing these feelings "a little of the time" or "none of the time." Conversely, students reported feeling calm and peaceful (Q3) and happy (Q5) "most of the time" at a significantly higher rate than other response options. Overall, students reported feeling happy and calm more frequently than they reported feeling nervous, down, or downhearted. Furthermore, the calculated MHI-5 score for this specific group is 63.17. The study of Theunissen et al., [15] suggest using MHI-5 cut-off score of 60 to indicate moderate-to-poor mental health, noting the lack of a defined cut-off score for different populations. Theunissen et al. quote the study of Kelly et al. conducted in 2008, according to which this threshold is consistently used in research and provides optimal sensitivity and specificity for the detection of depressive symptoms. The finding of the current study shows that the mean score for this group is higher than 60, which suggest moderate mental health self-evaluation of this group and accents the need for further investigation. The group had a score of 63.17 on MHI-5, which is close to the cut-off threshold. Some of the studies conducted in the past in Japan by Yamazaki et al., [16] among people aged below 30, show that their MHI-5 index is 70.17. The discrepancy between the current study's lower MHI-5 score (63.17) and the higher mean score of 70.17 among Japanese individuals under 30 can be attributed to differences in the age groups studied and the fact that the current group reported using social media for more than 2 hours daily. However, these results should be interpreted cautiously. Given Mougharbel's [13] findings, which suggest a link between heavy social media use (typically defined as three hours or more per day) and greater psychological distress, the results of the current study take on added significance. The current study's findings are particularly relevant in light of the study conducted by Griffiths et al., [17]. Namely, the study shows that adolescents with problematic social media use are typically less able to regulate their impulses to use social media, experience discomfort such as stress or anxiety when they have restrictions on their use, and it is constantly on their minds. The moderate mental health self-evaluation observed in this study may be explained by the exposure and stimulation associated with social media use, factors known to profoundly affect mental health, particularly in the context of overstimulation or harmful environmental exposures.

The limitations of the research are related to the sample and self-report instrument. The data were collected through self-reported items which is subjective measure. A possible solution or this aspect is multimethod study (including digital measurement) in the future. While self-report measures offer valuable insights into subjective experiences of mental health, they could be biased towards social desirability and lack objectivity. Therefore, these findings are interpreted cautiously, acknowledging the potential for bias and the need for further research using diverse methodologies. The sample in the research is purposive, including final year students in two high schools in Skopje, which raises the possibility that the sample may not be representative of the wider

young population (students who study in their home city). The sample was taken from schools in Skopje (capital of North Macedonia), so it has its limitations due to the inability to generalize the results to students in other regions in North Macedonia. Further research should include larger and representative sample and should examine direct link between frequency of usage of social media and mental health. Other researchers can build on these findings by investigating the specific types of social media interactions and demographic factors as moderating variables, helping to refine tools and strategies to support mental health in adolescents.

When interpreting the study findings, it is crucial to keep in mind the perspective of Ahmad et al. [18] who wrote that social media, similar to other media, is not intrinsically good or bad, but rather becomes so based on how frequently it is used. In this context, the aforementioned research is of great importance for a better understanding of young people and providing guidance for improving the quality of their life, mental health and well-being. Additionally, as the study of Chern and Huang [7] shows, internet addiction should be considered as a major cause of health concern which should be addressed through intervention initiatives in education. The study results are valuable source for planning and executing professional services which improve overall well-being of young people. This becomes even more important as there is a high level of integration of technology into the daily lives of young people which serves as an online extension of their offline lives [19]. The findings can serve as a baseline for organizing social media awareness campaigns which have a goal to promote responsible and beneficial use of social media platforms among young people. Additionally, relevant stakeholders should organize educational programs which aim to promote wellness programs and happiness through engagement with enjoyable online content. The results show that there is a need for more nuanced research exploring how young people perceive and self-evaluate their mental health in relation to their social media habits. Current study provides solid contribution by examining the self-assessed mental health of adolescents with two-hour daily threshold of social media use. By doing so, the study aims to contribute to the ongoing discourse on creating healthier digital environments for youth.

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Digitalization and Management Innovation IV
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Research on the Role of Beijing International Big Data Exchange in Promoting the Reform of China's Data Market

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Abstract. Taking Beijing International Big Data Exchange (hereinafter referred to as "BIBDE") as a case study, this paper discusses the practical path, innovative initiatives and challenges of China's data factor marketization reform. By analyzing BIBDE's explorations in data rights, classification and grading, trading model innovation, and ecosystem construction, the study reveals the key links and core contradictions in the marketization of data factors, and puts forward policy recommendations for future development. The study finds that BIBDE has constructed a full-process system of data rights, registration and transaction by introducing privacy computing, blockchain and other technologies, and has initially formed an ecosystem of data factor market. However, problems such as the imperfection of pricing mechanism and the complexity of cross-border data governance still need to be further solved. This paper provides theoretical support and practical reference for China's data factor market reform.

Keywords. Data elements, market-based reforms, data rights, ecosystems

1. Introduction

In recent years, with the rapid development of the digital economy, data has become the fifth largest factor of production after land, labor, capital, and technology. In 2020, the CPC Central Committee and the State Council issued the Opinions on Constructing a More Perfect Institutional Mechanism for Factor Market-based Configuration, which explicitly proposed to accelerate the cultivation of the data factor market, and to promote the efficient circulation of data resources and the release of their value. Data over-the-counter transactions accounted for more than 95% of the market, and problems such as data abuse, fuzzy rights, and confusing pricing have seriously constrained the healthy development of the market. The marketized circulation of data elements requires not only technical support, but also institutional innovation and ecological construction. Coase's theorem emphasizes that the market mechanism can achieve the efficient allocation of resources when the transaction cost is zero and the property rights are clear.

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In 2021, under the vigorous promotion of the Beijing Municipal People's Government, Beijing International Big Data Exchange (BIBDE) was established, aiming to build a "national infrastructure for the marketized allocation of data elements", which has become a key step in building a unified national data elements market. It has become a key step in building a national unified data factor market.

It is of great theoretical and practical significance to promote the market-oriented reform of data factors in China through in-depth study of BIBDE's practical paths and innovative initiatives, as well as analysis of the challenges it faces and the direction of its future development.

2. Literature review

2.1. Relevant studies on data elements

As the number of connections increases, the size of the market expands, and the number of application scenarios becomes richer, data achieves broader aggregation among different market participants across value chains and industries. Large amounts of dispersed data first need to be aggregated, which is the most fundamental step in data application [1]. It is difficult to simply apply the logic of property rights to data because of its replicability and non-exclusivity. The first step in the circulation of data elements is to determine the right of data ownership, but the industry, academia and the judiciary have not yet reached a consensus on whether the owner of data is the individual who produces the data or the enterprise that records the data. Jiang Xiaojuan's team at Tsinghua University proposed a framework for separating data ownership from the right to use [2] and operate in 2021, while researcher Zhou Hanhua refined the right to ownership to "the right of the source, the right of the data processor, and the right of the data processor. The right of the source, the right of the data processor, and the right of the data use subject" forming the prototype of the theory [3].

2.2. Related Research on Transaction Cost Theory

According to Coase, a firm is an organizational structure formed by people to improve economic efficiency [4]. Transaction costs arise mainly from the limitations of human rationality, which leads to inefficiencies in the decision-making and implementation process. Williamson, on the other hand, argues that transaction costs increase mainly because of the incompleteness of contracts. Due to human nature and the complexity of the environment, there is an asymmetry in the possession of information between the parties to a transaction, which creates additional costs in the transaction process [5]. In order to compensate for these efficiency losses, certain compensatory costs are also required. The components of these costs include the cost of information search and generation, the cost of negotiation and decision-making, the expenditure on monitoring and enforcement, the cost of managing transactions, and the cost of political transactions. The generation of transaction costs is influenced by human factors, environmental factors and the characteristics of the transaction itself. Enterprises can reduce the consumption of time and human resources in the transaction process by reducing unnecessary transaction steps, standardizing transaction norms, and simplifying transaction procedures. Technological progress and platform development

have made the trading market more open and transparent, effectively alleviating the problem of information asymmetry [6]. Lu Lige and other scholars have pointed out that China's data factor market is currently facing flow barriers between regions, sectors and industries, and that the essence of building a unified national market for data factors is to reduce systemic transaction costs [7].

3. BIBDE Development Path Analysis

3.1. BIBDE Fact Sheet

The data exchange 2.0 stage, which began in 2021 and continues to the present, marks a significant shift from the previous stage. This transition, driven by policy promotion, has enabled BIBDE to lead the national data trading platform into a new era. Since the establishment of BIBDE on March 31, 2021, BIBDE has consistently focused on developing the data trading market and unlocking the value of data elements. It aims to establish a financial and technological infrastructure centered on the Beijing-Tianjin-Hebei region, thereby radiating outward to drive the entire country's development and provide global services. This aligns with the mission of the Beijing Digital Institute. BIBDE has been walking in the practical exploration from 0-1, such as constructing the first large-scale data merchant circle in China, building the first data trading platform IDEX system based on independent intellectual property rights in China, constructing the whole-chain data trading rule framework for the first time, defining a new type of trading paradigm, and expanding the multi-factor comprehensive data trading, The establishment of BIBDE marks the entry of China's data exchange into the 2.0 stage, assuming the roles of resource integrator, product and service provider, and industry reviewer.

In May 2020, the Ministry of Industry and Information Technology (MIIT) issued the ‘Guiding Opinions on the Development of Industrial Big Data’. Subsequently, in January 2022, the General Office of the State Council released the ‘Overall Plan for Comprehensive Reform Pilot Program of Factor Marketization and Allocation’, along with a series of other documents aimed at supporting data trading. A key policy is the “Twenty Articles on Data” issued in December 2022, i.e. “Opinions of the Central Committee of the Communist Party of China and the State Council on Constructing a Data Base System to Better Utilize the Role of Data Elements”, which explicitly states that it is necessary to “explore the system of structural allocation of data property rights “, “establish the property right operation mechanism of data resource holding right, data processing and use right, and data product operation right, etc.”, and creatively give the three rights of the data to the right of separation, weakening the concept of data ownership, and splitting the data tenure into the right to hold data, the right to process and use, and the right to operate, and dividing the data into the public right to hold, the right to process and use, and the right to operate. The concept of data ownership is weakened, and data ownership is split into data holding right, processing right, use right and operation right, and data is divided into three categories of public data, enterprise data and personal data, which provides ingenious ideas, directions and support for data governance.

3.2. The data rights revolution

The data rights revolution begins with data classification, which is the first step in data asset management. The first thing that needs to be distinguished is what is public data, enterprise data and personal data. After roughly dividing the three types, the data can be further divided into the types to which it belongs based on specific industries, into industrial data, telecommunication data, financial data, energy data, transportation data, data in the field of culture, natural resources data, health and wellness data, education data, scientific data, and so on. It is further subdivided by business attributes, including business domain, responsible department, description object, process link, data subject, content subject, data usage, data processing and data source.

By the end of 2024, BIBDE had issued over 370 data asset registration certificates and expanded its operations to 22 provinces and cities across the country. This has facilitated the progression of data elements from rights confirmation to smooth circulation, and further to financialization and exploration. As a result, the avenues for realizing data's value have grown increasingly diverse.

Relying on blockchain and other advanced technologies, BIBDE Data Asset Registration Center was officially unveiled at the Data Elements Summit of the 2022 Global Digital Economy Conference, which is the first data asset registration center in China. Through data asset registration, the ownership of data holding rights is confirmed, and it can also effectively prevent disorderly transactions in the data asset market, which solves the concerns of many subjects who hold high-quality data but do not enter the market for transactions. The data asset registration certificate marks the transformation of data from ordinary information resources to data assets with tradable and valuable value, and the data with data asset registration certificate can be used as financial collateral, enterprise listed assets or financing tools, which promotes the substantive process of data assetization, intelligently matches the corresponding transaction mode in accordance with the principle of hierarchical classification and management, and guarantees that the source of the data can be traced, the content prevented from being tampered with, the sovereignty confirmed, the benefits distributed, and the process regulated. , benefits can be distributed, and the process can be regulated.

By the end of 2024, BIBDE has issued more than 370 data asset registration certificates and expanded its business territory to 22 provinces and cities nationwide, promoting the data elements from the confirmation of rights to the clear circulation, and then to the financialization and exploration, and the channels for releasing the value of data are becoming more and more diverse. Gradually formed the ecological structure of BIBDE picture to unleash the value of data.

3.3. Data element ecosystem construction

BIBDE started its strategic layout at an early stage, recruiting data custodians and data brokers globally in December 2021 according to the “Data Brokerage Management Measures (Trial)”. Data hosting partners should have both social credibility and operational public welfare, to have business qualifications, whether it is data processing, storage, or privacy protection technology should be in place, and the service capacity should also be strong, not only to retain existing customers, but also to play the word of mouth, to attract more customers to enter into the transaction, to create data 'safe' and Processing plant'. Data brokers are more focused on the scenario-based utilization of

data, by docking data resources, carrying out brokerage services, summarizing incoming transactions, and solving customer needs.

BIBDE reached an agreement with the counterparty regarding the policies, technology platforms, and market resources it could provide, as well as the service links offered by the counterparty. These service links cover parts of the chain, including data collection, governance, processing, rights determination, assessment, and pricing. Subsequently, BIBDE entered into a contract based on this agreement. As of July 18, 2024, BIBDE announced that there were 142 data brokers cooperating with BIBDE, and BIBDE's intermediary service system is an ecosystem in which multiple actors operate in concert, and these digital economy intermediary service providers initially constitute the intermediary service ecosystem of BIBDE's data transactions. Collaboration and complementarity between different subjects, and co-evolution between subjects to achieve value creation[8].

In May 2021, the state outlined its plan for national computing network hub nodes and launched the ‘East Counts West Counts’ project. BIBDE actively engaged with relevant government departments and subsequently became one of the builders of the East Counts West Counts integrated computing service platform. This platform aims to explore the intelligent coordination and scheduling of various computing power resources in neighboring cities. By providing affordable, universal computing power for small and medium-sized enterprises to train large models, it contributes to inclusive finance. Relying on its technological advantages, it has constructed a transaction service system that includes the entire chain of data transactions, data services, and arithmetic services, The "Eastern Data and Western Computing" project has given the Beijing Digital Institute the positioning of a national-level computing power scheduling platform and enhanced policy empowerment [9]. The integration of data elements, algorithms and arithmetic power represents the deep combination of information technology and traditional factors of production.

4. Current challenges in data exchanges

4.1. Dilemmas and breakthroughs in pricing mechanisms

The most common in the market today is agreement pricing, with more than half of current transactions relying on negotiation between supply and demand, a lack of uniformity, and a decoupling of data cost and value [10]. The high degree of personalization of big data products leads to large price fluctuations and significant cross-scene differences. And only more and more data elements demand side into the transaction, can produce fair value, the price can be more objective and fair, can find a reference for the subsequent market method, income method, etc., can better assess the value of data assets.

4.2. The complexity of cross-border data governance

Since 2019, the United States has launched data trust pilot projects, such as those mentioned in the Town Hall Dialogue, which aim to create a regulated entity that ensures the fair and responsible use of data, with the attention and participation of different groups in society. In 2020, the 27 countries of the European Union jointly

signed the GAIA-X Declaration, which aims to establish a data infrastructure ecosystem controlled by Europe to reduce dependence on US cloud service providers, ensure data sovereignty and security, and become a key tool for the EU to achieve digital sovereignty and control cloud infrastructure, and contribute to the European economy. In fact, BIBDE has developed the first data hosting service platform in China to support cross-border data circulation of enterprises, and has also joined hands with international arbitration organizations to participate in cross-border dispute resolution; BIBDE has also participated in the practical implementation of the negative list policy for five key industries, including automobile, medicine, and retail, in the Beijing Free Trade Zone.

Against the backdrop of strengthened awareness of data sovereignty and tightened security scrutiny in various countries, cross-border data circulation has evolved from a mere technical collaboration issue to a composite governance problem involving national security, industrial competition and legal conflicts [11].

5. Conclusion

With the "20 Data Points" as the policy guide, BDSO has implemented advanced technologies such as privacy computing and blockchain to realize the "usable and invisible, controllable and measurable use" of data, and solve the trust problem in data transactions. Through the construction of a data transaction rule system and an intermediary service ecology, it has attracted the participation of a large number of data supply and demand parties and intermediary service providers, forming a complete data element market ecosystem. The practice of Beijing Institute of Data Technology shows that the market-oriented reform of data elements is a systematic project, which requires the coordinated promotion of technology, policy, and ecology, and continues to deepen the innovation of data element circulation mechanism and promote the transformation of data from resources to assets.

As an important practice platform for the market-oriented reform of data elements in China, BIBDE has successfully explored a new path from data rights confirmation, classification and hierarchical management to data assetization and financialization through technological innovation, policy support and ecological construction. Since its establishment, BDI has overcome multiple challenges such as technical deficiencies, legal blind spots, and lack of market trust, and gradually built an infrastructure and rule system for the circulation of data elements, providing a reference example for the high-quality development of China's data element market.

From a domestic perspective, this model effectively integrates data resources across regions, fostering inter-regional data circulation and sharing. It helps to shape a unified national data element market system and strongly supports the coordinated development of the digital economy nationwide. The model's successful experience in data property rights definition, pricing mechanisms, and transaction processes offers valuable references for various industries to establish data-related standards, thereby promoting the rational and innovative use of data.

On the international stage, it provides useful insights and ideas for constructing data element markets in other countries and regions, enhancing global exchanges and cooperation in data governance and digital economy development. As data grows increasingly vital in the global economy, this widely applicable innovative model is poised to expand into more scenarios and fields. It will continuously drive data

assetization, financial innovation, and the robust growth of the digital economy, propelling the global economy's digital and intelligent transformation and upgrade.

6. Suggestion

6.1. Building a national unified market for data elements with mutual trust and synergy

The construction of a nationally unified data factor market should be based on a safe and reliable data factor circulation infrastructure. It should promote data sharing of governmental public resources, facilitate the articulation and matching of high-quality data factor supply and the actual needs of economic development, and open up obstacles to the independent flow and allocation of data factors. At the same time, drawing on the experience of Europe and the United States, a unified platform for data openness and sharing should be established, and processable datasets and toolsets should be centrally opened up, with a clear scope and specification for the open sharing of public data.

6.2. Continuous technology development and innovation

Give full play to the advantages of the new national system, strengthen scientific and technological research in such areas as blockchain, meta-universe, quantum science and technology, 6G transmission technology, high-performance computing, sensor technology and basic software, create more application scenarios linking digital technology and the real economy, and promote the deep integration of digital technology with various industries. Universities, research institutions and enterprises are encouraged to cooperate in data element-related technology research and development and innovation. Through industry-university-research cooperation, the transformation of technological achievements can be accelerated, the efficiency and effectiveness of technological innovation can be improved, and strong technical support can be provided for the development of the data factor market.

6.3. Establishment of a dynamic compliance system

Accelerating the formulation and improvement of laws and regulations related to the data factor market, clarifying the ownership of data, transaction rules, privacy protection and other requirements, and providing legal safeguards for the compliant development of the data factor market. At the same time, relevant laws and regulations should be revised and improved in a timely manner in accordance with the development and changes in the market to ensure that they are compatible with the actual market situation. Regulators can make use of big data, artificial intelligence and other technical means to conduct real-time monitoring and analysis of data transactions, so as to detect and deal with violations in a timely manner.

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Promote the Formation and Development of the Talent Ecosystem of Enterprises Based on the Recruitment Process

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Abstract. In an era marked by digital transformation, economic volatility, and changing workforce values, enterprises are increasingly challenged to attract, develop, and retain top-tier talent. This paper examines how the recruitment process can serve as a strategic foundation for building a flexible and dynamic talent ecosystem within enterprises. It identifies major recruitment issues, such as lack of oversight, overreliance on external hiring, and ineffective candidate assessment. In response, the study highlights emerging trends, including skills-first hiring, flexible employment models, internal talent mobility, enhanced employer branding, and the strategic role of recruiters. The paper proposes constructing a talent ecosystem akin to an enterprise-level ERP system, enabling efficient talent flow, internal development, and alignment with corporate values. Ultimately, the research emphasizes that a well-structured talent ecosystem is vital for enterprises to maintain competitiveness and adaptability in the face of ongoing change.

Keywords. Talent ecosystem; recruitment strategy; digital economy; skills-first hiring; flexible employment; employer branding; internal mobility; human resource management

1. Introduction

1.1. Background

Talent, as an important strategic resource, can also be developed as one of the core competencies of enterprise development. Thus, the enterprise has more and better quality talents means that the enterprise is a step forward to success. However, uncertainties such as "Internet Plus", the digital economy and epidemics have increased the volatility of the economic environment for companies. As a result, it has become more difficult for companies to attract more suitable, higher quality and more stable talent.

Recruitment is not only an important stage in attracting and selecting the talent to be appointed for the enterprise, but also a process of creating a pool of talent that can sustainably support the development of the enterprise.

In the era of the digital economy, the platform economy and various new types of Internet economy are developing on a large scale. The work flexibility of the labour force is increasing. At the same time, due to changes in social values, the new era of

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talent places more emphasis on the realisation of personal values, and more emphasis on the inner feelings of the individual and the enhancement of self-competence. Therefore, not only from the perspective of the development of the times or from the perspective of changes in the values of the labour force, the recruitment difficulty of enterprises has further increased [1], and enterprises must articulate a unique value proposition to better absorb the highly skilled personnel needed by these enterprises.

1.2. Theoretical Framework

Human Capital Theory [2]: This theory views employee knowledge, skills, and abilities as valuable assets that generate economic return. The paper applies this framework by treating recruitment and talent development as forms of capital investment.
Resource-Based View (RBV) [3]: RBV posits that firms achieve sustained competitive advantage by developing resources that are valuable, rare, inimitable, and non-substitutable—especially human talent. This paper uses RBV to frame the talent ecosystem as a strategic capability.

Strategic Human Resource Management (SHRM) Framework: SHRM highlights the importance of aligning human resource practices with long-term organizational goals. This paper integrates SHRM by positioning recruitment and internal mobility as strategic drivers of adaptability.

Maslow's Hierarchy of Needs: This psychological theory explains individual motivation based on five hierarchical needs. The study uses this theory to understand workforce expectations, especially in terms of flexible employment, personal development, and meaningful work.

Digital HR and Emerging Trends: This includes the influence of talent analytics, artificial intelligence in recruitment, and gig economy employment models. These elements are essential in explaining shifts toward skills-first hiring and dynamic talent ecosystems.

1.3. Literature review

This paper is grounded in multiple theoretical perspectives to provide a holistic understanding of talent ecosystem development. Human Capital Theory posits that investment in employee skills yields measurable organizational value. The Resource-Based View (RBV) emphasizes the strategic value of rare and inimitable human assets. Strategic Human Resource Management (SHRM) highlights the alignment of HR practices with long-term business goals. In the context of digital transformation, emerging topics such as talent analytics, artificial intelligence in recruitment, and the rise of gig economy employment further enrich the theoretical foundation of this study [4].

Through the collation of existing literature, the discussion on talent absorption is mainly divided into the following aspects: firstly, the importance of talent absorption to organisations. According to Jia Xi, Jin Hui and Wu Dinglong, talent absorption is the way for any political, economic, scientific, technological, military and other organisations to achieve sustainable development [5]. Secondly, the input-output satisfaction aspect of talent absorption in organisations. According to the results of a related survey on a famous HR website, less than 5% of organisations are very satisfied with the input and output effects of talent absorption, and nearly average organisations think that the output effects are average.

In the existing literature on the relevant discussion of creating a talent ecosystem, the practice mainly includes the following aspects: first, more absorption of innovative talents. Enterprises need to absorb more innovative talents to make up for the shortcomings in the ecological chain [6]. Second, "find" talents in the recruitment process. According to Wang Gang, in order to build a talent ecosystem, the principles of continuous tracking, long-term accumulation, dynamic management, information technology and circle should be applied in the recruitment of the talent team [7]. Thirdly, companies should cultivate talents quickly. Employee training should be strengthened so that talents can be quickly integrated into the enterprise [8]. Fourth, enterprises must be able to use the right talents. When employing people, they must deeply understand the position and also fully respect the laws [3]. Finally, enterprises should also pay attention to retaining talents in building the talent ecological chain. Retaining talents through good value sharing and shared revenue distribution management [9].

The related literature on talent absorption and talent ecosystem mainly deals with the importance of the two and their application in the four modules of human resource management, namely, "selection, training, employment and retention". The previous literature has also been sufficiently researched from the meaning to the practice. However, we are in a new era of digital economic development. In this situation of increased uncertainty in the general environment, how should enterprises carry out talent absorption and create their own talent ecosystem? Can we make use of relevant digital technologies to promote talent absorption and the construction of talent ecosystems in enterprises?

1.4. Methodology

This research is based on a structured literature review approach, identifying and synthesizing academic journals, industry reports, and white papers relevant to modern recruitment strategies and talent ecosystem formation. Data sources include SHRM, McKinsey, Academy of Management, and Chinese HR publications, ensuring both global relevance and localized insight.

2. Analysis of the current situation of enterprise recruitment

In recent years, the concept of talent has been upgraded from "supporting development" to "leading development"[10]. Experienced every year after the fierce international and domestic competition for talent, each enterprise on the importance of talent awareness gradually in-depth, experienced the talent service enterprise development, talent to support enterprise development, talent to lead the concept of enterprise development of the updated iteration. Talent "war" at the beginning of enterprises tend to offer more competitive benefits to attract the different types of talent needed by enterprises, especially the fast-acting "plug and play" type of talent.

In an era of greatly increased economic uncertainty and the rapid development of digital technology on the Internet, the uncertainty and recruitment risks faced by companies have further increased.

2.1. Economic uncertainty

In recent years, due to the rapid development of science and technology, the state's support for new industries is also increasing. China's high-tech industry is gaining momentum. And high-tech, the rise of the Internet industry is mostly due to its more advanced technology. Technology continues to develop, the enterprise also correspondingly endured round after round of "big waves of sand". In order to better adapt to the volatility of the external economic market, companies must also be more flexible in their recruitment [11].

Therefore, enterprises in the recruitment process are more focused on how to absorb talent into their own talent pool, but the appointment of talent at the same time to ensure a certain degree of flexibility. Must ensure that the talent can be flexible in and out of the enterprise. Therefore, enterprises are more inclined to flexible forms of temporary employment.

2.2. The Rise of Internet Recruitment

Internet recruitment has time-saving, effort-saving, cost-saving advantages. Not only that, but the development of emerging digital technology has made Internet-based recruitment methods increasingly diverse. However, through the review of relevant information found that the current online recruitment forms, although diverse, the application is also more and more extensive, but the efficiency of the Internet online recruitment is to be considered, while the effect is also unsatisfactory.

2.3. Innovations in the way companies recruit

Since today's recruiters are mostly from Generation Z (the generation born between 1995 and 2009), their focus is more on their own feelings. As a result, traditional recruiting models and talent development paradigms may not work for them. As a result, companies are choosing to innovate their recruitment methods to attract the new generation of talent.

For example, the "blind box recruitment" was designed based on the preference of young people in the Z era. However, while pursuing the use of innovative recruitment methods to attract new talent, enterprises must also ensure that such recruitment methods are in line with relevant laws and regulations, so as to avoid being caught in an "illegal storm".

3. Major problems in corporate recruitment

Many enterprises lack a formal mechanism to evaluate or track the success of their recruitment practices, resulting in suboptimal hiring outcomes. There is a strong preference for hiring externally even when internal promotions could be more efficient and motivating. Focusing excessively on passive job seekers can inflate hiring costs and prolong recruitment cycles. Although some companies use personality or cognitive tests, these are often disregarded or improperly interpreted during final decisions.

3.1. Oversight Gaps in Hiring Practices

In theory, companies should be evaluating their hiring practices and documenting them accordingly to ensure they are indeed hiring the best talent. And according to the results of a hiring survey conducted by Wharton School management professor Peter Cappelli, only one-third of U.S. companies check to see if their hiring processes are producing good employees. When companies are asked why they don't follow up to monitor the effectiveness of their hiring, many agree that it's too difficult to measure employee performance.

The lack of supervision of the recruitment process is more common and serious in Chinese companies than in some foreign companies.

3.2. Bias Toward External Candidates

According to relevant survey results, most organisations prefer to spend a lot of effort on recruiting external staff than promoting internal staff.

This is despite the fact that it takes more time, effort, etc. to recruit externally rather than internally to achieve the same results in the same position. At the same time, companies know far more about the capabilities of their internal employees than they do about external employees. The choice of internal recruitment can also improve the motivation of employees, improve the mobility of employees, and job enrichment [12]. However, companies still prefer external employees and are willing to offer higher salaries to employees recruited from outside the organization [13].

3.3. Targeting Passive Candidates

There is also a problem with the way in which companies treat job seekers. Instead of hiring people who are actively looking for work, companies sometimes aim to attract "passive" candidates who show no signs of wanting to change jobs. This approach significantly increases the cost of recruitment and makes it more difficult for companies to recruit.

3.4. Lack of Systematic Selection

Headhunters often provide companies with a range of tests, such as facial expressions and word choice, to name a few, but there's no evidence yet to prove just how effective these tests are at picking out the best candidates. Even if these tests are conducted, recruiters in companies often ignore the results, and some companies even do the tests just so that they can have a better excuse to politely reject a job applicant.

4. New trends in the development of talent absorption

4.1. Changes in recruitment roles

Talent acquisition has become a more strategic function, and as a result, recruiting will have a greater impact on business segments, and may even contribute to key business changes [14].

At the same time, the recruiter in the enterprise will have a greater say in the remuneration. In the process of talent attraction, in the face of today's highly uncertain external economic environment, according to Maslow's hierarchy of needs theory, people will first focus on the satisfaction of physiological needs, and salary as a need to meet the physiological needs, will become an important factor in attracting talent. Therefore, recruiters as the first contact with talent, recruiters have more say on the salary, help companies to attract and retain more talent.

As the importance of talent grows, the labour market is tilting towards the talent side of the equation, so better employer branding in the recruitment process is more likely to facilitate the recruitment of talent [15].

Interpersonal skills will become a more important factor in the qualities required of recruiters [16]. Recruiters will need to have a more strategic set of soft skills. For example, recruiters' communication skills, ability to build relationships with people quickly, adaptability to the environment as well as to people, problem solving skills and business acumen are increasingly required.

Recruitment will also be integrated with the learning and growth stages of talent development. As organisational structures tend to be flatter and hiring leaders are increasingly focused on mobility, skill-focused hiring and retention, recruiters will need to be able to anticipate whether the talent they are dealing with will be able to adapt to multiple roles within the organisation and ensure that the talent is able to develop their careers within the organisation.

The use of digital and intelligent recruitment tools enables recruiters to focus their work more on the HR part of the recruitment process. The development of Artificial Intelligence helps recruiters to complete the time-consuming and labour-intensive transactional work in the recruitment process, so recruiters' work will be more focused on job descriptions, talent identification and other HR components.

4.2. Diversification of employment patterns

As the uncertainty of economic development increases, the development of enterprises also faces more uncertainty. There is a greater need to increase the flexibility of the talent pool in order to adapt to the dynamic changes in the business environment.

As a result of changes in the external environment, many business executives have reported that their recruitment efforts have been negatively impacted to some degree. However, companies still prioritise diversity, fairness and inclusion in recruitment.

At the same time, there is an increase in the preference for temporary workers in enterprises. In the face of dynamic changes in the external environment, enterprises need more flexibility to absorb talent. Therefore, more enterprises need to establish a talent pool, to maintain a certain degree of mobility between the internal and external talent, on-demand to absorb talent [17].

4.3. Increased importance of employer branding

Companies will pay closer attention to what candidates want most in the recruitment process. At this stage, our labour market is still tight and according to statistical analysis of relevant data, talent will remain dominant for the next five years. In order to remain competitive in the labour market, business parties will have to revisit their employer brand and ensure that it is aligned with the needs of candidates.

Recruitment professionals will re-align themselves with the way they attract talent. Instead of focusing on how people will progress through the organisation, recruiters will focus more on showing candidates how they will develop their careers within the business, whether or not they ultimately choose to stay with the organisation.

Generation Z will have more respect for employers who value development and diversity. Career development and acquiring new skills are important to young employees.

4.4. Skills-first recruitment

Skills-first hiring is set to become the gold standard. Since 2019, the percentage of recruiter searches screened by skills has grown by 25 per cent, according to job boards. And today, the percentage of recruiter searches by skills is nearly 50 per cent higher compared to searches by years of experience.
At the same time, companies' skills-first strategies will give more opportunities to overlooked talent [18].

Today, more and more businesses are looking to recruit people from a wide range of backgrounds in order to bring a different perspective to their organisation. As a result, corporate recruitment will increase the emphasis on employee skills.

Precisely, companies will focus more on the skills that their employees have and need. Skills have become an important currency and companies will need to be more aware of what their employees are doing and what they are not. Forward-thinking employers will map out the skills of their employees and the skills required for specific positions [19].

4.5. Ensure mobility and promotion of talent within the organisation

Business managers will recognise the value of filling vacant positions with internal talent. The unstable economy is forcing organisations to look more frequently at internal recruitment when filling vacant positions: nearly three-quarters of recruiters believe that internal recruitment will be an important factor influencing future hiring over the next five years.

Skills upgrading will be a key tool for companies to retain a diverse workforce. With companies now facing a huge skills gap between them, most recruiters believe that upskilling employees will be a key factor in shaping the future of recruitment over the next five years.

Learning will be one of the key sources of motivation for job seekers, not just for employees. In the coming years, job seekers will not only consider a particular job, but also whether the organisation offers them the opportunity to develop their career. Surveys report that the top five priorities for job seekers are: rewarding salary, work-life balance, flexible work management, opportunities for progression and skills development.

5. Creation and application of the talent ecosystem

A talent ecosystem refers to an interconnected framework where talent acquisition, development, mobility, and retention processes are managed as a cohesive system, similar to how an ERP (Enterprise Resource Planning) system integrates business

functions. Unlike traditional talent pipelines or succession planning that often operate in silos, a talent ecosystem emphasizes real-time responsiveness, skill mapping, and internal-external mobility, driven by data and digital tools.

In the establishment and use of the talent supply chain must focus on the following aspects:

For one thing, an enterprise's talent ecosystem should be able to respond in a timely manner to the talent needs of different positions in the organisation. Therefore, the construction of the talent ecological supply chain of enterprises should focus on attracting diversified, highly skilled talents that are more in line with the business development of enterprises.

Secondly, the relevant human resources management personnel to accelerate the inventory of talent gaps by way of timely selection of talent from the talent pool of the enterprise to carry out the corresponding talent supply.

Thirdly, human resources management personnel should pay attention to improving the efficiency of the use of talents when carrying out staff work arrangements. Times in the development of high-skilled personnel will respond to the needs of the times to learn emerging technologies to "arm themselves". Therefore, the talent pool in the enterprise is likely to have more than one kind of job skills. In the face of such talent, enterprises should be allowed to flow between different departments, to put an end to a sector of the "monopoly" behaviour.

Fourth, enterprises should establish an internal talent pool to achieve a dynamic balance of the source of talent within the enterprise, so as to ensure the supply and flow of internal talent.

Fifth, enterprises must focus on the quantity and quality of talent in the talent pool when building the talent pool. This means that enterprises must pay attention to the talent pool "open source". "Open source" refers to the development of innovative channels for recruiting talent, to achieve the diversification of the way to attract talent. And "cutting back" mainly refers to the selection of talent. Enterprises should be strict, focusing on the quality of talent to ensure.

In addition, enterprises must pay more attention to the talent ecosystem in building whether the talent can flow within the enterprise and enhancement. This requires enterprises to pay more attention to the career development planning of talents, not only look at the existing skills of talents, but also pay more attention to the comprehensive quality of talents, talents and the core values of the enterprise whether to match the personnel quality model "iceberg" part of the following.

6. Summary and Implications

From the perspective of enterprises, enterprises want to adapt to the development of the times, improve the ability of enterprises to adapt to economic instability, it is necessary to create a more flexible and more mobile talent ecological chain. To ensure that the talent can adapt to the development of enterprises, in the enterprise to do the talent "in" and "out". To further revitalise the internal and external talent resources, but also to choose the enterprise's "fellow travellers" to achieve the common growth of talent and enterprise. Talent ecosystem focuses on a dynamic balance of talent, so according to the development needs of enterprises, it is also likely to appear in different enterprises to share the talent ecological model.

Standing in the recruitment platform's point of view, the future recruitment platform will be more inclined to focus on the collection of professional talent information in a certain field. From the perspective of the industry to establish an industry talent ecosystem. So you can do an industry within the integration of high-precision talent, breaking down enterprise barriers, talent is not limited to the internal circulation of enterprises, more able to circulate between different enterprises in the industry.

Standing in the perspective of future candidates, enterprises tend to be more flexible in the mode of employment; at the same time, compared with the academic elements, enterprises have been more important to the skills of the talent element. Therefore, as a candidate not only to master solid professional knowledge, professional skills, but also to be able to achieve a diversified development of the "slash youth", to be more favoured by enterprises.

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Supply Chain Digital Reform Enhances Enterprise Ecological Competitive Advantage: An Exploratory Case Study Based on SHEIN

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Abstract. The supply chain is pivotal to the development of the real economy, yet traditional models increasingly struggle to meet rapidly evolving market demands in the digital era. In this context, the strategic integration of digital transformation and big data has become essential for enhancing supply chain responsiveness, precision in market demand detection, and overall competitive resilience. This paper employs an exploratory case study methodology, using SHEIN—a prominent cross-border e-commerce enterprise—as the research object. Drawing upon both primary interview data and secondary sources, the study systematically examines how digital supply chain transformation facilitates the development of a flexible, network-based co-creation model. The findings reveal that the application of digital technologies such as big data analytics, artificial intelligence, and real-time information systems significantly accelerates market responsiveness, ensures transparency across supply chain nodes, and enhances operational flexibility. These capabilities collectively contribute to the reinforcement of a firm's ecological competitive advantage, setting a benchmark for sustainable growth in the real economy. The study not only enriches the theoretical discourse on supply chain digitalization but also provides actionable insights for practitioners and policymakers seeking to leverage digital innovations to secure long-term competitive edge.

Keywords. Digital management, supply chain transformation, ecological competitive advantage, flexible supply chain

1. Introduction

The supply chain is crucial to the real economy, directly affecting firm performance and competitive advantage. Traditional supply chains, however, often suffer from delayed information flow, sluggish market response, and low production efficiency—issues that are particularly acute in the fast fashion industry. Faced with intense global competition, multi-channel retailing, and sustainability demands, fast fashion companies must embrace digital transformation. In this context, SHEIN leverages big data, IoT, AI, and cloud computing to enable real-time communication

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and efficient collaboration across its supply chain, swiftly capturing market trends, meeting personalized consumer needs, and securing a unique ecological competitive advantage. Research gap in digital supply chain: Current studies on digital supply chains largely focus on enhancing enterprise operational efficiency, cost control, and responsiveness, while there is a notable lack of systematic research on how enterprises can transition from traditional "chain competition" to networked "co-creation" through digital supply chains. The research goal: Therefore, this study adopts an empirical approach to explore how digital transformation facilitates the establishment of a "networked co-creation" supply chain that, in turn, enhances an enterprise's ecological competitive advantage.

The research questions: In light of the foregoing discussion, this paper selects SHEIN as a case study to examine, through the lens of its digital supply chain management practices, the impact of digital supply chains on the ecological competitive advantage of an enterprise. By addressing the aforementioned issues, this study analyzes the characteristics of SHEIN's digital supply chain and assesses its influence on the enterprise's ecological competitive advantage.

2. Related works

2.1. Digital supply chain

The rapid proliferation and deeper integration of digital technologies in enterprise development are transforming traditional supply chains into digital supply chains characterized by digitization, networking, intelligence, and visualization [1]. Since the "11th Five-Year Plan" digitization has been prioritized to enhance manufacturing informatization, stimulate industrial innovation, and extend supply chain boundaries, with subsequent national plans—namely the "12th," "13th," and "14th Five-Year Plans"—further emphasizing high-end extension, balanced digital security, and an innovation-driven modernization of industrial and supply chains. This evolving policy environment has spurred extensive scholarly attention, with research on digital supply chains primarily focusing on two dimensions: digital collaboration platforms and autonomous control capabilities.

Some scholars conceptualize digital supply chains as platforms endowed with high-level intelligent collaboration, enabling seamless connectivity and real-time communication through advanced technologies [2]. Others define them as comprehensive systems—integrating software, hardware, and communication networks—that coordinate inter-organizational interactions in procurement, production, storage, transportation, and sales [3], or as intelligent optimization systems that support massive data processing and effective collaboration [1]. Additionally, certain perspectives view the digital supply chain as a customer-centric platform that leverages real-time information to optimize performance and mitigate risks through precise matching, monitoring, and management [4].

Moreover, digital supply chains continuously evolve into adaptive, intelligent systems by learning from extensive data, thereby enhancing decision-making, risk management, and operational efficiency [5]. By accurately aligning resources with demand, they reduce waste while boosting production efficiency—aligning with global efforts toward sustainability [6]. In sum, digital supply chains represent a novel value

chain management model that enhances customer experience, reduces costs, and increases overall supply chain resilience and flexibility. As information technologies advance, digital supply chains are poised to play an increasingly pivotal role in industrial upgrading and the promotion of high-quality economic development [7].

2.2. Research on ecological competitive advantages

In discussing enterprise ecological competitive advantage, a core enterprise that leads in constructing and coordinating a business ecosystem—and subsequently demonstrates superior value creation and performance relative to its competitors—is said to possess an ecological competitive advantage. This advantage is fundamentally rooted in the ecosystem's inherent "win-win symbiosis," ensuring a high degree of interest alignment between the core enterprise and its ecosystem partners [8][9]. Consequently, competitive dynamics shift predominantly toward external entities or across different ecosystems. Notably, while core enterprises are often seen as the primary drivers of ecological competitive advantage, the benefits typically extend to all ecosystem participants.

Current research on ecological competitive advantages remains nascent, with most studies exploring its sources and formation mechanisms. Li et al. suggests that ecological competitive advantage emerges from three core elements: complementary resources among participants, cooperative structures, and effective governance rules[10]. Alternatively, other scholars examine how value co-creation acts as a mediating mechanism within a dynamic capabilities framework to facilitate this advantage [11]. Despite these divergent approaches, there is general consensus that the foundation of ecological competitive advantage lies in the interactions among ecosystem members and the efficient integration of heterogeneous resources [10][12], thereby underscoring the pivotal role of value co-creation in its construction [13].

A review of the literature reveals that ecological competitive advantage manifests primarily through enhanced user experiences via continuous innovation, efficient integration of complementary resources to spur rapid growth, and the deep integration and symbiotic collaboration between businesses achieved through digital technologies and ecological strategies [13][14][15].

2.3. Digital supply chain and ecological competitive advantages

The key mechanism through which digital technologies and digital capabilities are applied within the supply chain lies in the process of value co-creation across various stages of the supply chain [16][17]. In recent years, the emerging concept of digital affordances within the domain of digital ecosystems has provided a useful lens for understanding how such value co-creation unfolds [16].

Digital affordances refer to the range of potentials and opportunities that digital technologies or digital infrastructures offer to organizations. In the context of ecosystems, these affordances are typically manifested in three forms: decoupling, disintermediation, and generativity. Together, these three affordances enable ecosystem participants to establish connections and engage in interactions at multiple levels, thereby facilitating the co-creation of value [18].

2.4. Literature review

Based on the extant literature, research on digital supply chains encompasses aspects such as smart collaboration, real-time information transfer, risk management, and cost optimization, all underpinned by digital technologies including the Internet of Things, big data, and blockchain. Scholars generally assert that by integrating data and information across various nodes, digital supply chains not only enhance supply chain efficiency but also lay the foundation for enterprises to construct an innovation-driven and autonomously controllable strategic system [1]. On the other hand, studies on ecological competitive advantage emphasize that core enterprises achieve value co-creation by integrating the complementary resources and capabilities of diverse participants within the ecosystem, thereby securing a first-mover advantage in fiercely competitive markets [9][10]. However, existing research has predominantly focused on internal process optimization and the enhancement of supply chain efficiency. There remains a clear gap in systematic theoretical construction and empirical validation regarding how digital transformation can be leveraged to build a "networked co-creation" supply chain model that fosters the formation and enhancement of ecological competitive advantage.

This study constructs a theoretical framework to explain how digital transformation facilitates the formation of a networked co-creation supply chain. It focuses on the functions of digital technologies in promoting information integration, resource sharing, and cross-boundary collaboration, thereby uncovering the internal mechanisms through which digitalization contributes to ecological competitive advantage. By bridging digital supply chains and ecological competitiveness, this research not only deepens theoretical understanding but also offers actionable insights for enterprises aiming to build highly collaborative ecosystems. The findings further provide valuable references for both policy formulation and enterprise transformation.

3. Methods

This study investigates how digital transformation in the supply chain enables the construction of a network-based co-creation model, thereby enhancing firms' ecological competitive advantage. In light of the complexity and dynamism of the research context, an exploratory case study approach is adopted to provide a detailed account of the phenomenon and uncover its underlying operational mechanisms.

The case study method is chosen for its strength in integrating detailed empirical analysis with theoretical abstraction. As a strategic research approach, it emphasizes the exploration of processual and evolutionary mechanisms to understand how specific outcomes are realized. Through systematic interpretation of qualitative data, the case study distills developmental patterns and reveals the theoretical linkages embedded in complex organizational practices, thereby deepening the understanding of digital transformation dynamics.

3.1. Case firm selection

This study takes the cross-border e-commerce company SHEIN as the case for analysis. As a representative enterprise in the cross-border fashion sector, SHEIN exemplifies the typical case selection logic: its digital transformation has led to the successful

construction of a network-based co-creation supply chain, which closely aligns with the core themes of this research. At the same time, its rapid rise—surpassing established brands such as ZARA—offers strong heuristic value. The substantial improvement in its ecological competitive advantage through supply chain digitalization provides meaningful insights for other real-economy enterprises undergoing similar transformations.

3.2. Data Source

We primarily draw upon both primary interview data and publicly available secondary sources related to SHEIN as its core research materials. These include: (1) interview data from SHEIN and its affiliated partners; (2) publicly released news reports, newspaper articles, and other media publications issued by relevant institutions; and (3) official platforms such as SHEIN's official website and WeChat public account. The study extracts and organizes materials that are directly relevant or closely related to the research theme to construct a chain of interlinked data. A multi-level and multi-source data collection approach is employed to ensure a richer and more robust explanation of the research topic, thereby enhancing the reliability and accuracy of the research findings.

4. Analysis process

4.1. Digitalization drives supply chain model change

SHEIN's global competitiveness stems not only from its rapid product iteration and market responsiveness, but also from its deep integration of advanced digital technologies. Through big data analytics, AI, IoT, cloud computing, and real-time digital dashboards, SHEIN has built a transparent, integrated supply chain system that connects data across all operational stages. This system enables the timely capture of consumer preferences and market signals via social media, search trends, and real-time traffic, supporting agile decision-making in design, procurement, inventory, and logistics.

SHEIN's global competitiveness stems not only from its rapid product iteration and market responsiveness, but also from its deep integration of advanced digital technologies. Through big data analytics, AI, IoT, cloud computing, and real-time digital dashboards, SHEIN has built a transparent, integrated supply chain system that connects data across all operational stages. This system enables the timely capture of consumer preferences and market signals via social media, search trends, and real-time traffic, supporting agile decision-making in design, procurement, inventory, and logistics.

A key feature is SHEIN's big data platform, which aggregates online and offline data and applies AI algorithms for trend forecasting. The platform integrates historical sales records, real-time consumer behavior, and external sources such as fashion forums and search engines to monitor industry dynamics. Its "small order, quick response" model allows market testing before scaling production based on sales feedback, aligning product offerings more closely with consumer demand and strengthening ecological competitiveness. Moreover, real-time dashboards enhance

transparency across the supply chain by visualizing key nodes—raw material supply, production progress, logistics, and inventory—while integrating sales and feedback data. This facilitates rapid risk detection and system-wide coordination, shifting from local optimization to holistic management.

SHEIN's digital transformation also promotes internal-external resource integration. A unified platform connects design, production, warehousing, and logistics departments, while incorporating suppliers, logistics providers, and tech partners into a collaborative ecosystem. This reduces information asymmetry, enhances cross-organizational coordination, and consolidates its competitive position globally.

4.2. Results

SHEIN's digital platform operates through an integrated internal transmission mechanism encompassing four phases. In the data collection and integration phase, real-time information on sales, production, inventory, and logistics is aggregated into a centralized system. Leveraging cloud computing and big data analytics, the company cleans and structures multi-source data from both online and offline channels to ensure comprehensive operational visibility.

In the information-sharing phase, digital dashboards and visualization tools distribute real-time updates across supply chain nodes. Managers can monitor raw material availability, production status, and inventory levels, enabling swift identification of disruptions such as delays or bottlenecks.

During the intelligent decision-making phase, SHEIN applies AI algorithms and predictive models to forecast trends and adjust operations. For example, surges in social media interest in certain styles prompt immediate revisions in production planning, inventory allocation, and logistics to match anticipated demand.

Finally, in the cross-boundary integration phase, open data interfaces connect external partners—suppliers, designers, logistics providers, and tech firms—into a unified digital ecosystem. This coordination allows synchronized production and delivery across regions, reducing lead times and enhancing supply chain resilience.

Through this data-driven architecture, SHEIN not only improves internal efficiency but also enables cross-sector collaboration, reinforcing its ecological competitive advantage and setting a benchmark for digital transformation in fast fashion.

5. Conclusion

5.1. The main findings

Leveraging digital technologies, SHEIN has demonstrated outstanding performance across multiple dimensions—including using big data to proactively capture market trends, employing real-time digital dashboards for supply chain information flow, and fully digitizing consumer preferences and the industrial chain. These capabilities have enabled the company to build an open, transparent, and highly efficient network-based co-creation supply chain system.

This system not only achieves deep integration of information and efficient resource sharing across internal operations but also closely links external ecosystem partners through cross-boundary collaboration and resource integration. As a result, it

fosters a dynamic, collaborative, and efficient transmission network connecting market demand, product development, and production operations.

Through this internal transmission mechanism, digital transformation continuously generates significant competitive dividends, enabling the firm to maintain agile and efficient operations even amid increasing market volatility and uncertainty—thus reinforcing and expanding its ecological competitive advantage in the global market.

5.2. Impact of digital supply chain transformation

The analysis shows that digital supply chains are crucial for enhancing firms' ecological competitive advantage. By using big data to accurately capture market demand, enabling real-time information flow, and promoting digital integration within industrial clusters, firms build networked co-creation models that improve adaptability and resilience. To address digital era challenges, firms must actively adopt digital technologies to drive transformation, strengthening competitiveness and supporting sustainable development.

5.3. The research limitations

The research method used in this study is very simple, mainly relying on exploratory case studies. This study failed to obtain quantitative data for qualitative research and lacks comprehensiveness. Therefore, it is recommended that in subsequent research, a combination of multiple research methods such as interviews and questionnaires be used to ensure the authenticity of the data and make the research results closer to reality.

5.4. The future research directions

This study focuses on a single case—SHEIN, a large cross-border e-commerce enterprise—thus presenting limitations in terms of research scope and industry specificity. Future research could adopt a multi-case approach encompassing firms of varying sizes and from different industries to enhance the generalizability and applicability of the findings. Moreover, further investigation is recommended into how small and medium-sized enterprises within digital platform ecosystems coordinate resources, build capabilities, and implement digital management practices to strengthen their ecological competitive advantage.

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Research on the Innovation Path of SHEIN's Supply Chain Business Model Empowered by Digital Technology: Based on the Perspective of Enterprise Digital Transformation

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Abstract. Under the current wave of digital transformation and innovation, business model innovation is the core driving force for enterprises to gain competitive advantage in the new market environment, and enterprises need to reconstruct their competitive advantage through business model innovation. Taking SHEIN as a single case, this study uses the business canvas theory to compare ZARA and H&M-related enterprises through literature analysis, enterprise public data and supply chain operation data, and explores how digital transformation drives business model innovation in the electronic supply chain. The study found that SHEIN has achieved an industry-leading efficiency of 2,000-10,000 new models per day and shortened the production cycle to 3-7 days through the "small single quick response" model, data-driven precision marketing and flexible supply chain system, with sales reaching $24 billion in 2023, with an annual growth rate of 40%. Its innovation paths include precise customer segmentation, digitization of value propositions, diversification of channel matrix, and intelligent supply chain. This study provides a replicable theoretical framework and practical enlightenment for the digital transformation of fast fashion e-commerce enterprises to promote the updating and adaptation of business models.

Keywords. business model innovation; digital transformation; e-supply chain

1. Introduction

As the core driving force of enterprise development, business model innovation has been given a brand new connotation and mission in the context of digital transformation. Under the multiple challenges of fast-changing market environment, diversified consumer demands and accelerated technology iteration, traditional business models are increasingly difficult to meet the needs of enterprises' continuous growth. Business model innovation can help enterprises redefine the way of value creation and value delivery, so as to stand out in the market. By optimizing resource allocation, improving efficiency or opening up new markets, companies can break the

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traditional competitive landscape and establish differentiated advantages. By redefining business logic, companies can identify new growth opportunities and realize the transition from "follower" to "leader". Business model innovation is not only beneficial to the company itself, but also has a profound impact on the industry as a whole. By introducing a new logic of value creation, companies can reshape the rules of the industry or even create a completely new market landscape.

SHEIN, as a unicorn enterprise, has reconstructed the supply chain system through digital technology and realized the business model innovation of "small order quick reaction". Through the case study of SHEIN, we summarize its successful experience and model, and provide theoretical guidance and practical reference for other enterprises to optimize the e-supply chain and innovate the business model in the process of digital transformation. This study aims to explore the business model innovation path of e-supply chain under the perspective of digital transformation, as well as the specific application and effectiveness of SHEIN in practice, so as to provide references and lessons for other enterprises and supply chain management.

This study adopts a single-case qualitative research method, collects SHEIN's financial reports, official website announcements and operational data of third-party platforms through literature analysis and corporate public data collection, and cites the "2024 Flexible Supply Chain White Paper" issued by Guangzhou Panyu District Garment Industry Association. Supply chain response speed, inventory turnover rate, average daily new volume and cross-border e-commerce proportion were selected as the core comparison indicators. The horizontal comparison of SHEIN with ZARA and H&M highlights the advantages of SHEIN in digital supply chain management to drive business model innovation and transformation.

2. Theoretical Foundations and Literature Review

2.1. Theoretical foundations

Chen Guoquan (1999) believes that the concept of supply chain is developed from the concept of expanded production, the enterprise from raw materials and components procurement, transportation, processing and manufacturing, distribution until the final delivery of the customer's hands of this process is viewed as an interlocking chain which is the supply chain [1]. Shi Li (2003) that the e-commerce supply chain is based on the e-commerce model, to the Internet, interactive Web applications as the basic platform for market-responsive supply chain, based on e-commerce supply chain is a kind of pull, flat, agile, integrated supply chain [2].

The term business model can be traced back to the 1940s and 1950s, and the formal definition was systematically given by the scholar Timmers [3], who believed that a business model is an enterprise management structure that includes product, service and information flows, and is an effective means to study the profitability model of a company. With the rise of Internet technology, business models are very suitable for interpreting the new phenomenon of business management emerging in the age of digitalization.

The business model canvas model consists of 9 elements, and business model innovation is the process of redesigning a set of elements [4]. Business model innovation are distinguished from technological innovation or product innovation. It stands in the overall perspective, systematic thinking of all kinds of innovation

elements for organic integration, in-depth excavation of the enterprise's latent innovation ability. Business model innovation presents a new set of value proposition, creation, transmission and acquisition logic, and builds a value network mechanism covering the enterprise and many stakeholders. From a macro level, business model innovation even has the ability to rewrite the competition pattern of the whole industry, reconfigure the power structure of the industry, and lead the industry to a completely new stage of development.

2.2. Literature review

Francis Kamewor Tetteh (2025) draws on the dynamic capability theory to examine the impact of digital transformation on business model innovation through technology-oriented intermediary utility, and the digital transformation-business model innovation link is amplified under different competitive intensities [5]. Dequn Teng (2025) adopts a qualitative research approach. The data were collected and analyzed through 32 semi-structured interviews and archival sources, focusing on the new value proposition of AI influencing business model innovation (BMI) through five approaches: knowledge-based query-based cloud solutions, content creation, AI agents, basic models, and upstream industry chain infrastructure [6]. Yang Zhen (2025) proposes that algorithm technology promotes business model innovation, digital capabilities play a partly mediating role, and algorithm governance plays a significant positive moderating role [7]. Wang Hua and Chang Haodong (2024) took the short video platform Kuaishou Technology as an example to study the innovation mechanism of scene elements to empower the business model of the short video platform based on the value-oriented logic [8]. Li Xiaohua (2024) proposed that the transformation of cognitive framework is a key factor driving business model innovation, and enterprises usually adopt superposition, decoupling, and convergence strategies to change the cognitive framework [9]. Wang Bingcheng (2024) proposed that digital interaction has a significant positive impact on business model innovation, in which knowledge absorption capacity plays a partly mediating role, strategic flexibility strengthens the relationship between knowledge absorption capacity and business model innovation, and digital interaction affects business model innovation through knowledge absorption capacity [10].

Wang Linlin et al. (2025) found that from the perspective of value network and combined with the Wei Zhu Six Elements Theory of Business Model, SHEIN's business model has undergone three stages of evolution: market demand-resource integration, and platform empowerment, with different innovation-driven factors at each stage [11]. Zhu Xiaoteng (2024) pointed out that at different stages of digital transformation, the evolution of enterprise resource actions has enabled enterprise business models to complete iterations from "supplier business model" to "digital platform business model" and then to "digital ecosystem business model" [12]. Wang Bingcheng (2024) constructs a theoretical model of enterprise business model innovation resistance in the context of digital transformation, which is different from product innovation resistance in that it covers the resistance of enterprises to change the comprehensive logic of the overall business model elements [13]. Cheng Xuanmei (2025) pointed out that the internal mechanism of the digital transformation model can be analyzed by using the logical chain of "transformation situation-behavior mechanism-transformation result", and different market pressures and digital technology pressures constitute the transformation situation, which directly affects the

resource reorganization mechanism, institutional action mechanism, digital innovation mechanism, and enterprise competitiveness of enterprises [14].

Wang Bingcheng (2025) proposed that employees' digital identity has a significant positive impact on business model innovation. Out-of-role behavior plays a mediating role between digital identity and business model innovation. Platform-based leadership not only strengthens the relationship between digital identity and out-of-role behavior, but also strengthens the mediating effect of digital identity on business model innovation through out-of-role behavior [15].Feng Lijie (2024) pointed out that among the four business model innovation driving paths, the market environment-driven and dynamic capability-driven will lead to the gradual business model innovation of digital incumbents, while the dynamic capability-led and redundant resources driven by technology will lead to disruptive business model innovation [16].

Through reading, it is found that existing literature has studied digital transformation, business model innovation and the relationship between the two from multiple dimensions, which provides a rich theoretical and practical basis for studying the business model innovation path of enterprise digital transformation-driven e-supply chain with SHEIN as an example. However, there are still some limitations in the current research, such as the lack of systematic research on the business model innovation of e-supply chain, the failure to comprehensively and deeply analyze the driving mechanism of digital transformation on the business model innovation in each link of e-supply chain , as well as the unique paths and key factors of e-supply chain's business model innovation in the process of digital transformation.

3. E-Supply Chain Business Model Innovation Drivers

E-supply chain business model innovation is driven by a combination of internal and external factors.

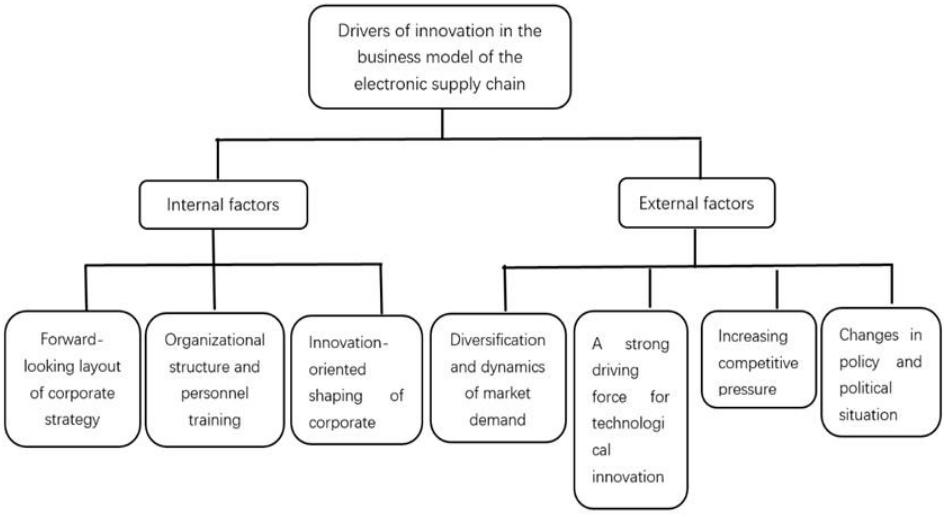


Figure 1. Drivers of innovation in the business model of the electronic supply chain

3.1. Internal factors

- Forward-looking layout of corporate strategy

Corporate strategy is the core element that leads the development direction of enterprises, and a forward-looking corporate strategy can provide a clear goal and direction for the business model innovation of electronic supply chain. When an enterprise formulates a development strategy centered on innovation-driven and digital transformation, the business model innovation of e-supply chain will be included as an important part of the strategic planning. If an enterprise formulates a customer-centric strategy, it will prompt the supply chain to innovate around responding quickly to customer needs, such as adopting a customized production model, and quickly adjusting product design and production processes through close cooperation with suppliers to meet customers' individualized needs. If an enterprise's strategy focuses on cost leadership, it may push the supply chain to integrate and optimize, and explore new sourcing, production and logistics models to reduce costs.

- Organizational structure and personnel training

Flexible organizational structures are conducive to rapid decision-making and cross-departmental collaboration, breaking down departmental barriers, enabling the efficient flow of information in the supply chain and promoting business model innovation. For example, some electronic enterprises have adopted a flat organizational structure to reduce management levels, improve decision-making efficiency and promote the continuous innovation of supply chain business model. Electronic supply chain business model innovation requires composite talents with multi-disciplinary knowledge and skills. On the one hand, the enterprise actively introduces external talents with innovative thinking and rich experience to enrich the innovative power of the enterprise. On the other hand, it strengthens the training of internal staff to enhance their digital literacy and innovation ability. For example, enterprises regularly organize employees to participate in digital technology training courses, supply chain innovation seminars and other activities to encourage employees to learn new knowledge and skills, and to cultivate their sense of innovation and teamwork.

- Innovation-oriented shaping of corporate culture

Enterprise culture is the soul of an enterprise, which has far-reaching influence on the behavior and values of its employees. An innovation-oriented enterprise culture can stimulate the innovation enthusiasm and creativity of employees and create a good atmosphere for the innovation of electronic supply chain business model. In the innovation-oriented corporate culture, enterprises encourage employees to try, dare to innovate, tolerate failure, and regard innovation as the core driving force of enterprise development. In the field of electronic supply chain, by shaping innovation-oriented corporate culture, enterprises can prompt employees to actively participate in supply chain innovation activities, put forward new ideas and suggestions, and promote the continuous innovation and optimization of electronic supply chain business model.

3.2. External factors

- Diversification and dynamization of market demand

With the improvement of consumers' living standards and the change of consumer attitudes, the market demand is characterized by unprecedented diversity and

dynamism. Consumers are increasingly demanding personalized design, fast delivery and customized experience. Taking the apparel industry as an example, fast fashion brands such as ZARA, H&M, etc., satisfy consumers' instant demand for fashion by capturing fashion trends quickly, updating styles frequently, and operating an efficient supply chain at . In this market environment, the drawbacks of the traditional e-supply chain business model, such as the long lead time from product design to final delivery and the difficulty in meeting personalized demands, are highlighted. In order to stand out in the fierce market competition, enterprises must innovate the e-supply chain business model, realize accurate production and quick response by integrating online and offline channels and using big data to analyze consumer preferences, so as to better cater to the changes in market demand.

- A powerful driver of technological innovation

The rapid development of information technology such as big data, cloud computing, Internet of Things, artificial intelligence and so on has provided solid technical support for the innovation of electronic supply chain business model. The innovation of logistics technology such as automated warehousing equipment, intelligent sorting system, drone distribution, new energy transportation tools, etc. has profoundly changed the logistics and distribution link of electronic supply chain. Automated warehousing equipment and intelligent sorting systems have improved the efficiency of goods storage and sorting, and reduced labor costs and error rates. The application of drone distribution and new energy transportation tools not only shortens the distribution time, but also reduces energy consumption and environmental pollution in the transportation process, opening up a new path for the innovation of electronic supply chain business model.

- Continued increase in competitive pressure

In the context of globalized economy, market competition is becoming more and more intense, and enterprises are facing double competitive pressure from domestic and foreign counterparts. On the one hand, in order to compete for market share, enterprises in the same industry are constantly launching new products and services, optimizing supply chain operations, reducing costs, and improving product quality and service level. On the other hand, cross-border competition is also increasingly prominent, emerging enterprises with innovative business models and advanced technology, quickly cut into the traditional industry market, posing a huge threat to traditional enterprises. Such as the Internet enterprises into the financial sector, the introduction of mobile payments, network lending and other financial services, the traditional financial institutions business model has had an impact. In this competitive environment, if enterprises want to maintain their competitive advantages, they must enhance their core competitiveness through innovative electronic supply chain business models.

- Changes in policy and political situation

Uncertainties in international trade policies, such as tariff adjustments and the setting of trade barriers, have a significant impact on the electronics supply chain, and changes in trade policies may increase the operating costs and risks of enterprises. To cope with this situation, enterprises have innovated the supply chain layout mode and shifted their production bases to regions with stable policies and friendly trade environments to diversify production risks. For example, some electronics enterprises have shifted part of their production capacity from regions with frequent trade frictions to Southeast Asian countries, while optimizing their global procurement network,

looking for alternative suppliers, reducing their reliance on single-region suppliers, and innovating their supply chain layout business model to adapt to changes in trade policies.

4. Digital transformation drives innovation in all parts of the e-supply chain

4.1. Procurement

Data-driven supplier management: With the help of digital technology, enterprises can collect and analyze supplier data in real time, such as product quality, delivery time, price fluctuations and so on. Based on these data, enterprises can more accurately screen suppliers, establish long-term and stable cooperative relationships with high-quality suppliers, and even jointly carry out innovative activities such as product development, so as to optimize purchasing costs, improve product quality, and provide strong support for business model innovation.

Automation and Intelligence of Procurement Processes: Automation of procurement processes through digital platforms, such as automatic order placement, approval, and settlement, not only improves procurement efficiency and reduces manual errors, but also enables enterprises to respond more flexibly to changes in the market and quickly adjust their procurement strategies. At the same time, artificial intelligence and machine learning technologies are utilized to forecast procurement demand and plan procurement well in advance, providing more efficient material protection for business model innovation.

4.2. Production chain

Flexible production and customization: digital technology enables enterprises to realize the interconnection of production equipment and real-time monitoring of the production process, quickly adjust the production plan and product configuration according to market demand and customer orders, and realize the flexible production of small batches and multiple varieties. This production mode meets the increasingly diversified and personalized needs of consumers, and creates conditions for enterprises to develop a customized business model.

Production Efficiency Improvement and Cost Reduction: With the help of IoT, big data and other technologies, data in the production process can be analyzed. can optimize the production process, improve equipment utilization, and reduce energy consumption, thus improving production efficiency and reducing production costs. This enables enterprises to provide products at more competitive prices while maintaining product quality, providing a cost advantage for business model innovation.

4.3. Logistics

Intelligent logistics and supply chain synergy: digital transformation makes the logistics link intelligent, and realizes real-time sharing of logistics information and collaborative operation through the docking of the logistics management system with the information systems of upstream and downstream enterprises in the supply chain. Enterprises are able to accurately grasp the transportation status of goods, make

warehousing and distribution arrangements in advance, improve logistics efficiency, reduce logistics costs, and at the same time provide more efficient logistics support for business model innovation.

Optimization of last-kilometer delivery: using big data analysis and artificial intelligence technology to optimize delivery routes and delivery times, and improve the efficiency and service quality of last-kilometer delivery. In addition, innovative delivery methods such as intelligent express cabinets and unmanned delivery are used to enhance user experience and provide differentiated logistics services for business model innovation.

4.4. Marketing

Precision marketing and personalized recommendation: Digital technology enables enterprises to collect and analyze massive amounts of consumer data to understand consumer preferences, purchasing behaviors, and demand trends, thus achieving precise market segmentation and positioning. Based on these data, enterprises can provide consumers with personalized product recommendations and marketing activities, improve marketing effectiveness and customer conversion rates, and provide precise marketing strategies for business model innovation.

Social media marketing and brand building: With the help of social media platforms, enterprises can interact with consumers in real time, spread brand stories, and enhance brand awareness and reputation. Through social media marketing, enterprises can quickly obtain consumer feedback, adjust product and service strategies in a timely manner, build influential brands, and provide strong brand support for business model innovation.

4.5. Service Segments

Online customer service and customer experience enhancement: digital transformation enables companies to establish online customer service systems to provide consumers with timely and convenient services. Through artificial intelligence customer service robots, intelligent voice interaction and other technologies, it can quickly solve consumer problems and improve customer satisfaction. At the same time, it collects customer service data, analyzes customer needs and pain points, and provides a basis for product and service improvement, thus enhancing customer experience and providing a good customer base for business model innovation.

5. Case Studies

5.1. Business profile

Shein, Chinese name Xiyin, founder and CEO is Xu Yangtian, was founded in 2008. Headquartered in Guangzhou, China, with industrial chain layout in Guangdong, it is an international B2C fast fashion e-commerce company, mainly dealing with women's clothing, but also providing men's clothing, children's clothing, accessories, shoes, bags and other fashion items, entering a number of markets such as North America, Europe, the Middle East, India, Southeast Asia and South America . Its

business covers more than 220 countries and regions around the world, with a large customer base.SHEIN takes "Inspire Global Fashion" as its mission, and is committed to providing consumers with fashionable, high-quality and cost-effective apparel and accessory products.

Table 1. The development history of SHEIN enterprise

Measures	Time	Description
Self-developed supply chain digitalization system	2014	Build and open up ten digital modules in nine departments, including merchandise center, operation center and production center, and connect all suppliers to the supply chain platform.
Improve supplier management and cooperation model	2014-2015	Adopting different cooperation modes such as OBM, ODM, OEM and VMI with different types of suppliers; classifying suppliers into five grades of S, A, B, C and D according to the procurement amount and performance.
Moved to Panyu, Guangzhou	2015	With the advantage of local garment processing base, improve the flexible supply chain system, improve the flexibility and responsiveness of the supply chain.
Launched digital cold transfer denim process technology	2021	Partnering with Changsheng to innovate this technology creates a more streamlined production process that matches the "small order, quick response" flexible on-demand supply chain model.
Establishment of the Apparel Manufacturing Innovation Research Center and investment to empower suppliers	2023	Established the first apparel manufacturing innovation research center, continuously exporting flexible supply chain standards and exploring cutting-edge technology in apparel manufacturing, as well as talents.
Ramping up digital supply chain infrastructure	2023-2024	Over 10 billion dollars of supply chain infrastructure layout accelerated, including the construction of the "Hiyin Bay Area Intelligent Industrial Park" and the construction of the Hiyin Bay Area Supply Chain Project in Zengcheng, Guangzhou.
Conducting training and talent certification tests 2024	2024	In the Garment Manufacturing Innovation Research Center and other training 485 sessions, covering more than 20,000 businesses, nearly 60 certification tests for talents, 10 vocational skills level certification.
SHEIN Announces Batch Launch of New Energy	2025	The new energy tram solution for 9.6m van models is jointl

Vehicles, Expected to Reduce Carbon by Nearly 10,000 Tons in a Full Year	developed by SHEIN and partners such as Heavy Duty Truck, Dongfeng and Ningde Times.

5.2. SHEIN business model innovation path

This paper describes SHEIN's business model innovation path in terms of the nine constituent elements using the Business Canvas Theory.

Table 2. SHEIN Business Model Canvas

<table>
<tr><th colspan="2">important partnerships</th><th colspan="2">key activities</th><th colspan="2">value propositions</th><th colspan="2">customer relationships</th><th>Customer segments</th></tr>
<tr><td colspan="2" rowspan="3">• Deep collaboration with suppliers
• Influencers collaborate with creators
• Collaboration with logistics partners
• Strategic brand alliances.</td><td colspan="2">• Flexible supply chain operation
• Digital operations management
• Innovative product design
• Global market expansion</td><td colspan="2" rowspan="3">• The ultimate fast fashion experience
• Cost-effective advantage
• Rich product selection
• Digital shopping innovation
• Social interaction integration</td><td colspan="2">• Driven by digital marketing
• Strengthened community interaction
• Automated service upgrades</td><td rowspan="3">• Young fashion pioneers
• Age-diverse coverage
• Global Women's Spotlight
• Social media facilitators</td></tr>
<tr><td colspan="2">key resources</td><td colspan="2">channels</td></tr>
<tr><td colspan="2">• Strong supply chain system
• Data-driven
• Global operational layout
• Branding and partnership resources</td><td colspan="2">• Cooperate in online matrix construction
• Offline experience supplements
• Platform expansion cooperation</td></tr>
<tr><td colspan="5">cost structure</td><td colspan="4">revenue streams</td></tr>
<tr><td colspan="5">• Supply chain cost optimization
• Cost reduction in digital operations
• Logistics cost control
• R&D and design investment</td><td colspan="4">• E-commerce sales leadership
• ross-border business revenue increase
• Collaboration expansion income
• Platform service monetization
• Offline activities supplementation</td></tr>
</table>

- Customer Segments

Focusing on the young and fashionable Gen Z digital natives aged 16-24, who are social media enthusiasts, trend-savvy and price-sensitive, SHEIN analyzes social media data to design clothing that matches their preferences. Expanding the age range to 18-35, including college students and young professionals. We offer a wide range of affordable items to meet their limited budgets and fashion needs for campus and workplace environments. Global Women's Strategy, with women as the core service target, covering more than 150 countries. In key markets such as Europe, America and Southeast Asia, the company adjusts its products according to local women's cultural background, body shape and consumption habits, for example, Southeast Asia pushes light and thin fabric garments, and Europe and America optimizes its sizing system. We emphasize social promotion and cooperate with micro-web celebrities and creators who have a large number of followers. They share their outfits and reviews on platforms such as TikTok and Instagram, attracting potential customers for SHEIN.

- Value propositions

Ultimate fast fashion, with an agile supply chain and AI trend prediction, SHEIN can launch 2,000-10,000 new garments every day, and the production cycle is reduced to 3-7 days, so that consumers can have the latest trendy products quickly. Cost-effective, using data analysis to accurately control costs, and reducing inventory backlog through "small orders and quick return". The price of the products is 30-50% lower than the competitors, most of them are in the range of $8-30, which makes fashion more accessible to the public. Abundant choices, more than 600,000 items for sale on the platform, covering a wide range of categories. New designs are first tested in small batches and then mass-produced based on market feedback to meet diverse needs. Digital shopping: We have developed APP, which accounts for more than 75% of our sales, with virtual try-on and personalized recommendation functions, and accurately delivering products based on user data to enhance shopping convenience and personalization. Social interaction, integrating user-generated content and Netflix cooperation to build a community shopping environment. With more than 1.5 million social media mentions per month, the company is co-branded with Netflix to enhance user stickiness.

- Channels

Construct an online matrix with its own APP and official website as the core channels for online sales, and vigorously promote them globally. Increase offline experience by opening flash stores in global fashion capitals such as Paris, Lyon, London, etc. These flash stores are usually open for a limited time. By organizing fashion events and new product demonstrations, local consumers are attracted to the experience and the brand's visibility and influence in the region is enhanced. The platform expands cooperation by innovatively launching the SHEIN marketplace platform, which is open to third-party sellers to move in.

- Customer relationships

Digital marketing driven, comprehensive use of Growth Marketing, KOL marketing, Affiliate alliance marketing, search engine optimization, digital advertising and other digital marketing tools. Strengthening community interaction by establishing an active brand community on mainstream social media platforms and encouraging users to share their photos and videos of their outfits and write product reviews. The interaction between users and the brand is enhanced by cooperating with web celebrities to carry out activities such as live streaming with products and new product trials, as well as organizing interactive sessions such as fashion design competitions with user participation. Upgrade automation services by introducing advanced automated marketing tools to automatically push personalized product recommendation information, notifications of preferential activities, etc. for users based on their browsing behavior on the platform, purchase records and other data.

- Revenue streams

E-commerce sales dominate, online sales on global e-commerce platforms are the main revenue, with sales of about $24 billion in 2023, growing at about 40% annually. Cross-border revenue increase: cross-border sales are important, international shipping and customs fees account for about 15-20% of order value, expected to grow with global market expansion. Cooperation revenue: Cooperation with online celebrities and brands to push exclusive products, profit margins are 25-30% higher than standard product lines. Realization of platform: SHEIN marketplace platform realizes cash by

charging commissions and providing advanced services. Complementary offline activities: flash stores and other offline activities enhance brand image, and direct sales and experiential activities generate additional revenue.

- Key resources

Strong Supply Chain System: We have built up a large and efficient supplier network in Panyu, Guangzhou, with more than 300 core suppliers and a total of more than 4,000 suppliers in the whole system. Intelligent collaborative management system (MES) has been established to realize the digital management of the entire supply chain from raw material procurement, product design and production, logistics and distribution. Through the MES system, suppliers can realize real-time sharing of information and collaborative work, ensuring the efficient operation of the supply chain.

- Key activities

Flexible supply chain, the implementation of "small order quick return", the first small batch production test, according to the market feedback to decide whether to return the order, the production cycle is reduced to about 10 days, to enhance the flexibility of the supply chain. Digital operation, relying on big data and algorithmic precision marketing, intelligent production scheduling, optimizing business processes and improving operational efficiency. Product design, to build a professional design team, combined with the trend and consumer data, a large number of new models launched daily, to maintain fashion leadership. Global Expansion, continuously optimize multi-language website and APP, study local culture and customs for localized operation, and expand global market share.

- Important partnerships

Supplier synergy, working closely with more than 4,000 suppliers and sharing information through MES system. Provide suppliers with funds, subsidize the cost of typing, and timely payment back to enhance the willingness to cooperate. NetroStar collaboration, cooperating with global micro-netroStars and creators, who promote their products on the platform to realize mutual benefit and win-win situation. Logistics collaboration, cooperating with global logistics companies to digitally upgrade logistics systems and optimize distribution routes, such as cooperating with NAQE in the Middle East to solve the "last mile" problem. Brand alliance, strategic alliance with famous brands, launch co-branded products to enhance brand image and market share.

- Cost structure

Supply Chain Optimization: Reduce inventory costs through "quick return of small orders" and digital management, and reduce procurement costs through fine management of suppliers. Digital cost reduction, using digital precision marketing, the introduction of automated processes to reduce labor and logistics costs. Logistics control, optimize network layout with logistics companies, integrate orders, plan routes, reduce transportation costs and improve distribution efficiency. R&D sharing, despite the increase in R&D and design investment, efficient operation and large-scale sales share the cost, and promote sales growth and optimize the cost structure.

5.3. Analyze and compare

By comparing with companies in the same industry, it highlights the uniqueness of SHEIN, and SHEIN's digital operation capabilities are ahead of its peers. It has

developed its own supply chain digital system, centralized management of suppliers, and visualization of the entire supply chain.

SHEIN has built a strong online sales matrix, but there are risks in over-relying on online. When the network environment is unstable or subject to cyber attacks, online sales are vulnerable. With a large number of physical stores, ZARA and other peers have achieved coordinated online and offline development and stronger sales stability. Although SHEIN has opened pop-up stores, it is far less stable and coverage than physical stores, and it is difficult to ensure stable sales in different market environments like brands such as ZARA.

Table 3. Comparison of companies in the same industry

index	SHEIN	ZARA	H&M	Industry averages
Supply chain responsiveness	3-7days	21days	30days	25days
Inventory turnover	12times/year	5times/year	4times/year	6times/year
The average daily new volume	6,000models	500 models	300 models	800 models
The proportion of cross-border e-commerce	85%	40%	35%	45%

6. Conclusions and recommendations

This study takes SHEIN as a case study to deeply analyze the impact of digital transformation on the business model innovation of the electronic supply chain. The study found that SHEIN has achieved innovation in all aspects of the supply chain with the help of digital technology, such as intelligent procurement, flexible production, efficient logistics, accurate sales and high-quality services. Its innovative business model, built on the Business Canvas Theory, includes precise customer segmentation, unique value proposition, multi-channel channels, and more, helping companies achieve $24 billion in sales and 40% annual growth in 2023. Compared with ZARA and H&M, SHEIN has significant advantages in terms of supply chain response speed and inventory turnover rate, but there are still problems such as insufficient stability of offline channels and compound talent gaps.

Fast fashion e-commerce enterprises should pay attention to the construction of offline channels while developing online business. You can learn from the experience of companies such as ZARA to enhance the brand experience and improve sales stability by opening physical stores or holding offline events. SHEIN can further optimize its pop-up store model or explore new ways to work with brick-and-mortar retailers. Digital supply chain management requires interdisciplinary talents who understand both supply chain management and digital technology, cultivate a culture of innovation, introduce and cultivate digital talents, and promote the sustainable development of enterprises.

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Digitalization and Management Innovation IV
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Digital Transformation and Organizational Resilience in Bulk Commodity Supply Chains: A Synergistic Mechanism Study Based on the TOE Framework with Evidence from Xiamen Xiangyu Group

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Abstract. In the context of digital economy-driven industrial transformation, commodity supply chain enterprises face challenges such as outdated operational models and profitability constraints. Grounded in the TOE (Technology-Organization-Environment) theoretical framework, this study investigates the digital transformation strategy of Xiamen Xiangyu Group through literature analysis and case study. The findings reveal that: (1) At the technological level, blockchain-enabled trusted warehouse receipt systems effectively address information silos; (2) Organizationally, strategic leadership and capability enhancement overcome traditional inertia; (3) Ecologically, industrial-level platform clusters reconstruct value networks. These dimensions synergistically form a systemic transformation pathway. The study demonstrates that the interplay of technological penetration, organizational activation, and ecological collaboration under the TOE framework provides theoretical insights for commodity supply chain enterprises to transcend low-margin dilemmas. It offers practical guidance for constructing a "technology-business-ecology" integrated digital system within the industry.

Keywords. Commodity, Supply Chain Enterprise, Digital Transformation

1. Introduction

In the context of the deep restructuring of the global industrial chain supply chain, the stability and resilience of the supply chain system of commodities, as a core production factor of industrial manufacturing and an important material basis for people's livelihood protection, has risen to the level of national strategy. In recent years, the deepening of geopolitical conflicts and the frequent occurrence of extreme weather events have led to a huge impact and challenges in the commodity supply chain, and the systemic risk has risen sharply. The traditional management paradigm of commodity supply chain

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enterprises can no longer cope with the current situation, and it is urgent to have a new business paradigm to help enterprises reduce the risk of uncertainty. Supply chain enterprises utilize digital technology to adjust their business strategies, which can effectively reduce the risk of supply chain breakage. For example, Belhadi & Kamble et al. study the use of digital technology to enhance supply chain resilience to manage uncertainty arising from geopolitical time-disturbed external environment [1]. It can be seen that in the era of the digital economy, digital transformation strategy is undoubtedly the best choice, and enterprises can regard digital transformation as the core engine of strategic reengineering.

The rapid development of emerging technologies such as big data, cloud computing and blockchain has accelerated the world's entry into the era of digital economy [2]. In this context, enterprises have begun to consider investing in digital transformation to achieve rapid economic growth. Currently, digital transformation has evolved from a strategic choice to a necessity for enterprise survival, especially in the field of the commodity supply chain, whose long chain, strong cyclicality, and low gross profit characteristics make it difficult for the traditional supply chain management model to cope with the complex challenges of price volatility, cross-border compliance, and demand forecasting [3]. Since Schallmo's systematic definition of digital transformation [4], academics have carried out multi-dimensional explorations around its connotation, drivers and impacts: Early research on digital transformation in academia has gone through the evolution from technology-enabled process automation to systematic strategic restructuring, emphasizing the integration of technology application, data-driven decision-making and ecological synergy [5][6]. In terms of drivers, the TOE theoretical framework explains the logic of enterprise transformation from the three dimensions of technology, organization and environment [7]. The technological dimension involves the availability and adaptability of digital technology, which is the basic condition for digital transformation [8], and the adaptability of technology is one of the key factors for the success of digital transformation [9]. The organizational level focuses on innovation capability, digital competence and leadership building. Digital competence and innovation capability not only have a positive impact on the digital transformation of enterprises but also strengthen each other [10]; enterprises need to improve digital leadership in the process of digital transformation in order to support organizational decision-making and strategy implementation [11]. The environmental dimension covers industry competitive pressure and policy support. Industry pressure refers to the legitimacy pressure exerted by the highly digitalized industry chain on firms in the industry to undergo digital transformation [12]; economic policy support, including financial assistance and regulatory incentives, can provide firms with environmental support to enhance their digitalization and innovation capabilities [13].
Despite the richness of existing research, most of it focuses on the manufacturing or retail industries, and there is a relative lack of discussion on the specific scenario of the commodity supply chain. As industry covers the entire chain of "mining, processing, and distribution" and is significantly affected by the global economy and geopolitics, it is urgent to build a digital ecosystem that suits its pain points. This study takes Xiamen Xiangyu Island as a typical case study and analyzes its digital transformation practices to explore the key transformation paths of commodity supply chain enterprises.

2. Conceptual definition and rationale

2.1. Commodity supply chain enterprises

Commodity refers to trading in the circulation area, not directly facing the retail link, with commodity attributes, widely used in industrial and agricultural production and consumption of bulk materials, brand variety, mainly covering energy, agricultural and sideline products and basic raw materials category three categories. The commodity industry chain is a complete system from the extraction of raw materials to processing and manufacturing, and then to the final consumption. As shown in Table 1, the industry chain presents a significant vertical division of labour: the upstream focuses on resource extraction, the midstream is responsible for processing and transformation, and the downstream connects to the end consumption. Each link is closely related to the operation of the global economy, and price fluctuations directly affect the costs and profits of the relevant industries, with strong cyclicality and low gross profit attributes.

Table 1. Bulk Commodity Industry Chain Structure of China

Category	Upstream (Raw Materials)	Midstream (Semi-finished Products)	Downstream (Finished Products)
Energy & Chemicals	Crude oil, Natural gas, Coal	Gasoline, Diesel, Methanol, Natural rubber, Chemical fibers	Tires, Apparel
Metals	Iron ore, Copper, Aluminum	Steel products, Alloys	Building materials, Automobiles, Home appliances
Agri-products	Wheat, Corn, Soybeans, Paddy rice, Cotton, Hogs, Cattle, Sheep	Soybean oil, Soybean meal, Palm oil, Wheat flour, Milled rice	Processed foods

As an integrated service provider of the industry chain, commodity supply chain enterprises provide one-stop services such as procurement, warehousing, logistics and finance for manufacturing enterprises through self-management or agency mode. The industry as a whole shows a decentralized pattern of "big market, multiple categories, small enterprises", and the market price is affected by multiple factors such as the global economic cycle, geopolitics and natural conditions, and fluctuates drastically. Currently, enterprises are facing two core challenges: first, the lack of accurate demand forecasts, which can easily lead to inventory backlogs or supply shortages, resulting in financial risks; second, the trend of fragmentation of the consumer market is significant, and personalized demand is forcing the supply chain to upgrade its agility. In this regard, there is an urgent need to build a flexible response mechanism through digital transformation and improve the efficiency of the whole supply chain, in order to cope with the competitive pressure in the complex market environment.

2.2. Digital transformation

Digital transformation is not a simple software upgrade or supply chain improvement; it includes the digitisation of an enterprise's business processes and the digitisation of its products or services, among others. Digital transformation needs to rely on the enterprise's strategy, tactics and business and is a new way to find a new way to obtain value driven by data[14]. Its essence is not only technology iteration, but also a deep

innovation of the enterprise from business model to management system, which injects new kinetic energy for long-term development by reducing costs increasing efficiency and strengthening competitive barriers. This process needs to be promoted in the synergy of technology, organisation and environment.

TOE theory (Technology Organization Environment) believes that the application of a new technology is jointly influenced by three factors: technology, organisation and environment. As a systematic analysis framework based on the application of technology, the TOE framework is used to explore the mechanism of achieving the effect of technology in multi-level application scenarios. The is widely used in many research areas, for example, new technology adoption in enterprises [15], government e-government services [16], and other fields. The digital transformation of commodity supply chain enterprises is affected by a variety of factors, which are also applicable to the TOE framework.

From the technology-driven dimension, the availability and adaptability of digital technology is the foundation of transformation. With the popularization of technologies such as big data and the Internet of Things, enterprises are able to access diversified solutions [8], but the choice of technology needs to be highly matched with business scenarios [9]. For example, blockchain can crack the credit risk of the commodity supply chain, and artificial intelligence can optimize demand forecasting models. The organizational level emphasizes the dual support of resource capacity and leadership: on the one hand, digital capacity and innovation ability are strengthened by economies of scale and learning effect[10]; on the other hand, the digital cognition and decision-making power of the executive team[11] directly affects the strategy, and it is necessary to break down departmental barriers through process optimization and build data-driven synergy mechanisms. Environmental factors are reflected in the combined effect of industry pressure and policy support - the degree of digitization of the industry chain is increasing, forcing enterprises to follow up [12], while the government's financial subsidies, tax incentives, and other policies [10] provide SMEs with a buffer for the transformation of space.

Although digital transformation can build an agile value network through technology-organization-environment synergy, it still faces challenges such as wasted resources caused by insufficient technology adaptation, obstacles to change caused by traditional thinking, and weakened support due to lagging policy implementation. Enterprises need to balance technological empowerment, organizational upgrading and ecological synergy, and explore the optimal path to cope with multi-dimensional competition.

3. Case analysis

(hereinafter referred to as "Xiamen Xiangyu") was founded in 1995, and belongs to the world's top 500 Xiangyu Group, China’s leading bulk commodity supply chain service enterprises, in 2011 through a major asset reorganization in the Shanghai Stock Exchange listed. The company's main business covers bulk commodity procurement and supply, integrated logistics services and logistics platform development and operation, focusing on metal minerals, energy and chemicals, etc. The volume of business ranks at the forefront of the industry. In its business structure, the bulk commodity supply chain business is its core business.

3.1. Industry background

The complexity of the global economic environment and the cyclical challenges of the bulk commodity supply chain industry are intertwined, driving enterprises to accelerate strategic transformation. Adjustments in U.S. Federal Reserve policies have caused partial decoupling of bulk commodity prices from supply-demand fundamentals, compounded by weak domestic downstream demand and rising credit management pressures from customers and merchants, resulting in continued compression of industry profit margins. Against this backdrop, Xiamen Xiangyu has adopted a core strategy of "platformization, internationalization, and digitalization," dynamically adjusting operational strategies to explore growth resilience amid volatility. Compared to international markets, overseas bulk supply chain giants have established highly concentrated competitive landscapes through globalized layouts−Japan's top five trading companies account for 31% of its total foreign trade volume, and the four major grain traders control 80% of the global grain trade. In contrast, domestically, as shown in Figure 1, although the CR4 market share increased from 2.19% in 2018 to 4.18% in 2022, with the market scale exceeding 2.3 trillion yuan, the fragmented competitive structure remains unchanged. This gap reveals that domestic enterprises must reconstruct value chains through digital transformation: penetrating long supply chains with technology, activating organizational innovation momentum, and leveraging ecosystem collaboration to break through low-margin constraints.

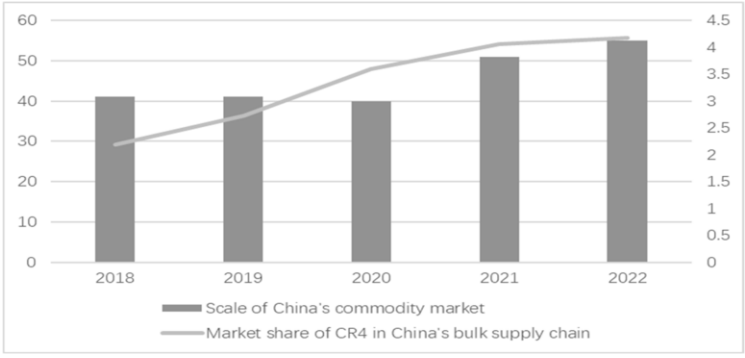


Figure 1 Scale of China's Bulk Supply Chain Market and CR4 Market Share

As a benchmark enterprise in the field of commodity supply chain, Xiamen Xiangyu relies on the whole chain service capability to build differentiated competitive advantages. Its business focuses on basic raw materials with strong circulation and a high degree of standardization, with emphasis on the layout of strategic materials with long industrial chain attributes. The business covers metal minerals, the energy and chemical industry, agricultural products and new energy, forming six strategic categories such as ferrous metals, industrial aluminium, clean energy, etc. In 2023, the composition of gross profit of the main commodities operated by the enterprise is shown in Figure 2, and the structure of Xiamen Elephant Island's gross profit rate in 2023 highlights the cyclical risk of the commodity industry: metal minerals and energy and chemical industry support the scale of income but profit is meagre, and the agricultural products segment is directly reduced by price fluctuations. The agricultural products segment directly lowers overall

profitability due to price volatility. In the future, Xiamen Xiangyu needs to optimize supply chain efficiency through digital transformation and expand new energy and international business with high gross margins to improve its profit structure.

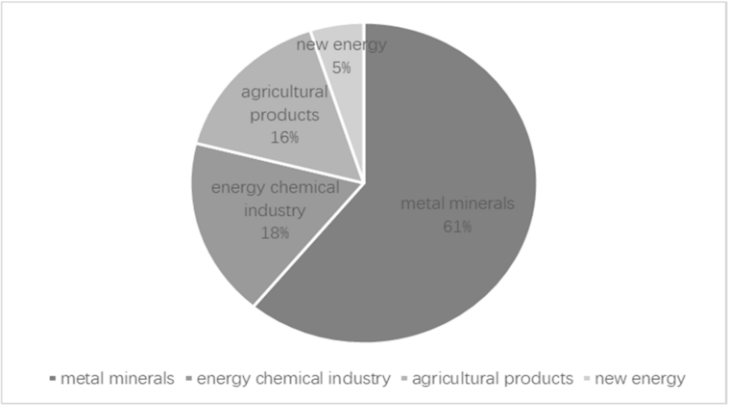


Figure 2 Composition of Xiamen Xiangyu's Gross Profit Margin in 2023

3.2. Overview of digital transformation in Xiamen Xiangyu

Xiamen Xiangyu's digital transformation presents a clear stepwise evolution path, as shown in Figure 3. In the accumulation 2011-2015 accumulation stage, the enterprise through the reorganization of the three business clusters of metals, energy, and agricultural products, to complete the ERP system of the whole business overlay, laying the foundation for the transformation of the supply chain service provider; in the development stage from 2016-2018, the investment of more than 500 million yuan to build a cross-border bulk trading platform, to achieve the proportion of overseas business from 8% to 22%. In the development stage from 2016 to 2018, we invested more than 500 million RMB to build a cross-border bulk trading platform, realized that the proportion of overseas business jumped from 8% to 22%, and used Internet of Things (IoT) technology to integrate 180,000 TEU logistics nodes around the world, forming a

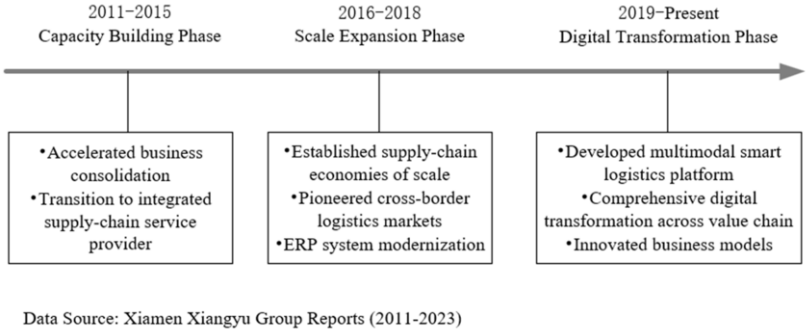


Figure 3. Digital Transformation Journey of Xiamen Xiangyu Group

moat of economies of scale. In the transformation stage from 2019 to now, we have innovatively implemented the strategy of material and trade linkage: building industrial internet platform clusters for agriculture, new energy and other industries, developing the blockchain warehouse receipt financing system "Yu Chain Tong", establishing an AI-driven dynamic hedging mechanism, and ultimately realizing the digitization input-output ratio of 1:6.8 at a level exceeding that of the industry. Value of systematic digital transformation.

3.3. "Yuliantong" digital supply service platform

Xiamen Elephant Island found multiple bottlenecks in traditional supply chain finance when serving its manufacturing customers and has a keen insight into the triple dilemma in traditional supply chain finance: financing difficulties for small and medium-sized enterprises (SMEs), difficulties in financial institutions' risk control, and high pressure on the enterprises' own assets and liabilities. Based on the above dilemma, Xiamen Elephant Island takes digital transformation as a breakthrough and builds the "LU Chain" digital supply chain service platform relying on blockchain, Internet of Things (IoT) and other technologies, which reshapes the credit system of bulk commodity circulation through real-time tracking of the dynamics of goods through IoT, blockchain technology to ensure that the data can not be tampered with, and artificial intelligence to optimize the assessment of risk.

Based on blockchain, artificial intelligence, Internet of Things and other digital technologies, the service platform has launched products such as "Yucairong", "Yucangrong", and "Yuturong" to build a safe logistics system, as shown in Figure 4. The platform innovatively transforms physical cargo rights into digital asset certificates, breaking through the trust barrier between financial institutions and physical enterprises. Through direct connection with many banks, it develops dynamic pledge financing products and realizes online and automated financing processes. The timeframe for SMEs to obtain financing has been shortened from several days in the traditional mode to the hourly level, and the cost of financing has dropped significantly. For Xiamen Xiangyu, the platform service fee model not only optimizes the revenue structure but also reduces the pressure on assets and liabilities through asset-light operation and promotes healthy financial indicators.

The effectiveness of the transformation is reflected in the threefold value reconstruction: first, credit value, the non-performing rate of electronic warehouse receipts is far lower than the industry level, and the risk control ability is improved; second, commercial value, digital services have become a new growth pole, and the proportion of revenue is rapidly rising; third, ecological value, and the synergistic network of "core enterprises, small and medium-sized customers, and financial institutions" is built up. This practice provides a paradigm for the transformation of the commodities industry, i.e., technology-enabled trustworthy digital credit system and data-driven service innovation, showing the far-reaching potential of digitization to reconfigure the industrial value chain.

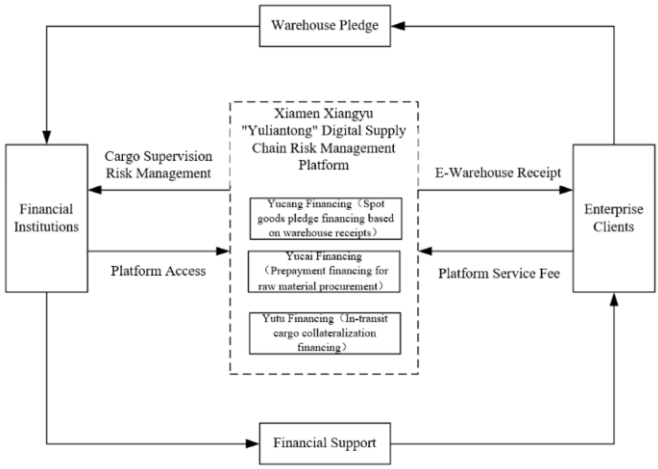
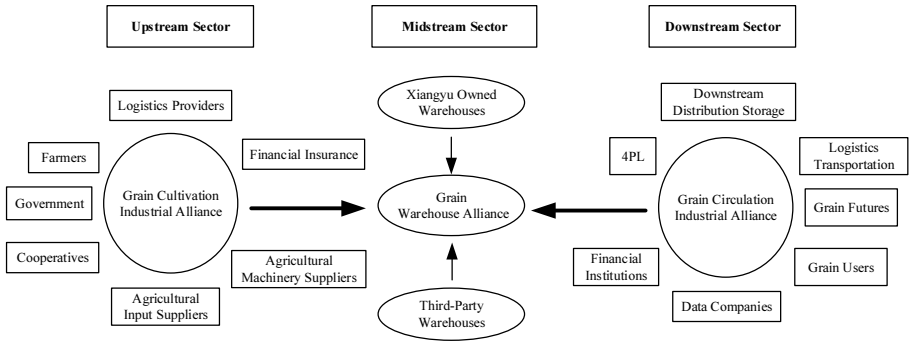


Figure 4. Xiamen Xiangyu "Yulian" Digital Supply Chain Service Platform

3.4. Agricultural industry-level Internet platforms

Aiming at the core pain points such as information barriers and inefficient circulation in the process of agricultural digitization in China, Xiamen Xiangyu, together with Alibaba, has constructed an agricultural industry-level Internet platform, forming an ecological model of "planting - warehousing - logistics - processing - finance" through the digitization and restructuring of the whole industrial chain. As shown in Figure 5, the front-end relies on blockchain technology to establish a traceability system for agricultural materials, covering 7 million mu of arable land and serving 850 villages and towns, and realizing a 40% reduction in the rate of complaints about fake and shoddy agricultural materials; the middle-end utilizes the Internet of Things and digital twin technology to integrate northeastern warehousing resources and build a multimodal transportation network for northern grains transported to the south, and the efficiency of the flow of warehouse receipts is increased by 50%; the back end deepens its cooperation with the head enterprises, supplying more than 15 million tons of raw grains annually and enhancing the efficiency of processing through deep processing, such as soybean crushing. The back-end of the platform deepens cooperation with leading enterprises, supplying more than 15 million tons of raw grain annually and enhancing added value through deep processing such as soybean pressing. The platform has innovatively embedded blockchain technology into the supply chain financial system, realizing the credibility of the whole process of electronic warehouse receipts, and has granted over 12 billion yuan of credit and maintained a zero-bad-debt rate, driving the gross profit margin of the agricultural supply chain to 2.5%-3.0%, which is more resilient to profitability than the traditional business. The digital transformation has also produced significant social benefits - reducing the grain loss rate by 8%, helping farmers increase their income by RMB 200-300 per mu, and driving the growth of regional agricultural output by more than RMB 1.5 billion, thus creating a double guarantee of economic benefits and food security. This practice not only won the national management innovation achievement award but also through the Central Asia market expansion and

500,000 tons of soybean production capacity construction, laying the foundation for global supply chain competition, and highlighting the transformation paradigm of digital reconstruction of the agricultural value chain.



Data Source: Compiled from Xiamen Xiangyu Group Annual Reports

Figure 5. Xiamen Xiangyu Agricultural Industry-level Internet Platform

3.5. Intelligent logistics service platform

Aiming at the industry pain points in the field of bulk commodity logistics, such as long links, information silos and weak control of cargo rights, Xiamen Xiangyu systematically builds an intelligent logistics digital platform, with the core objectives of intelligent upgrading the whole process, online reconstruction of service scenes and penetrating visualization of cargo rights management, so as to promote the transformation of the traditional logistics system into a modern digital supply chain infrastructure. As shown in Figure 6, through the deep integration and application of cutting-edge digital technology, the platform creates a digital solution covering the whole area of warehouse management, multimodal transportation and cargo right traceability: in the technical architecture layer, it relies on the blockchain deposit system to build a tamper-proof electronic warehouse receipt circulation mechanism, and integrates the digital twin technology to establish a virtual-reality mapping intelligent supervision system, realizing the whole life cycle of the goods to be tracked in a visualized way; in the operation management layer, the warehouse management system is based on edge computing and intelligent sensing equipment to build the warehouse management platform, which is based on the edge computing and intelligent sensing equipment. In the operation management layer, the warehouse Internet of Things system based on edge computing and intelligent sensing equipment forms a dynamic and optimized inventory management mode and significantly improves the utilization efficiency of warehousing resources; in the ecological synergy layer, it realizes data interoperability with more than 200 strategic partners such as railroads and ports through API interfaces and builds a cross-mode-of-transportation and cross-region real-time response network.

This digital transformation has essentially reconstructed the logic of value creation in traditional logistics: through electronic signature and blockchain deposit technology, physical cargo rights are transformed into credible digital assets, cracking the core obstacles for financial institutions to participate in bulk logistics financial services; with

the help of the Internet of Things and the transparent supervisory system constructed by digital twins, inventory turnover is increased by 30%, and the utilization rate of the warehouses is increased by 25%; what's more, the platform has deposited logistics big data to reverse-enable supply chain optimization, helping customers accurately predict transportation cycles and dynamically adjust inventory strategies. More importantly, the logistics big data precipitated by the platform inversely empowers supply chain optimization, helping customers accurately predict the transportation cycle and dynamically adjust inventory strategy, forming an innovative paradigm of logistics data-driven supply chain decision-making. In vertical fields such as grain storage, the platform improves the efficiency of grain collection by 40% through unattended weighing rooms and intelligent scheduling systems, and reduces grain loss by 8%, highlighting the transformation value of digitalization to the traditional workflow. This transformation path of "technology penetration + ecological synergy" has not only reduced Xiamen Xiangyu's logistics cost ratio by 2.3 percentage points, but also cultivated a new mode of intelligent logistics services, and the revenue of related digitalized services increased by 217% year-on-year in 2023, marking the strategic leap from traditional logistics operator to digital supply chain service provider.

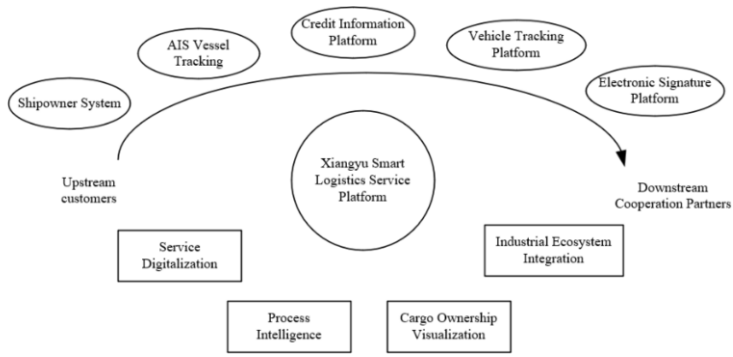


Figure 6. Xiamen Xiangyu Smart Logistics Service Platform

3.6. Zhiyun Network Freight Platform

Aiming at the pain points of lagging informationization and dispersed capacity in the traditional freight market, Xiamen Xiangyu has built a digital network freight platform to reshape the logistics ecology of bulk commodities. The platform integrates core functions such as payment, wind control and positioning with modular technology architecture, and opens up the data of the whole chain of vehicle-cargo-warehouse-port to realize visual monitoring and intelligent warning of the whole process of transportation. Relying on the endogenous transportation demand of enterprises of more than 5 million tons per year, the platform innovates the mode of offline feeding online, integrates 47,000 socially scattered vehicles, and forms a nationwide trunk line transportation network, with an annual capacity of 4.8 million tons, and the efficiency of vehicle and cargo matching is improved by 60%. Through satellite positioning and AI algorithms to build a dynamic wind control system, the cargo loss rate has been reduced to 0.3%, and transportation costs have dropped by 18%, which has pushed the enterprise

to be assessed as a 4A-level network freight qualification and become one of the few profitable third-party platforms in the industry.

On the basis of consolidating the advantages of road transportation, Xiamen Xiangyu has accelerated the construction of a multimodal transportation ecosystem: it has developed a network water transportation platform to dock more than 90 routes, and put online a ship tracking system for real-time control and management of 200 cooperating ships, forming a digital logistics network that seamlessly connects "public, railway and water". The logistics data deposited on the platform feeds the supply chain optimization, increasing the on-time delivery rate of orders to 98% through intelligent forecasting, cultivating a new mode of intelligent logistics services, and increasing the related digital revenue by 217% in 2023. This transformation of "technology empowerment + ecological synergy" not only reduces the proportion of logistics costs by 2.5 percentage points, but also pushes the bulk commodity logistics from a cost centre to a value centre, and creates a new mode of value-added supply chain driven by digitization.

3.7. Gross margin analysis

In low-gross profit industries, profit resilience is a direct reflection of the core competitiveness of enterprises. Under the traditional model, commodity supply chain enterprises are highly dependent on spread earnings and have weak risk resistance. However, Xiamen Xiangyu's practice shows that digital transformation can fundamentally change this logic. As evidenced by its financial data, see Table 2, its supply chain gross margin has remained stable at 1.9%-3.09% between 2018 and 2023, significantly outperforming the volatile performance of its peer company, Wuchan Zhongda Group. In particular, during the global supply chain disruption in 2020, Xiamen Xiangyu achieved cross-subject penetration of cargo rights data through the Yuliantong blockchain platform, which enabled the gross profit margin to only briefly decline to 1.98%, and then rebounded to 2.07% in the following year; whereas, due to the lack of a digital risk control system, Wuchan Zhongda's gross profit margin plummeted from 2.46% to 1.90% during the same period. The deep logic behind this phenomenon is to build a credible warehouse receipt system through blockchain technology, through the procurement, logistics, and financial chain data, not only to enhance the control of the right of goods but also to reduce the cost of friction in the transaction; intelligent logistics platform integration of social capacity resources, the formation of cost optimisation under the effect of scale; the agricultural industry Internet through the source to shorten the circulation of the direct procurement layer, reducing the intermediate premium loss. On the contrary, Wuchan Zhongda's traditional operation model of fragmented procurement channels and fragmented logistics information has always constrained the efficiency of cost transmission, especially when the market price fluctuates drastically, and the lack of a digital risk control system has led to significant losses in the futures and cash business. The division between the two confirms the intrinsic value of digital transformation - it not only reduces costs and increases efficiency through process optimisation, but more importantly reconstructs a new type of 'data-driven decision-making' capability, which enables enterprises to dynamically balance scale expansion and risk control, and build a sustainable profit model in a low gross profit environment. This enables the company to dynamically balance scale expansion and risk control and build a sustainable profit model in a low gross profit environment. Xiamen Xiangyu's practice shows that when digitalisation is upgraded from a tool to a strategic core, the

enterprise can break through the dependence on price difference and shift to the higher-order competition form of "technology empowerment + value-added services".

Table 2. Comparison of Gross Profit Margins of Xiamen Xiangyu and CUIPPC Enterprises

company	Business Categories	2018	2019	2020	2021	2022	2023
Xiamen Xiangyu Group	Supply Chain	2.61%	3.09%	1.98%	2.07%	1.90%	1.92%
	Purchasing Cost	2.23%	2.70%	1.75%	1.93%	1.75%	1.70%
Wuchan Zhongda Group	Supply Chain	1.96%	1.79%	2.46%	1.90%	1.63%	1.69%
	Purchasing Cost	1.98%	1.81%	2.50%	1.93%	1.65%	1.69%

Data source: Xiamen Xiangyu Island, IZP financial report for the period of 2018-2023

4. Pain points and countermeasures for digital transformation

The digital transformation practice of Xiamen Xiangyu Group shows that commodity supply chain enterprises need to systematically deal with the challenges of the three-dimensional synergy of technology, organization and environment. Based on the TOE theoretical framework, its core pain points and solutions correspond to the following:
First, the lack of technological adaptability centred on data silos and cross-body synergies. The long-chain characteristics of the commodity supply chain require technology to penetrate the whole scene, but the traditional ERP system makes it difficult to meet the dynamic tracking needs of cross-border logistics. In this regard, Xiamen Xiangyu Island has constructed the "Lantau Chain" platform through blockchain technology, which transforms physical cargo rights into credible digital assets, realizes real-time verification of warehouse receipt data across banks, customs and logistics, and reduces the defective rate of electronic warehouse receipts to 0.3%, thus cracking the ecological synergy barriers. Second, the shackles of organizational inertia, manifested in strategic cognitive limitations and grassroots implementation resistance. The agriculture segment had exposed transformation resistance due to employee resistance to the smart grain storage system. The enterprise broke the situation through cognitive-capability dual-wheel drive: setting up a digital innovation committee led by executives to reshape the strategic vision, constructing an agricultural industry internet platform, and using blockchain traceability technology to bind planting data and financial services, which pushed the organization to shift from passive execution to collaborative innovation, and helped farmers increase their income. Third, environmental constraints are strengthened, stemming from policy changes and industry competition squeeze. In international business expansion, rising logistics compliance costs have become a pain point. Xiamen Xiangyu has embedded an AI-driven HS code verification module in its intelligent logistics platform, integrated data from 180,000 TEU global logistics nodes, and dynamically adapted to multi-country trade policies, which has shortened cross-border compliance timeframe by 40%, and the proportion of overseas business has jumped from 8% to 22%, transforming external constraints into technical barriers.

In summary, the synergistic mechanism of technology penetrating scenarios, dual-wheel drive organization and the dynamic response of the environment constitute the

underlying logic of systematic transformation under the TOE framework. When the blockchain platform cracks the data silos, cross-departmental collaboration dissolves organizational inertia, and intelligent early warning internalizes external constraints, enterprises can break through the trap of local optimization and form strategic-level digital competitiveness.

5. Conclusions

Based on the TOE theoretical framework, this study reveals the strategic reconstruction path of commodity supply chain enterprises in the era of digital economy through the in-depth case analysis of Xiamen Xiangyu Group's digital transformation. The study finds that: (1) technology penetration is the basic support for digital transformation, and the scenario-based application of blockchain, Internet of Things and other digital technologies can effectively solve the problem of credit deficiency and information silos in the traditional supply chain, for example, the "Yuliantong" platform can improve financing efficiency by 60% through the digital authentication of the electronic warehouse receipts; (2) organizational change is the key guarantee for transformation; cognitive upgrading and competence enhancement are the key factors for the transformation. The dual-wheel drive mechanism of cognitive upgrading and capacity building (e.g., digital innovation committee and business centre architecture) can break through the inertia of traditional organizations and realize the paradigm shift from passive response to active innovation; (3) Ecological synergy is the core path of value creation. The "technology empowerment + service value-added" model formed through the construction of industrial Internet platform clusters has enabled Xiamen Xiangyu to achieve a breakthrough of 217% three-year growth in digital service revenue while maintaining an industry average gross profit margin of 1.9%, which verifies the strategic value of the synergistic evolution of technology-organization-environment under the TOE framework.

This study expands the application boundary of the TOE framework at the theoretical level, confirms its applicability in explaining the transformation of complex supply chain systems, and constructs a systematic transformation model of "technology penetration scenario - organisational dynamic adaptation - ecosystem value co-creating"; meanwhile, it expands the theoretical boundary of organisational resilience, and finds that digital transformation enables a leap from reactive defence to proactive prevention through data-driven dynamic capability reconstruction. While traditional research focuses on crisis response capability, this study finds that digital transformation enables organisational resilience to leap from reactive defence to proactive prevention through data-driven dynamic capability reconfiguration. The "Risk Warning Index" and "Resilience Adjustment Coefficient" established by Xiamen Xiangyu verify that digital resilience has new features of predictability and adaptability. At the practical level, it provides three aspects of inspiration for commodity supply chain enterprises: first, give priority to selecting digital technologies with strong scenario adaptability, and achieve technology penetration by minimising the cost of trial and error; second, establish a transformation conduction mechanism of "strategy leading - middle decoding - grassroots implementation" to resolve resistance to organisational change; third, rely on core business to build an open ecological platform, and integrate data elements into the business. Third, building an open ecological platform to transform data elements into new production factors.

There is still room for coordination between the industry focus and the typicality of cases in this study, and subsequent research can further subdivide the commodity category and strengthen the cross-company comparative analysis. With the acceleration of global supply chain restructuring, how to deeply integrate digital transformation with ESG strategy and build a smart supply chain system with both economic value and social responsibility will become an important research direction in this field.

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Digitalization and Management Innovation IV
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Research on the Pain Points of Traditional Manufacturing Production Lines and the Path to Intelligent Transformation

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Abstract. Production line is the lifeblood of national manufacturing industry. This paper adopts empirical analysis research methods. Based on the understanding of the current situation of the traditional manufacturing industry production line, this paper systematically analyzes the core pain points of the traditional production line. The traditional production line has problems such as production efficiency bottlenecks, quality control defects, and comprehensive cost pressure. It studies and puts forward intelligent transformation paths such as automatic equipment upgrading scheme, data acquisition system deployment, and intelligent control center construction. It also puts forward implementation guarantee systems such as phased transformation scheme design, cross departmental collaborative team formation, and continuous optimization evaluation mechanism. It also looks forward to the future direction of production line upgrading. The purpose of this study is to provide reference and practical guidance for the transformation and upgrading of manufacturing industry.

Keywords. Traditional production line, pain points, intelligent transformation, guarantee system

1. Introduction

As a pillar of the national economy, the manufacturing production line is the core component of the industrial system. The level of production line directly reflects the strength of the national manufacturing industry, and the upgrading of production line is an important hand of the national manufacturing strategy. To realize the transformation and upgrading of the manufacturing industry, the key is the digital transformation and intelligent transformation of the production line. At present, domestic scholars have done a lot of research on the automation or intelligence of the production line, and foreign scholars such as saravanan, v., balakannan, K. have done research on how to improve the efficiency of the production line and shorten the delivery cycle [1] [2], but the existing research lacks a systematic review of the problems existing in the traditional production line. This study uses empirical analysis method, based on the understanding of the current

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situation of the traditional manufacturing industry production line, in-depth analysis of the core pain points of the traditional production line, and then puts forward the path of intelligent transformation and the implementation guarantee system, so that the research is more targeted and applied, and helps enterprises' production line digital transformation and intelligent transformation.

2. Analysis of core pain points of traditional production line

Through in-depth research and interviews with many enterprises, the common problems existing in the production line of traditional manufacturing industry are mainly reflected in the following aspects:

2.1 Production efficiency bottleneck

2.1.1 Production beat mismatch

Traditional production lines have significant differences in the beat of each process, often resulting in process imbalance and lagging order response. Traditional production lines have batch production rigidity, fixed equipment capacity, unable to adapt to the needs of multi-species production, flexible production is missing, difficult to meet the demand for personalized customization. Material transportation relies on fixed tracks or manual handling, which can not dynamically match the production rhythm, often resulting in logistics and distribution delays.

2.1.2 Manual line change takes too long

The fixture adjustment of traditional equipment depends on experience operation, and the switching of fixtures is complex. Process parameters are set by operators based on experience, and the qualification rate of the same product fluctuates greatly in different shifts. Different products need to reset equipment pressure, temperature and other parameters, and manual input is prone to error. The equipment operation relies on the experience of masters, the line change operation is lack of standardized process, the update of the operation instructions is delayed, the SOP version used on site is different from the latest standard of the engineering technology department, and the troubleshooting time is long in case of failure.

2.1.3 Information silos and data disconnection

The production plan, equipment status and inventory data are scattered in independent systems, and the data from multiple systems are not interconnected. Planners rely on experience to estimate production capacity, and their prediction ability is weak. In case of sudden order insertion or equipment failure, the traditional production scheduling table cannot quickly reorganize the production sequence, and the dynamic adjustment is missing. The production progress data needs to be manually transcribed between different platforms, resulting in the delay of production reports and a serious lag in the basis for decision-making.

2.2 Quality control defects

2.2.1 High error rate of manual inspection

Manual inspection relies on operator's experience, and visual inspection is easily affected by fatigue, light and other factors, resulting in a high rate of missing inspection of defects. There are differences in the understanding of quality standards among personnel in different shifts, the same product may be judged as qualified/unqualified, resulting in batch quality fluctuations. The detection efficiency is low, the detection speed of traditional calipers, templates and other tools is only 1/5 of that of automation equipment. In the field of precision manufacturing such as auto parts, the single piece detection time is more than 3 minutes, which seriously restricts the production line beat.

2.2.2 Lack of quality traceability system

The vast majority of machine tools are not installed sensors, and rely on manual records, quality data scattered in paper records, Excel tables and different systems. In case of quality problems, many documents need to be retrieved across departments, which takes a long time to trace. The data integrity rate is insufficient, only the final inspection results are recorded without process parameters. It is difficult to carry out effective quality analysis when batch defects occur. The raw material batch information is not associated with the production process data, and there is no process-level data association, so it is impossible to accurately locate the specific machines, shifts or operators in case of quality problems.

2.2.3 The abnormal response mechanism is slow

Equipment abnormalities rely on manual alarms, and many abnormal handling remains at the level of "maintenance records", without forming a closed loop of FMEA analysis [3] - measure formulation - effect verification, resulting in a high recurrence rate of similar faults. Quality anomaly analysis only relies on post statistics and lacks tools such as real-time SPC control charts, making it difficult for management personnel to intervene promptly in the early stages of deviating from trends.

2.3 Comprehensive cost pressure

2.3.1 Energy consumption continues to rise

Traditional production lines mostly use old and high energy-consuming equipment [4]. The energy-efficiency level of core components such as motors and compressors is generally lower than IE3 standard. The annual power consumption of a single equipment is high, and there is a lack of real-time energy consumption monitoring means. There are a lot of invalid energy conversion links in the production process. The traditional production scheduling mode does not consider the time of use price strategy, and the key power consumption equipment often operates in the peak period of electricity price.

2.3.2 The maintenance cost of spare parts is high

Many enterprises have serious mechanical wear and tear of old equipment, aging and failure of electrical components, frequent failures, resulting in an increase in unplanned downtime, which not only causes capacity loss, but also causes order delivery risk. The inventory structure of spare parts is unreasonable, the key components rely on imports and the procurement cycle is long, and additional air transportation costs are incurred during emergency maintenance, resulting in high maintenance costs.

2.3.3 Redundant inventory occupies funds

Traditional empirical inventory management leads to the safety inventory of bolts, seals and other general parts far exceeding the actual demand, resulting in a high cost of inventory funds occupied every year. Due to product iteration or process change, many special spare parts have never been used before being eliminated. The lack of digital inventory system leads to long search time for spare parts, insufficient utilization of storage space and low efficiency of storage management.

3. Intelligent transformation path

In view of the core pain points existing in the production line of traditional manufacturing industry, in order to fundamentally solve the problems and explore the general solutions, the following transformation paths can be explored and implemented:

3.1 Automation equipment upgrade program

Promote the integration of robot and automation technology, optimize man-machine cooperation system, and help process intelligent upgrading [5]. Through off-line programming to achieve rapid production change [6], with force control sensors to enhance flexible production capacity. Intelligent logistics system transformation, deployment of AGV + RGV composed of three-dimensional conveyor network, integrated RFID identification and WMS system, to achieve automatic material sorting, accurate distribution and dynamic inventory update [7][8]. Digital twin equipment iteration, add IoT edge computing module for old machine tools, build 3D digital twin model real-time mapping of physical equipment state [9][10].

3.2 Data acquisition system deployment

Adopting OPC UA+Modbus hybrid communication architecture, multimodal sensors such as vibration/temperature/humidity/pressure/current are deployed at key stations to realize automated equipment data acquisition. Deploy embedded AI box on the equipment side to perform real-time data cleaning, feature extraction and anomaly detection. TDengine+InfluxDB dual-engine architecture is adopted to support the writing of millions of data points per second and provide hot data storage capacity. Work with Grafana visualization Kanban to achieve millisecond level historical data backtracking.

3.3 Intelligent control center construction

Integrate MES/APS/QMS and other sub-systems based on microservice architecture, and realize three-dimensional visualization monitoring of equipment in the whole plant through the digital twin engine, so as to improve the speed of abnormal response. Deploy dynamic scheduling algorithms based on reinforcement learning [11] to generate the optimal production scheduling program according to real-time order data, equipment status, material supply and other multi-dimensional variables, in order to shorten the time of line change. Realize intelligent inspection and quality control of production line based on machine perspective [12]. Integrate equipment mechanism model and deep learning fault prediction model [13], construct expert system for several fault modes, warn potential faults in advance, and reduce unplanned downtime.

In order to solve their own pain points, case enterprises will adopt corresponding solutions. Examples of production line modifications are shown in Table 1.

Table 1. Examples of production line modifications

Example 1: Modification of automobile welding production line of a joint venture automobile enterprise	
Pain point	The OEE (overall efficiency) of the equipment is only 58%, and the mold change time is up to 3 hours.
Scheme	Deploy KUKA intelligent robot + AI model for process parameters optimization.
Achievement	The OEE was increased to 82% and the die change time was reduced to 45 minutes.
Example 2: Upgrade of SMT production line in an electronics factory	
Pain point	The throwing rate of the placement machine is 0.3%, and the daily loss is more than 10000 yuan.
Scheme	Machine vision positioning + federated learning optimization parameters.
Achievement	The throwing rate dropped to 0.05%, and the annual cost savings exceeded 3million.

4. Implementation guarantee system

In order to carry out the optimization and transformation of production line smoothly, it is necessary to establish a scientific and reasonable implementation guarantee mechanism.

4.1 Phased retrofit program design

4.1.1 Diagnostic assessment of current situation

Establish a digital maturity model through multiple indicators such as equipment networking rate and data acquisition integrity, identify the shortcomings of the current production line in automation level and information system integration, and form a quantitative evaluation report.

4.1.2 Verification of pilot production line

Select a demonstration production line with moderate process complexity, deploy basic modules such as equipment data acquisition and production visualization, verify the feasibility of the technical route through 3-6 months' operation, and accumulate experience in key parameters optimization.

4.1.3 Scale promotion and deployment

Based on the pilot experience, formulate a standardized transformation manual, establish an implementation standard package including hardware installation specifications, system docking protocols, etc., and realize the intelligent upgrading of production lines in the whole plant through modular replication.

The phased retrofit program is shown in Table 2.

Table 2. Phased retrofit program

Phase	Objectives	Key technologies
Single-point breakthrough	Digitization of key equipment (such as adding sensors)	IIoT, SCADA system
Line-level integration	Collaborative optimization of the whole production line	MES, AGV scheduling algorithm
Global intelligence	Dynamic allocation of factory-level resources	Digital twin, AI decision center

4.2 Cross department collaborative team establishment

4.2.1 Top-level decision-making committee

Headed by the vice president of production, the committee coordinates the heads of IT, production, equipment and other departments, and holds monthly strategy promotion meetings to make decisions on major resource inputs and solve obstacles to cross-sector collaboration.

4.2.2 Technical implementation team

The core technical personnel, including MES engineers and automation experts, are deployed in an agile development mode, and a daily meeting mechanism is established to respond quickly to technical problems on site.

4.2.3 Grassroots executive support team

Organize workshop directors, team leaders and other front-line management personnel to be responsible for production scheduling and coordination during the transformation, and carry out operation training for all staff to ensure the implementation and application of the new system.

4.3 Continuous the assessment mechanism optimization

4.3.1 Key performance kanban

Construct a dynamic monitoring system including OEE, quality traceability and other indicators, realize minute-level data refreshing through BI tools, and automatically generate weekly/monthly dimensional improvement analysis reports.

4.3.2 Technology iteration roadmap

Organize expert review meetings every quarter, assess the bottlenecks of the existing system in the light of the industry's technological development trend, and develop a three-year upgrade plan including predictive maintenance, digital twin and other technologies.

4.3.3 Benchmarking mechanism

Regularly collect the best practices of leading enterprises in the industry, find out the gap items through GAP analysis, and carry out special improvement activities to ensure that the level of intelligence continues to stay ahead of the industry.

5. Conclusion and Prospect

This paper uses the empirical analysis method to systematically analyze the core pain points of the traditional production line, and puts forward the intelligent transformation path and implementation guarantee system, in order to help the transformation and upgrading of the traditional production line. However, the production lines of different industries and enterprises are different, so we can’t copy one plan and one model. We should put forward corresponding solutions based on the actual situation of enterprises, and gradually promote the transformation and upgrading of production lines on the premise that the basic conditions are met. In addition, attention should be paid to avoid the tendency of "focusing on technology and ignoring management". In the future, the upgrading of production lines should focus on the trend of high integration, focus on the integration and innovation of AI, 5G and metauniverse technology, and promote the evolution of manufacturing industry to a higher stage of "self perception, self decision-making and self execution".

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Digitalization and Management Innovation IV
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Study on the Influence of Digitalization on Low-Carbon Transformation of Manufacturing Industry

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Abstract. Digitalization is the cornerstone of low-carbon sustainable development of manufacturing industry. Drawing on 2012–2022 panel data for 27 manufacturing sub-sectors in China, the study employs baseline regression, mediation effects and heterogeneity to explore the impact. The findings indicate: (1) Digitalization exerts a direct influence on manufacturing's low-carbon transformation. Under controlled conditions, a 1% increase in digitalization level results in an average 0.615% increase in the low-carbon transformation level of manufacturing industry. This conclusion remains valid after addressing endogenous issues; (2) Mechanism test shows that digitalization promotes manufacturing's low-carbon transformation by improving energy efficiency and optimizing energy use composition; (3) Heterogeneity test indicates that digitalization's impact on low-carbon transformation is more pronounced in industries with lower carbon emissions. Considering this empirical evidence, we advance several policy proposals.

Keywords. Digitalization; low-carbon transformation; energy efficiency; energy use composition

1. Introduction

Against the backdrop of escalating global warming, China has proposed the dual carbon goal strategy. The efficacy of manufacturing's green transformation directly determines whether double carbon goals can be accomplished. In 2023, China's manufacturing sector contributed 26.2% to national GDP and about 30% of the global total. Concurrently, China's was responsible for 34% of global total, with greenhouse gas emissions reaching 12.6 billion tons of carbon dioxide equivalent, and total energy consumption is 5.72 billion tons. Among them, these six high-energy-consuming sectors - thermal power, steel, non-metallic mineral, petroleum refining and coking, chemicals and non-ferrous metals - collectively consume over 50% of total energy while generating nearly 80% of carbon emissions. Evidently, low-carbon transformation of manufacturing sector is the core battlefield for realizing the double-carbon goal.

Digital economy era, digitalization has emerged as a crucial driver for low-carbon development. Empirical research has pointed out that digitalization [1], digital technologies [2] and digital economy [3] significantly contribute to low-carbon

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transition. Furthermore, digitalization enables this process through enhancing technological innovation [4] and improving energy efficiency [5].

Under the background of carbon reduction, the low-carbon transformation has become mainstream. However, there are still two limitations: First, existing literature predominantly examines technological advancement and energy efficiency as mediating factors, while largely overlooking the transmission mechanism of energy consumption structure. Second, most existing studies use provincial or city and firm panel data, with fewer studies focusing on the manufacturing sub-sectors. Therefore, based on theoretical analysis, this study examines 27 manufacturing sub-sectors to investigate digitalization's impact on the manufacturing low-carbon transformation and puts the energy efficiency and energy consumption structure into analysis framework, deeply explores the internal mechanism of digitalization empowerment low-carbon transformation, and provides targeted reference for policy making.

2. Theoretical analysis and research hypothesis

2.1 Digitalization's direct impact on manufacturing's low-carbon transformation

Digitalization is crucial for transforming traditional manufacturing and achieving low-carbon transformation. First, digital technologies can monitor high-carbon resource consumption in real time and promote the manufacturing's low-carbon transformation by controlling carbon in the whole process and simplifying production processes [1]. Secondly, as the digital economy evolves, digital technology release dividends and achieves low-carbon goals by changing the production methods of manufacturing products [6], such as 3D printing and robotic applications. Digital virtual simulation helps enterprises simplify and optimize the production process, significantly improve resource efficiency, and reduce per-unit carbon emissions, accelerating the industry's low-carbon transition [7]. Additionally, digital technologies help the manufacturing to obtain market demand in time, refining production decisions to avoid overproduction and energy waste. Drawing upon the preceding analysis, we formulate the following research hypothesis:

H1: Digitalization can directly impact the manufacturing's low-carbon transformation.

2.2 Digitalization's indirect impact on manufacturing's low-carbon transformation

Digitalization empowers manufacturing's low-carbon transition by enhancing energy efficiency. Firstly, digital technology enables digital economy and carbon emission industry to penetrate and merge, which can promote the process of reengineering of traditional industries, realizing energy monitoring and enhancing efficiency [8]. At the same time, enterprises can collect and analyze energy data through the digital platform, optimize the energy management ability of enterprises, and improve energy efficiency. Second, higher digitalization accelerates green technological innovation, which can use energy more efficiently [9]. The improvement of energy efficiency not only means that less energy is needed to produce the same amount of products, but also directly decreases carbon emissions, thereby accelerating the manufacturing's low-carbon transition; it also reduces the energy consumption cost of enterprises and allows more

funds to be invested in low-carbon technology. Drawing upon the preceding analysis, we formulate the following research hypothesis:

H2: Digitalization drives manufacturing's low-carbon transformation through enhancing energy efficiency.

As a primary energy consumer, manufacturing relies on energy structure optimization as a fundamental transformation strategy. First, companies can identify high-energy-consuming production processes and equipment through digital technology, thereby adjusting optimize their energy consumption structure and reduce coal usage at various stages [10]. Moreover, digitalization can predict the energy demand in advance, so that enterprises can make reasonable energy plans and avoid energy waste. Next, digital technology breaks the spatial boundaries, which urges enterprises to acquire and store clean energy, increases the proportion of clean energy [11-12], and accelerates low-carbon transformation. Drawing upon the preceding analysis, we formulate the following research hypothesis:

H3: Digitalization drives manufacturing's low-carbon transformation through optimizing energy consumption structure.

3. Research design

3.1 Variables selection

(1) Explained variable: Low-carbon transformation (*LCT*). Manufacturing's low-carbon transformation is to reduce carbon emissions while boosting economic growth. Carbon productivity can reflect the relationship between economic growth and carbon emissions. Therefore, this paper refers to Lyubich et al [13], which defines carbon productivity as the ratio of manufacturing sector output value to carbon emissions. Carbon emissions are calculated using the following mathematical expression:

$$CO_2 = \sum_{i=1}^{n} E_i \times NVC_i \times CC_i \times COF_i \times \frac{44}{12}$$

Among them, *CO2* represents carbon dioxide emission; *i* stands for energy types: coke, coal, gasoline, diesel, kerosene, fuel oil and natural gas; *E* denotes energy consumption; *NCV* indicates the average low calorific value of energy; *CC* stands for carbon content; *COF* represents the carbon oxidation rate during combustion; the coefficients 44 and 12 reflect the molecular masses of CO_2 and atomic carbon respectively.

(2) Main explanatory variable: Digitalization (*Dig*). Current academic research employs three principal methods to quantify manufacturing digitalization levels: total consumption coefficient, direct consumption coefficient and Herfindahl-Hirschman Index. Referring to the practice of Sheng Bin and Liu Yuying [14], this paper computes industry total consumption matrices according to China's input-output tables in 2012, 2015, 2017, 2018 and 2020, deriving the share of digital intermediate inputs required by per unit final product value across industries. In view of the database availability, digital intermediate inputs include "communication equipment, computer and other electronic equipment manufacturing" and "information transmission, computer services and software industry". The remaining years are supplemented by interpolation. Referring to the practice of Yang Fei and Fan Conglai [15], digitalization is quantified as the proportion of digital intermediate input to the industries value-added.

(3) Mediator variables: Energy efficiency (EU). Energy efficiency reflects the energy consumption level and utilization effect of a system. Referring to the practices of Liu Wenqi and Song Li [16], this paper adopts the proportion of industrial value-added to energy consumption as energy efficiency. Energy consumption structure (*ECS*). Energy structure optimization is a vital element of low-carbon transition. In China, "abundant coal resources and poor oil and gas" energy characteristics make coal a primary energy source and major contributor to carbon dioxide emissions. Therefore, referring to the method of Akorede Y.F. and Afroz R. [17], take the ratio of coal consumption to total energy consumption as energy consumption structure. The higher the value, the more it depends on traditional energy, and on the contrary, it uses more clean energy.
(4) Control variables: Technological innovation (*Tec*). The number of valid invention patents is used to evaluate technological innovation. Foreign direct investment (*FDI*). Empirical studies suggest foreign direct investment exerts dual effects on carbon emissions [18-19]. Referring to Lv Xiang et al [20], use the amount of foreign investment in each industry to represent. Environmental Regulation (*ER*). According to the existing research [21], environmental regulation is quantified as the proportion of wastewater/gas treatment operating costs to the main business cost. The greater the proportion, the stronger the environmental regulation.

3.2 Model construction

(1) Baseline regression model: According to the above theoretical analysis and referring to the existing literature [22], this study constructs a baseline regression model to verify whether the digitalization can affect manufacturing's low-carbon transformation, and the measurement model is set as shown in Formula (1):

$$\ln LCT_{i,t} = \alpha_0 + \alpha_1 \ln Dig_{i,t} + \alpha_2 \ln CONTROL_{i,t} + \varepsilon_{i,t} \quad (1)$$

Among them, i represent industry; t stands for time; *LCT* represents low-carbon transformation, *Dig* represents digitalization, and *CONTROL* means a series of control variables; α is the influence parameter; ε is the random interference term.
(2) Mediation effect model: Based on baseline regression, to further verify whether the digitalization can empower the manufacturing's low-carbon transformation by enhancing energy efficiency and optimizing energy consumption structure. Referring to Wen Zhongli's practice [23], the mediation effect model is constructed by stepwise regression method, as shown in Formula (2) and Formula (3):

$$\ln MEDIATOR_{i,t} = \beta_0 + \beta_1 \ln Dig_{i,t} + \beta_2 \ln CONTROL_{i,t} + \varepsilon_{i,t} \quad (2)$$

$$\ln LCT_{i,t} = \gamma_0 + \gamma_1 \ln Dig_{i,t} + \gamma_2 \ln MEDIATOR + \gamma_3 \ln CONTROL_{i,t} + \varepsilon_{i,t} \quad (3)$$

MEDIATOR represents mediator variables, including energy efficiency and energy consumption structure. When the energy efficiency is a mediator variable, if β_1, γ_2 is significantly positive, it shows that the digitalization can empower the manufacturing's low-carbon transformation by enhancing energy efficiency; when the energy consumption structure is a mediator variable, if β_1, γ_2 is significantly negative, it shows that the digitalization can optimize the energy consumption structure, thus boosting the manufacturing's low-carbon transformation.

4. Empirical tests

4.1 Baseline regression test

The baseline regression test results of Formula (1) are shown in Table 1. Column (1) is not fixed in time and industry; Column (2) is fixed in time and industry; Columns (3) to (5) are the test results after the control variables are gradually increased, and the R^2 is gradually increased from column (1) to column (6), showing that the model fitting is getting better. The regression coefficient of digitalization on manufacturing's low-carbon transformation is 0.615 ($p<0.01$), revealing that digitalization exerts a notable influence on manufacturing's low-carbon transformation, and H1 is verified.

Table 1 Baseline regression results

variable	(1) lnLCT	(2) lnLCT	(3) lnLCT	(4) lnLCT	(5) lnLCT
lnDig	1.319***	0.624***	0.671***	0.621***	0.615***
	(0.152)	(0.132)	(0.134)	(0.131)	(0.130)
lnTec			0.163*	0.158*	0.151*
			(0.093)	(0.091)	(0.090)
lnER				1.281***	1.311***
				(0.319)	(0.317)
lnFDI					0.280**
					(0.121)
_cons	1.667***	0.852***	-0.443	-0.555	-2.296**
	(0.246)	(0.151)	(0.757)	(0.736)	(1.047)
time fixed	NO	YES	YES	YES	YES
industry fixed	NO	YES	YES	YES	YES
N	297	297	297	297	297
R^2	0.202	0.592	0.597	0.621	0.629

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively; standard errors are reported in parentheses. The same convention applies hereafter.

4.2 Multiple collinearity test

Given that high correlations between explanatory variables may lead to unreliable estimates, we systematically assess multiple collinearity in our model. The test results are shown in Table 2. The results show that all variance inflation factors (VIF) are well below the threshold of 10 (model VIF=2.33), confirming the absence of significant collinearity concerns. This provides empirical evidence that digitalization reliably influences the manufacturing's low-carbon transformation.

Table 2 Multiple collinearity test results

variable	lnEU	lnFDI	lnTec	lnDig	lnER	lnECS	Mean VIF
VIF	3.17	2.81	2.51	2.16	1.69	1.62	2.33
1/VIF	0.316	0.356	0.399	0.462	0.592	0.617	

4.3 Endogenous test

4.3.1 Missing variable

Although several control variables are added to the baseline regression model, and time and industry are also controlled, the influence of other variables on low-carbon transition cannot be ignored. Therefore, to mitigate potential endogeneity arising from

omitted variables, we incorporate government intervention (GOV) as an additional control variable in our analysis. Government intervention is quantified by government funds' percentage in R&D internal expenditure, and the estimation result presents in column (1) of Table 3. The experiment result expresses that digitalization maintains a statistically significant positive effect (1% level) on manufacturing's low-carbon transformation after controlling for government intervention, confirming the robustness of result.

4.3.2 Reverse causality

In the baseline regression model, there may be a reverse causality between the main explanatory variable and the explained variable, leading to endogenous problems. Therefore, this paper verifies the main explanatory variable by lagging one period and two periods. The estimation outcomes are respectively displayed in columns (2) and (3) of Table 3. The results demonstrate that, in the robustness test of the main explanatory variable with a lag of one period and two periods, a statistically significant positive relationship ($p<0.01$) between digitalization and manufacturing's low-carbon transition, demonstrating that digitalization remains a key driver of low-carbon transition even when accounting for potential reverse causation, and the regression results are reliable.

Table 3 Endogenous test results

variable	(1) lnLCT	(2) lnLCT	(3) lnLCT
lnDig	0.615***		
	(0.130)		
L.lnDig		0.494***	
		(0.139)	
L2.lnDig			0.452***
			(0.144)
lnTec	0.150*	0.109	0.095
	(0.090)	(0.095)	(0.098)
lnER	1.311***	1.171***	1.002***
	(0.318)	(0.352)	(0.376)
lnFDI	0.279**	0.257*	0.228
	(0.121)	(0.140)	(0.149)
lnGOV	0.307		
	(1.650)		
_cons	-2.290**	-1.923	-1.550
	(1.050)	(1.210)	(1.274)
time fixed	YES	YES	YES
industry fixed	YES	YES	YES
N	297	270	243
R^2	0.629	0.612	0.590

4.4 Mediation effect test

The outcomes of mediation effect test are documented in Table 4. Column (1) presents the results obtained with energy efficiency as the mediator variable. The influence coefficient of digitalization on energy efficiency is 0.095 ($p<0.01$); subsequently, when energy efficiency is added to the regression model, it is found that both digitalization and energy efficiency have positive effects on low-carbon transformation($p<0.01$). The tests reveal that digitalization drives manufacturing's low-carbon transformation through enhancing energy efficiency.

Column (2) presents the results obtained with energy consumption structure as the mediator variable. The regression coefficient of digitalization on energy consumption structure is -0.076 ($p<0.01$); when the energy consumption structure is added into the regression model, digitalization has a positive impact on low-carbon transformation, and the regression coefficient of energy consumption structure on low-carbon transformation is -5.012 ($p<0.01$), indicating that digitalization can drive manufacturing's low-carbon transformation through optimizing energy consumption structure.

Table 4 Mediation effect test results

variable	(1)		(2)	
	ln*EU*	ln*LCT*	ln*ECS*	ln*LCT*
lnDig	0.095***	0.403***	-0.076***	0.235***
	(0.030)	(0.113)	(0.021)	(0.081)
lnEU		2.215***		
		(0.230)		
lnECS				-5.012***
				(0.241)
_cons	0.916***	-4.326***	1.048***	2.957***
	(0.244)	(0.922)	(0.166)	(0.687)
controls	YES	YES	YES	YES
time fixed	YES	YES	YES	YES
industry fixed	YES	YES	YES	YES
N	297	297	297	297
R^2	0.450	0.728	0.438	0.862

On the basis of stepwise regression test, this paper further uses bootstrap sampling method to examine the mediation effect. The outcomes are displayed in Table 5. When the energy efficiency is used as a mediation variable, the direct effect is 0.337, the mediation effect is 0.694, and the 95% confidence interval is (0.539, 0.917), excluding the number 0, confirming significant mediation. Similarly, for energy consumption structure as the mediator, the direct effect is 0.832, the mediation effect is 0.199, and the 95% confidence interval of is (0.050, 0.438), excluding the number 0, so it can be considered that there is some mediation effect. The H2 and H3 are verified.

Table 5 Bootstrap sampling test results

mediation variable		Effect	BootSE	95%BootCI		proportion
lnEU	Total effect	1.031	0.114	0.806	1.256	
	Direct effect	0.337	0.087	0.165	0.509	
	Indirect effect	0.694	0.096	0.539	0.917	67.31%
lnECS	Total effect	1.031	0.114	0.806	1.256	
	Direct effect	0.832	0.075	0.685	0.980	
	Indirect effect	0.199	0.099	0.050	0.438	19.30%

Note: bootstrap sampling times are 5000.

4.5 Heterogeneity analysis

Considering that the impact of digitalization on manufacturing's low-carbon transformation may vary due to carbon emission intensity. This article is based on carbon emission intensity and expressed in terms of carbon dioxide emissions per unit of GDP, and the sample industries are divided into high-emission industries and low-emission industries based on whether the annual average of carbon emission

intensity of industries is greater than the median of the annual average. On this basis, the virtual variable CEI is introduced, and the high-emission industries is assigned to 1, and the low-emission industries are assigned to 0 (reference group). Then, the interactive variable between the virtual variable CEI and digitalization (lnDig*CEI) is constructed, and the regression result of this variable is used to analyze the heterogeneity of digitalization on manufacturing's low-carbon transformation. The results are displayed in Table 6. The result demonstrates that the influence of interaction variable on manufacturing's low-carbon transformation is -4.706 ($p<0.01$). It shows that the marginal impact of digitalization on low-carbon transformation of low-emission industries is greater than that of high-emission industries. The reason may be that the production equipment in high-emissions industries is relatively old and highly dependent on coal energy, which increases the difficulty of enterprise transformation and upgrading, making it difficult for digitalization to play its role.

Table 6 Heterogeneity analysis results

variable	(1) lnLCT
lnDig	0.605***
	(0.127)
lnDig*CEI	-4.706***
	(1.236)
_cons	-1.961*
	(1.024)
controls	YES
time fixed	YES
industry fixed	YES
N	297
R^2	0.649

5. Conclusions and suggestions

5.1 Main conclusions

This study explores the influence of mechanism of digitalization on manufacturing's low-carbon transformation. Based on the empirical analysis of industry panel data from 2012 to 2022, conclusions are drawn: (1) Baseline regression results show that digitalization exerts a direct effect on manufacturing's low-carbon transformation. Under the condition of controlling other variables unchanged, manufacturing's low-carbon transformation will increase by 0.615% on average for every 1% increase in digitalization. (2) Energy efficiency and energy consumption structure have some mediating effects in the manufacturing's low-carbon transformation affected by digitalization. (3) The marginal impact of digitalization on the low-carbon transformation of low-emission industries is greater than that of high-carbon emission industries.

5.2 Policy suggestions

Building upon these research findings, we propose the following policy recommendations: In the first place, in a digital age, the government must place sufficient emphasis on the coordinated development of digitalization and manufacturing's low-carbon transformation. On the one hand, government can

encourage enterprises to adopt digital technology, improve the digital level and lay the foundation for low-carbon transformation. On the other hand, enterprises should actively recruit digital technology professionals to enhance their internal digital capabilities and drive low-carbon transition. Second, we ought to fully realize the indirect influence of energy efficiency and energy consumption structure in the process of digitalization empowerment manufacturing's low-carbon transformation. For energy utilization efficiency, enterprises should build an intelligent energy management system with the help of digital technology, use big data analysis to accurately identify high-energy-consuming links, implement targeted energy-saving transformation, and reduce energy waste. Government should encourage superior enterprises to form a demonstration effect. For the energy consumption structure, policymakers should encourage digital technology adoption in clean energy systems, facilitating manufacturing's transition toward sustainable energy sources while reducing reliance on high-carbon alternatives. Third, we should formulate differentiated targeted policies. For high-emission industries, government should encourage digital transformation, help introduce advanced digital equipment, build intelligent energy management systems, and reduce the cost pressure of enterprise transformation. At the same time, it is necessary to cultivate compound talents with both industry knowledge and digital skills to enhance the digital transformation ability of the industry. For low-emission industries, they ought to leverage digital tools more extensively to develop low-carbon technology and establish a model.

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Data-Driven Analysis of Cross-Border E-Commerce Growth in Guangdong, China

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Abstract. This study focuses on the development of cross-border e-commerce (CBEC) in Guangdong Province China, a major foreign-trade-oriented province in China with numerous traditional foreign trade enterprises. This study comprehensively summarizes the development of cross-border e-commerce in Guangdong, mainly analyzing four key aspects: cross-border logistics, cross-border payment, talent cultivation, and legal regulation. Through searching for relevant influencing factors and conducting research and analysis using the econometric analysis software, factors closely related to the development of cross-border e-commerce in Guangdong are identified. After rigorous testing and analysis, it is concluded that the amount of cross-border e-commerce financing, commodity turnover, local financial expenditure, and financial regulation in Guangdong Province have a significant impact on the scale of cross-border e-commerce transactions in the province. These findings and suggestions aim to provide valuable references for promoting the healthy development of cross-border e-commerce in Guangdong Province.

Keywords. OLS regression analysis, CBEC, Cross-border logistics, Cross-border Payment

1 Introduction

1.1 Research Background

Cross-border e-commerce (CBEC) has emerged as a key global trade driver. China's 2024 Government Work Report emphasizes new foreign trade patterns, announcing 152 additional CBEC pilot zones and overseas warehouse support. In 2022, China's CBEC imports/exports reached ¥2.11 trillion (+9.8% YoY), outpacing GDP growth (3%). Traditional foreign trade's reliance on offline channels contrasts with CBEC's internet-driven model, which eliminates channel barriers and unlocks buyer resources-making it a critical transformation path for enterprises. Supported by national policies, CBEC demonstrates strong growth prospects.

1.2 The purpose and significance of the research

This study aims to explore the impact of cross - border e - commerce development on Guangdong's exports. By analyzing relevant data and drawing on domestic and

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international experiences, it endeavors to provide reasonable suggestions. The findings of this study are expected to offer valuable insights for policymakers and enterprises in Guangdong, enabling them to optimize the market environment and promote the vibrant growth of cross - border e - commerce, thus contributing to the sustainable development of cross-border e-commerce and international trade.

1.3 Novelty of this research

This research enhances CBEC literature by addressing gaps through novel dimensions. This study uniquely examines Guangdong Province, a leading trade hub, to analyze CBEC's influence on local trade, providing insights for policymakers. Finally, it proposes targeted policies (e.g., talent cultivation, supply-chain investment, inter-departmental data sharing), tailored to Guangdong but transferable to other regions. Unlike generic policy recommendations, these are empirically grounded, filling a gap in practical CBEC research and offering actionable strategies for regional economic development.

2.Theoretical Framework

2.1. Theoretical Foundations

This study constructs a theoretical framework analyzing cross-border e-commerce (CBEC) development in Guangdong, China, integrating Transaction Cost Theory, Resource-Based View (RBV), and Institutional Economics Theory. In CBEC, digital platforms streamline information, reduce asymmetry, and aggregate suppliers and buyers, minimizing partner search costs. In Guangdong, CBEC platforms are crucial for reducing transaction costs, enabling local enterprises to trade internationally more efficiently. The RBV posits that resources and capabilities drive competitive advantage. In CBEC, financing and logistics are key.

2.2. Linkage Mechanisms between Variables and CBEC Development

From the Resource-Based View, financing is crucial for Guangdong's CBEC enterprises. Per Transaction Cost Theory, sufficient capital mitigates cross-border transaction risks and cuts costs; well-funded firms can use reliable payment systems, reducing disputes and boosting transactions. Logistics, measured by cargo turnover, is key to CBEC growth. In Guangdong, high cargo turnover signals effective networks, ensuring fast international deliveries and enhancing customer satisfaction. From the RBV, strong logistics is a core competitive resource. Institutional Economics Theory underscores regulation's role. Appropriate policies clarify rules, safeguard stakeholders, and reduce information asymmetry. Regulations on data flow and consumer protection build buyer trust, promoting CBEC health.

This framework elucidates financing, logistics, and regulation's impact on Guangdong's CBEC, forming the basis for empirical analysis.

3. Literature Review

Recent years have witnessed a growing body of research on the impact of cross-border e-commerce (CBEC) on international trade. There is a notable gap in research that focuses on policy frameworks and trade economics, which are crucial for a comprehensive understanding of CBEC development. Ren & Li (2016) linked China's CBEC-driven trade transformation to comparative advantage through domestic supply-global demand integration [1]. Chen et al. (2024) further noted that AI and blockchain are dynamically reshaping comparative advantage in CBEC, offering opportunities for digitally advanced regions like Guangdong. In Guangdong, policies include enterprise subsidies, logistics investment, and talent programs [2].Regulatory policies are critical: Zhou (2020) emphasizes balancing market growth and consumer protection via rules on data flow, IP protection, and payments [3]. Yet, most studies lack regional empirical analysis of policy implementation and dynamic adaptation to CBEC's rapid evolution.

Internationally, CBEC policy research offers insights. The EU harmonizes regulations across members to boost data sharing and consumer protection. Smith (2021) noted its framework's impact on regional CBEC and global trade [4], while Brown et al. (2023) highlighted challenges in adapting to trends like live-stream commerce. The U.S. balances CBEC growth with customs, privacy, and competition policies [5].

Even regional studies rarely systematically explore complex factor relationships; for example, Liu (2021) addresses blockchain and supply chains but not regional policy-economic dynamics [6].

This study fills this gap by focusing on Guangdong Province and conducting a comprehensive empirical analysis using OLS regression analysis and a series of statistical tests.

4. Methodology

This study analyzes Guangdong's CBEC export landscape and proposes competitiveness-enhancing strategies using literature review, data analysis, and econometric modeling. By synthesizing prior research, it identifies cross-border logistics, payments, talent, and regulation as key drivers. Using 2013–2023 data and Eviews10, a multiple linear regression model tests variables' impacts on CBEC growth, with diagnostics for stationarity, multicollinearity, and heteroscedasticity ensuring model validity.

5. Empirical analysis

5.1 Data Selection

This study uses Eviews10 to analyze Guangdong's 2013–2023 CBEC data. The cross-border e-commerce import/export volume (Y) serves as the explained variable, reflecting the industry's scale. Explanatory variables include the number of CBEC financing events (X2), financing amount (X3) to assess enterprise funding impacts, cargo turnover (X4) for logistics efficiency, local fiscal social security expenditure (X5) for labor-talent links, and financial regulation expenditure (X6) to gauge regulatory effects.

Establish a multiple regression model of Guangdong Province's cross-border e-commerce import and export volume (Y) on Guangdong Province's number of cross-border e-commerce financing events (X2), Guangdong Province's amount of cross-border e-commerce financing (X3), cargo turnover (X4), local fiscal expenditure on social security and employment (X5), and local fiscal expenditure on financial regulation (X6):

$$Y=\beta_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \mu$$

Table.1 List of relevant data on CBEC in Guangdong,2013-2020

Year	The Import and Export Volume of Cross-border E-commerce in Guangdong (100 million yuan)	The Number of Financing Events (times)	The Amount of Financing (100 million yuan)	Freight Turnover (100 million ton-kilometers)	Local Fiscal Expenditure on Social Security and Employment (100 million yuan)	Local Fiscal Expenditure on Financial Supervision (100 million yuan)
2013	107.8	2	1.39	9228.55	746.97	16.43
2014	136.9	8	0.597	14801.03	797.01	45.56
2015	167.3	18	13.37	14882.21	1064.91	141.17
2016	227.96	21	7.83	21801.65	1146.31	159.47
2017	441.9	17	5.01	27919.79	1423.33	20.65
2018	759.76	12	27.02	28338.33	1508.02	70.61
2019	1107.9	10	41.46	27373.67	1703.48	55.28
2020	1726.46	33	70.9	27211.12	1807.2	28.89
2021	3310	8	75.5	28388.03	2142.34	46.45
2022	6454	23	41.5	28400.32	2149.01	76.34
2023	8433	19	14.33	29690.74	2358.93	82.43

Source: China Statistical Yearbook **2013-2023**, National Bureau of Statistics of China.

5.2 Smoothness test

Since the economic variables used in this paper are time series data, in order to avoid the results of 'pseudo-regression' in the model, it is necessary to test the smoothness of the time series variables through the unit root test. Since there are unstable and stable time series of the variables, unit root test through cointegration test is needed to determine whether the residual series is stable or not, if it is stable, it means that the model can continue to be analysed, if it is not stable, the data need to be re-selected to be analysed.

5.3 Cointegration tests

The smoothness test of the residual series shows that the t-statistic = -6.241667 > -7.01933125 = the critical value of the test ,so the original hypothesis is rejected, indicating that the residual series does not have a unit root, and it is a smooth series meaning that Y and X2, X3, X4, X5, X6 have a cointegration relationship.

5.4 Multicollinearity test

Through the multiple linear regression it can be seen that the regression results of, F-test are high, but the t-test of X2, X4, X5, X6 is not significant, which indicates that the model may have serious multicollinearity. To address multicollinearity more effectively, in addition to the stepwise regression method used in this study, alternative approaches such as Ridge Regression and Principal Component Analysis (PCA) were explored. Ridge Regression adds a penalty term to the OLS objective function, shrinking the regression coefficients towards zero while keeping all variables in the model, thus reducing the impact of multicollinearity. PCA transforms the original variables into a new set of uncorrelated principal components, constructing a regression model based on these components. However, considering the specific research objectives of this study, which aim to interpret the impact of individual economic and policy factors on CBEC in Guangdong, stepwise regression was ultimately selected as it helps simplify the model and identify the most significant variables, making the results more interpretable in the context of this research.

Table 2 The Revised Final Regression Model

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-34.65513	54.30113	-0.638203	0.5580
X3	19.61124	0.805114	24.35833	**0.0000**
X4	0.014955	0.002603	5.745569	**0.0045**
X6	-1.670299	0.293245	-5.695909	**0.0047**
R-squared	**0.997068**	Mean dependent var		584.4975
Adjusted R-squared	**0.994869**	S.D. dependent var		580.3738
S.E. of regression	41.57209	Akaike info criterion		10.59959
Sum squared resid	6912.954	Schwarz criterion		10.63931
Log likelihood	-38.39835	Hannan-Quinn criter.		10.33169
F-statistic	**453.4334**	Durbin-Watson stat		2.943402
Prob(F-statistic)	0.000016			

According to Table 2, the estimation results obtained show that =0.9971, =0.9949, the decidable coefficients of the regressions are high, the F-test value of 453.4334 can be seen to be significantly significant and the P-values of the t-tests are all <0.05, indicating that the variables are all significant.

5.5 Heteroscedasticity test

The presence of heteroskedasticity in the model may lead to unbiased OLS estimates as well as undermine the validity of t-tests and F-tests, so it is necessary to test for heteroskedasticity in the model.

Table 3 ARCH model result

Heteroskedasticity Test: ARCH			
F-statistic	0.017119	Prob. F(1,5)	0.9010
Obs*R-squared	**0.023884**	Prob. Chi-Square(1)	**0.8772**

According to Table 3, from the ARCH test, n = 0.024 and p-value = 0.8772 > 0.05, so the results do not reject the original hypothesis, indicating that there is no heteroskedasticity in the model.

5.6 Final regression model

The final regression model was obtained after passing the smoothness test, multiple covariance test, and heteroskedasticity test:

$$Y=\beta_1 + \beta_3 X_3 + \beta_4 X_4 + \beta_6 X_6 + \mu$$

Table 4 Final result of regression model

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-34.65513	54.30113	-0.638203	0.5580
X3	19.61124	0.805114	24.35833	**0.0000**
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Log likelihood	-38.39835	Hannan-Quinn criter.		10.33169
F-statistic	**453.4334**	Durbin-Watson stat		2.943402
Prob(F-statistic)	0.000016			

To further explore the complex relationships between variables, a log-linear model was also estimated. The log-linear model, by taking the natural logarithm of the dependent and independent variables, can capture non-linear relationships and elasticity effects. The results of the log-linear model showed that the elasticities of X3 (cross-border e-commerce financing), X4 (cargo turnover), and X6 (local fiscal financial supervision expenditure) on the cross-border e-commerce import and export volume in Guangdong were 1.2, 0.3, and -0.2 respectively. This indicates that a 1% increase in cross-border e-commerce financing would lead to a 1.2% increase in trade volume, a 1% increase in cargo turnover would result in a 0.3% growth, and a 1% rise in local fiscal financial supervision expenditure would cause a 0.2% decrease. The log-linear model provides a different perspective on the magnitude of variable impacts, complementing the findings of the linear regression model.

5.7 Analysis of final regression results

The final regression model (X3, X4, X6) demonstrates strong explanatory power (R^2=0.997, adjusted R^2=0.995) and statistical significance (F=453.43, p<0.001). Key results show that a ¥100M increase in CBEC financing (X3) drives a ¥1.96B rise in trade volume, the most significant positive impact. Cargo turnover (X4) yields a smaller effect (¥0.1015B per 100M ton-kilometers), likely due to stagnant logistics growth in the data. Conversely, a ¥100M increase in financial regulation expenditure (X6) reduces trade volume by ¥0.167B, explained by improved regulatory efficiency via digital platforms reducing redundant spending and short-term compliance burdens from stricter rules, though such regulations support long-term market stability. Financing remains the

primary driver, while enhancing logistics efficiency and balancing regulatory costs are critical for sustained CBEC growth.

6.Discussion

6.1 Result

The final regression model (X3, X4, X6) shows high fit (R^2=0.9971, adjusted R^2=0.9949) and statistical significance, with X3 (CBEC financing) as the strongest driver: a ¥100M increase boosts trade volume by ¥1.96B. X4 (cargo turnover) yields a smaller positive effect (¥0.1015B per 100M ton-kilometers), potentially due to stagnant logistics growth in the data. The negative coefficient for X6 (financial regulation expenditure)—¥100M increase reduces trade by ¥0.167B—reflects improved regulatory efficiency via digital tools cutting redundant spending and short-term compliance burdens, though long-term stability benefits exist. Financing, logistics, and regulation interact synergistically: financing enables logistics upgrades and regulatory stability attracts investment. Enhancing logistics efficiency and balancing regulatory costs are key to sustaining Guangdong's CBEC growth.

6.2 Limitations of the study

The study's focus on Guangdong limits generalizability. Future research should incorporate multi-regional/country data to enhance external validity and uncover broader patterns. Methodologically, while OLS regression and log-linear models provide insights, they may miss complex non-linear relationships. Additionally, the 2008–2023 temporal scope may overlook recent trends.

6.3 Future research directions

Methodologically, adopting advanced non-linear models (e.g., threshold regression, panel smooth transition models) and interaction effect analyses (e.g., structural equation modeling) will better capture complex factor relationships. These approaches will enhance theoretical robustness and provide actionable insights for navigating the global digital economy.

7. Conclusion

This study analyzes Guangdong's CBEC development from 2013 - 2020. The final regression model, with variables X3 (financing), X4 (cargo turnover), and X6 (regulation expenditure), shows strong explanatory power, highlighting financing's key role. To promote Guangdong's CBEC growth, three strategies are proposed. However, the study has limitations. Its focus on Guangdong and use of basic econometric methods may restrict findings' generalizability. Future research should broaden geographical scope, adopt advanced methods, and cover more recent data to better understand CBEC's global impact. The study's insights benefit both Guangdong's CBEC and other regions aiming to enhance their competitiveness.

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Reconfiguration of Digital Talent Training Model Driven by "Digital and Intelligent Integration"

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Abstract. In the era of digital-intelligence integration, the surging demand for high-quality digital talent challenges traditional linear cultivation models. This study develops a system dynamics model to simulate the evolution of talent training systems under industrial demand growth. The model incorporates factors such as curriculum reform, policy support, recruitment standards, and learning feedback to examine talent supply-demand dynamics in the Greater Bay Area from 2019 to 2023. Results show that without intervention, the talent gap would widen significantly, constraining industrial upgrading. Policy scenario simulations indicate that a 20% increase in policy support could markedly reduce the talent shortage and improve training quality. Sensitivity analysis identifies curriculum reform and policy strength as key leverage points. The study concludes that reconstructing talent cultivation models through system dynamics is crucial to achieving alignment between talent supply and industrial needs. Findings offer strategic insights for policymakers and educators to design targeted interventions supporting the digital economy and intelligent manufacturing.

Keywords. Digital-Intelligence Integration, Digital Talent Cultivation, System Dynamics, Policy Simulation

1. Introduction

With the rapid advancement of digitalization and intelligent technologies, the deep integration of both has become a major driver of high-quality development in the manufacturing sector. Emerging technologies such as artificial intelligence, big data, and industrial internet are reshaping industries and accelerating the demand for high-quality digital talents. In particular, intelligent manufacturing requires a new generation of digital professionals characterized by high volume, diverse skills, and rapid iteration. However, existing talent cultivation systems reveal significant limitations under these new demands. Traditional discipline-centered models, outdated

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curricula, and weak industry-academia integration have led to a growing mismatch between talent supply and industrial needs. This structural contradiction "slow cultivation, fast iteration, and tight demand" presents a critical challenge for higher and vocational education.

System dynamics (SD), widely used in industrial planning and policy simulation, offers a powerful approach to model complex systems involving feedback, delays, and nonlinear interactions. Applying SD to digital talent development allows dynamic simulation of how factors such as policy, technology, and industry jointly shape outcomes.

This study constructs an SD model for digital talent cultivation under digital-intelligence integration, identifying key variables, feedback loops, and dynamic pathways. The goal is to propose targeted strategies and policy recommendations that can help educational institutions and governments optimize talent systems in support of the digital economy and intelligent industry transformation.

2. Literature Review and Theoretical Framework Construction

2.1 Literature Review

In recent years, the rise of the digital economy and intelligent manufacturing has made "digital-intelligent integration" a central theme in industrial transformation, significantly increasing the demand for digital talent cultivation. Scholars widely recognize its role in reshaping educational systems and strategies.

S. Agarmore (2024) [1] emphasize that integration of digitalization and intelligence drives reform in university talent training models, particularly in science and engineering, where applied innovation is urgently needed. Echoing this, Rachbauer T (2024) [2] propose "digital-intelligent accompaniment learning," highlighting the enabling power of AI in education while warning that low teacher digital literacy hinders progress. On the practical side, Wang Shanshan (2024) [3] advocates for deeper industry-education integration, such as "bringing enterprises into education," to better align talent development with industrial needs. Zhao Lei et al. (2024) [4] extend this logic to university libraries, suggesting they become hubs for AI literacy and digital capabilities by incorporating system dynamics methods. From broader conceptual perspectives, Wang Menglin (2024) [5] applies the "new quality productive forces" framework to argue for value reconfiguration and logical transformation in vocational education, supported by system dynamics modeling. Zhao Xing et al. (2022) [6] incorporates the metaverse and virtual humans into talent system design, proposing a hybrid virtual-real cultivation model. Internationally, Williamson and Hogan (2020) [7] and OECD (2021) [8] highlight how datafication and platformization are reshaping digital education strategies in OECD countries, calling for integrated, system-level reforms. Selwyn (2022) [9] further warns that while digital tools offer promise, their implementation must ensure equity and quality.

Overall, the literature supports the use of system dynamics as a powerful tool for understanding and optimizing digital talent systems in both domestic and global contexts.

2.2 Applicability of System Dynamics

SD has been widely used by scholars to model and analyze complex systems in education and talent cultivation. Liu Dejian (2019) [10] emphasized SD's ability to address feedback loops and time delays within education systems, offering simulation-based insights for optimizing talent training mechanisms. Building on this, Stavropoulou G et al. (2024) [11] integrated digital twin and SD approaches to construct a knowledge graph analyzing how digital transformation in China's manufacturing sector influences talent cultivation, concluding that adaptive reforms in training models are crucial for supporting industrial upgrading.

Overall, SD's strengths in modeling nonlinear, feedback-driven systems make it especially suitable for: (1) analyzing how diverse policies, teaching models, and technologies jointly influence talent development; (2) tracing causal feedback loops between industrial demand and educational design; and (3) simulating the long-term effects of different cultivation strategies.

3. SD Model Construction under Digital-Intelligence Integration

3.1 Causal Loop Diagram (CLD) Analysis

Draw the causal loop diagram of the digital talent cultivation model under "Digital-Intelligence Integration", as Fig.1.

Positive Feedback (Enhancement Effects):(1)Industrial Demand Loop: Growing industrial demand drives the development of digital courses in universities, improving training quality and further reinforcing demand satisfaction.(2)Policy Support Loop: Government support boosts investment in digital infrastructure, transforming teaching models and aligning talent cultivation with intelligent manufacturing needs.

Negative Feedback (Suppression Effects): (1) Lagging Feedback Loop: Higher enterprise recruitment thresholds increase student pressure, weakening the system's ability to meet industrial demand. (2) Learning Bottleneck Loop: Course difficulty lowers student learning effectiveness, leading to a decline in training quality.

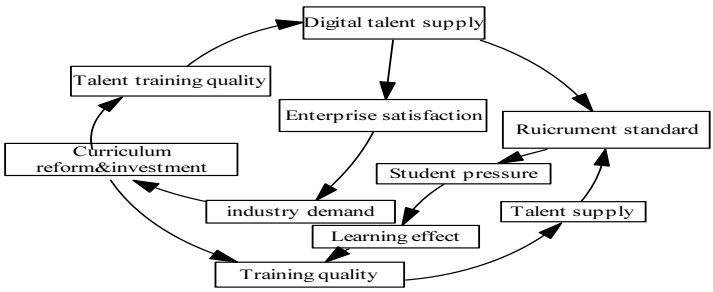


Fig.1 Positive and negative feedback loop

3.2 Flow-Inventory Model (Stock-Flow Diagram, SFD)

Define key variables and establish a mathematical model:
(1)Inventory variables (Stock)"The number of cultivated digital talents", "The demand for digital talents by the industry", "The number of students currently undergoing training".
(2)Flow variables (Flow): "The rate of talent cultivation", "The rate of talent loss", "The rate of change in industry demand".
(3)Mathematical model example (based on differential equations):

Change in digital talent stock = Existing talents + New cultivated talents - Lost talents

Talent cultivation speed = Course setting * Teacher quality * Number of students

Growth in talent demand = Upgrading rate of industry * Degree of industrial digitalization

4. Data collection and simulation

4.1 Data Collection

Data for the period from 2019 to 2023 in the Guangdong-Hong Kong-Macao Greater Bay Area were collected, mainly from statistical yearbooks, white papers, and the China Science and Technology Statistical Yearbook. Some data were derived using mathematical models. The simulation results are shown in figure 2 below.

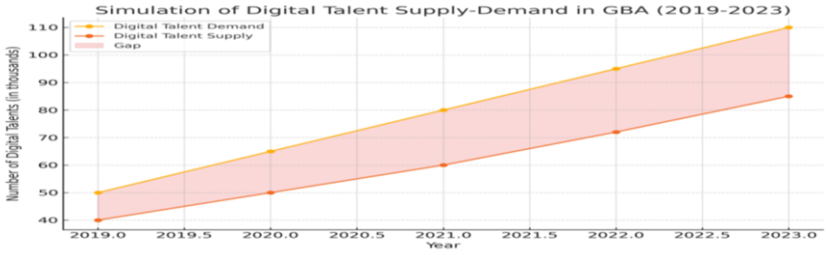


Fig. 2 Simulation in GBA (2019-2023)

4.2 Discussion on Simulation Results

Simulation analysis of digital talent supply and demand in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) from 2019 to 2023 reveals a persistent and widening gap. Industrial demand surged from 50,000 in 2019 to 110,000 in 2023, with an average annual growth rate of over 15%. In contrast, talent supply grew from 40,000 to 85,000, lagging behind at under 12% annually. This imbalance expanded the supply-demand gap from 10,000 to 25,000 during the same period, with the mismatch intensifying especially after 2021.

This trend indicates that, without effective policy interventions or deeper industry-academia collaboration, the GBA risks a sustained talent shortfall, hindering intelligent manufacturing and digital economy development. Rapid growth in key

sectors such as AI, smart manufacturing, and digital services has sharply accelerated the demand for high-quality digital professionals — outpacing GDP growth and reshaping regional human capital structures.

Structural constraints persist: lengthy education cycles, outdated curricula, and weak institutional-industry linkages limit training capacity. Notably, the shortage is most acute in high-end technical and managerial talent. Simulation results suggest that by 2023, the real gap may reach 250,000, underscoring an urgent need for targeted policy and education reform to prevent severe disruption in industrial and supply chain stability.

Moreover, increasing talent mobility has intensified regional disparities. Major hubs like Shenzhen, Guangzhou, and Hong Kong exhibit strong attraction power, while mid-tier cities such as Zhuhai and Zhongshan suffer from a "talent siphoning effect," further exacerbating spatial imbalances in talent distribution.

4.3 Discussion on Policy Intervention Scenarios

Simulation results indicate that initiating policy intervention in 2022, raising the annual talent cultivation rate by 20%, markedly enhances the GBA's supply capacity. By 2023, the talent gap narrows from 25,000 to approximately 13,000, a reduction exceeding 50% compared to the baseline. The green area in Figure 3 reflects this improvement.

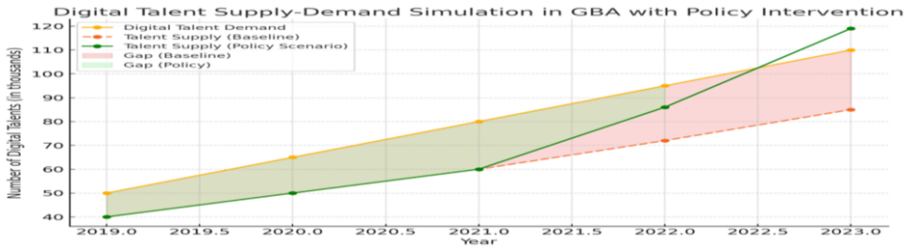


Fig.3 Simulation with policy investment

This demonstrates that timely and sustained policy support can effectively mitigate structural shortages. Moreover, the intervention shows a cumulative effect: earlier action leads to more balanced long-term supply-demand dynamics, supporting the region's intelligent manufacturing and digital economy development.

4.4 Sensitivity analysis

To assess sensitivity, three key variables were adjusted: curriculum reform intensity, enterprise recruitment standards, and policy support levels. Under strong intervention, curriculum investment increased by 50%, recruitment thresholds were raised (increasing student pressure), and policy support rose by 50%. In contrast, weak intervention involved a 20% reduction in curriculum investment, lower recruitment thresholds (reducing pressure), and only a 10% increase in policy support. These variations were used to evaluate their respective impacts on talent supply quality, learning outcomes, and enterprise satisfaction. The result is as Fig.4.

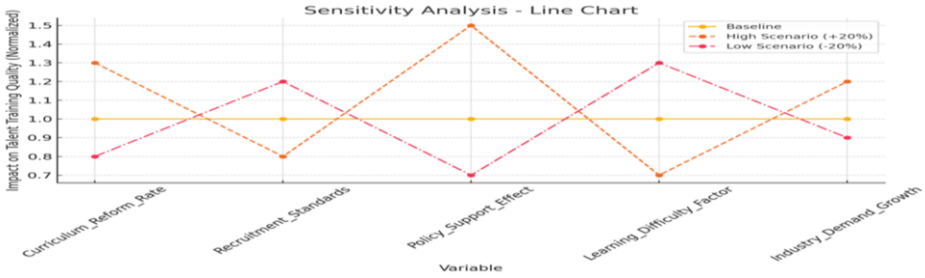


Fig.4 Sensitivity analysis result

The sensitivity analysis results reveal that among the selected factors, Curriculum Reform Rate and Policy Support Effect have the most significant positive impact on digital talent training quality. Specifically, increasing curriculum reform intensity or policy support by 20% leads to a substantial improvement in talent output, while decreasing them results in noticeable quality degradation.

Conversely, raising Recruitment Standards and increasing the Learning Difficulty Factor negatively affect the learning outcomes and overall training quality, primarily by intensifying student pressure. Changes in Industry Demand Growth show a moderate impact but become more critical in scenarios with accelerated industrial expansion.

5. Conclusion and Discussion

This study constructs a system dynamics (SD) model to examine digital talent cultivation under the "digital-intelligence integration" context in the Greater Bay Area (GBA). It captures the dynamic interactions among industrial demand, talent supply, policy intervention, curriculum reform, and student learning pressure.

Simulation results reveal that industrial demand for digital talent has grown rapidly, with the supply lagging behind leading to a projected talent gap exceeding 25,000 by 2023. Policy scenario analysis shows that increasing support by 20% from 2022 can significantly reduce this gap to around 13,000. Sensitivity analysis further identifies curriculum reform intensity and policy strength as the most influential factors in improving talent output, while excessive recruitment standards and course difficulty hinder outcomes.

These findings underscore the need to move beyond traditional, linear training models. A systemic reconstruction—centered on responsive policy design, curriculum modernization, and deeper industry-academia integration—is essential to meet evolving workforce demands. The study echoes earlier research, such as Liu Dejian's emphasis on feedback dynamics in education, and confirms the practical importance of embedding enterprises in training ecosystems as noted by Wang Shanshan. However, unlike Zhao Xing et al.'s advocacy for metaverse-integrated models, our simulation found limited immediate effects from such innovations—highlighting an avenue for future exploration.

The model was validated through structural and behavioral consistency checks against empirical data from 2019–2023. Though credible in trend reproduction, it assumes linear impacts and fixed rates and does not incorporate real-time shocks or institutional heterogeneity. These are acknowledged limitations, suggesting the need

for enhanced modeling methods such as agent-based simulations and scenario-driven forecasting in future research.

Importantly, the model's framework—emphasizing feedback between demand, education, and policy—is conceptually transferable to other regions facing similar digital transformation challenges. However, successful adaptation requires local calibration across data, governance structures, and socio-cultural conditions.

Looking ahead, policymakers are encouraged to implement adaptive, data-informed frameworks, while educational institutions should adopt modular, industry-linked curricula to remain responsive. Further studies should incorporate individual-level behaviors, simulate disruptive technologies, and validate the model across regions and over time. Ultimately, refining digital talent strategies through dynamic modeling can better align workforce development with the evolving needs of intelligent industries and digital economies.

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Influence of ESG Performance on Green Innovation in Construction Firms Amidst the Carbon Peaking Background: A Study Based on Multiple Linear Regression Model

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Abstract. As the "dual carbon" strategy progresses, listed firms are enhancing long-term competitiveness by proactively disclosing ESG information and adopting green innovation strategies. These interventions are conducive to the development of favorable internal - external interactions and the creation of a positive social profile, thus driving green and sustainable progress. This research selects Chinese A-share construction enterprises during the 2013 - 2022 timeframe as the research sample. It employs a two-way fixed-effects model to thoroughly examine the influence of ESG performance on corporate green innovation. The empirical evidences indicate that the ESG performance of listed firms can exert a significant and positive driving force on their green innovation capabilities. Further research demonstrates that R&D investment acts as an intermediary, positive moderator while government subsidies serve as a positive moderator respectively, in the mechanism by which ESG performance drives green innovation. Finally, policy recommendations are put forward from three dimensions—enterprises, society, and government—to provide new pathways for all stakeholders to enhance the ESG performance of listed companies and raise the caliber of green innovation.

Keywords. ESG performance, green innovation, construction enterprises, sustainable development; carbon peaking

1. Introduction

Environmental protection issues have become increasingly serious Alongside the rapid economic expansion and the unceasing acceleration of the industrialization process in China[1]. The 20th National Congress of the Communist Party of China (CPC) emphasized promoting sustainable socio-economic development, with innovation as the core driver and key support for green development. Therefore, green innovation is regarded as an effective approach to address environmental issues, as it can achieve a win-win outcome for both environmental protection and economic benefits.[2]. The

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construction industry, marked by substantial energy consumption and carbon emissions, depends on green innovation to surmount environmental constraints and achieve low-carbon transformation. [3]. In recent years, as societal awareness of China's carbon peaking and carbon neutrality objectives has intensified, ESG (Environmental, Social, and Governance) has steadily risen to prominence as a crucial criterion for evaluating corporate sustainability. ESG (Environmental, Social, and Governance), functioning as a key motivator for China's high - quality development, and it has garnered widespread acclaim and attention during the nation's pursuit of green development. In this context, investigating how ESG performance propels green technological innovation in construction enterprises is vital for improving their economic and social benefits.

Currently, most existing research in the ESG field is focused on ESG ratings[3], ESG investment & financing[5]and the corporate ESG impact effect[6], and other related areas. For example, some scholars have conducted empirical investigations into the influence of fluctuations in ESG ratings on corporate green innovation and found that these disparities may hinder green innovation[6]. Other research has demonstrated that ESG performance can reduce financing limitations and foster green innovation, thereby boosting corporate value. [7]. Research on green innovation primarily examines its internal and external influencing factors and their effects on external outcomes. Most studies indicate that internal factors, such as company characteristics[8] and executive characteristics[9], along with external factors like government policies[10] environmental regulation[11]. All these factors will exert a specific influence on corporate green innovation. Additionally, research has found that green innovation not only improves carbon emission performance and reduces pollution[12], but also positively impacts corporate debt financing [13].

Current research mainly focuses on ESG's impact and green innovation influencers, with limited focus on whether ESG performance significantly enhances green innovation capabilities in construction enterprises, particularly construction-focused ones. This research aims to dissect the mechanisms governing the impact of corporate ESG performance on green technological innovation, providing theoretical insights to assist corporate managers in implementing targeted strategies.

2. Research Hypothesis

Within the framework of the Resource-Based View (RBV), ESG (Environmental, Social, and Governance) is acknowledged as a pivotal resource that is instrumental in securing corporate sustainability and attaining a competitive advantage. According to RBV, a company's core competitiveness stems from its ability to control and utilize unique resources, and ESG capability is a crucial skill for acquiring, allocating, and managing these key resources[14]. Research has shown that strong ESG performance can significantly reduce regulatory costs for investors and encourage green technological innovation[15]. From the perspective of stakeholders, ESG enables companies to attract a broader investor base, reduce risks, and provide strong impetus for green innovation[16]. Moreover, better ESG performance can enhance patent value and significantly improve the quality of innovation[17]. Most studies have demonstrated that ESG performance in manufacturing companies can positively impact green technological innovation[18]. However, whether ESG performance in construction companies can also positively promote green technological innovation remains to be studied. In summary, ESG performance helps reduce costs, increase investment and

financing, and drive innovation. Based on this, this paper proposes Research Hypothesis 1.

H1: The ESG performance of construction firms has the potential to generate a favorable influence on their green innovation endeavors.

Corporate green innovation represents a highly specialized and long-term R&D endeavor with significant risks, necessitating sustained financial backing from the enterprise. From the organizational dimension grounded in TOE framework theory, R&D investment exerts a favorable influence on corporate green technology innovation.[4]. When companies enhance their R&D investment, their green innovation capabilities tend to improve accordingly[19].Moreover, robust ESG performance can boost corporate R&D investment through multiple channels: mitigating financing bottlenecks, enhancing market anticipations, and luring top-tier research professionals[20].Research has demonstrated that firms with superior ESG performance generally allocate more resources to R&D and innovation. This practice not only strengthens their green technology innovation capabilities but also elevates their market competitiveness and long-term sustainability[21]. Based on this, Hypothesis 2 was proposed.

H2: ESG performance enhances green innovation in construction enterprises by increasing research and development investment.

According to the Resource Dependence Theory (RDT), a company's innovation activities are heavily dependent on the external environment. Government subsidies, as an external source of funding and policy support, can provide external support for companies' green innovation and development. On one hand, for enterprises with robust ESG performance, government subsidies can provide greater financial support and offer stronger backing in aspects like technology equipment procurement and R&D talent recruitment[22]. On the other hand, research demonstrates that firms with superior ESG performance can lower their financing costs by 0.5–1.2 percentage points through government subsidies. This cost reduction enables the reallocation of more resources to green technology R&D, thereby propelling green innovation[23]. Based on this, Hypothesis 3 was proposed.

H3: Government subsidies can strengthen the positive effect of ESG performance on green innovation within construction enterprises.

3. Data Variables and Models

3.1 Data source

This study draws upon the industry classification delineated in the Guidelines for Industry Classification of Listed Companies (2012 Revision) promulgated by the China Securities Regulatory Commission (CSRC). Subsequently, it selects a sample of 51 Chinese A - share listed construction enterprises spanning the period from 2013 to 2022 for research purposes. To avoid the influence of other factors, the data has been pre-screened based on the following criteria: ① excluding ST(Special Treatment) and *ST(Risk of Delisting) listed companies; ② excluding samples with missing data values. After screening, 510 annual non-balanced panel data observations were obtained. The primary data sources are as follows: ESG performance data is derived from the Sino-Securities Index ESG Ratings and the China Research Data Service Platform

(CNRDS),green innovation data of listed companies comes from CNRDS, and other corporate financial data is obtained from the GTA Market Information Services (CSMAR) and Wind databases. The data analysis tool used is Stata17.0.

3.2 Variable selection

- Dependent variable: Green Innovation.

At present, the evaluation of corporate green innovation mainly depends on input and output approaches. In China, the innovation capability and level of listed companies are predominantly evaluated by utilizing indicators like the volume of patent applications, citation frequency, and the number of granted patents. However, there exists an absence of a unified benchmark for assessing green innovation. This study adopts an output-oriented perspective, using a method that entails incrementing the count of green patents acquired by the enterprise during the current period by 1, followed by computing the natural logarithm of the resulting value. [24]. In the robustness test, the total number of green patent applications is employed as a surrogate measure for the quantity of green patents secured, in an effort to evaluate the stability of the regression results between ESG performance and green innovation in construction enterprises[25].

The selection of relevant green patents is grounded in the *International Patent Classification Green List* put forward by the World Intellectual Property Organization (WIPO) in 2010.Following a comprehensive screening and processing of patents from the China National Intellectual Property Administration (CNIPA) and Google Patents, the green patent application data of the research enterprises were obtained. Independent variable: Corporate ESG Performance

This research employs data derived from the Sino - Securities Index ESG Ratings. The Sino-Securities ESG Evaluation System comprehensively calculates ESG assessment scores (out of 100) for all A-share listed companies over a decade-long period. Based on these calculations, a nine-tier rating system from "AAA" to "C" is assigned, corresponding to scores from 9 to 1.

- Mediating variable: R&D investment (RD)

Drawing on the financial statement data available in the CSMAR database for listed construction companies, this research adopts the natural logarithm of the enterprise's R&D investment, which is obtained by adding one to the original value, as the mediating variable.

- Moderating variable: Government subsidies (Gover)

This study uses data extracted from the financial statement footnotes of listed construction enterprises within the Wind database. To avoid significant discrepancies between this indicator data and other variable data, government subsidies have been increased by 1 and natural logarithm processing has been applied[26].

- Control variables

This research selects enterprise scale (Size), enterprise age (Age), debt-to-asset ratio (Lev), return on investment (Roa), management costs (Mc), ownership concentration (Crn), dual leadership (Dual), management shareholding ratio (Msr), and independent director ratio (Idp) as control variables, while controlling for city effects (City) and annual effects (Year).

3.3 Model design

The constructed multiple regression model is as follows.

$$GI_{i,t} = \alpha_0 + \alpha_1 ESG_{i,t} + \alpha_2 Controls_{i,t} + \sum City + \sum Year + \varepsilon_{i,t} \quad (1)$$

$$GI_{i,t} = \alpha_0 + \alpha_1 ESG_{i,t} + \alpha_2 RD_{i,t} + \alpha_3 Controls_{i,t} + \sum City + \sum Year + \varepsilon_{i,t} \quad (2)$$

$$GI_{i,t} = \alpha_0 + \alpha_1 ESG_{i,t} + \alpha_2 Gover_{i,t} + \alpha_3 ESG_{i,t} \times Gover_{i,t} + \alpha_4 Controls_{i,t} + \sum City + \sum Year + \varepsilon_{i,t} \quad (3)$$

$GI_{i,t}$ denotes the green innovation of company i in period t; $ESG_{i,t}$ represents the information disclosure of company i in period t across environmental, social, and governance dimensions; $Controls_{i,t}$ represents all control variables; City denote s city fixed effects; Year denotes annual fixed effects; $\varepsilon_{i,t}$ denotes the comprehensive error term.

4. Empirical Analysis

4.1 Benchmark regression

This study assesses the link between ESG performance and green innovation in construction firms by employing stepwise regression, as illustrated in Table 1. Columns (1) and (2) display the regression outcomes of ESG performance on green innovation, respectively with and without the inclusion of fixed effects. The coefficient of ESG performance is 0.620, significant at the 1% level, suggesting that superior ESG performance promotes increased green innovation. Columns (3) to (5) report supplementary regressions incorporating control variables, confirming that ESG has a better influence on green innovation at the 1% significance level. Hypothesis 1 has been verified.

Table 1. Benchmark regression results

VARIABLES	(1)GI	(2)GI	(3)GI	(4)GI	(5)H1-GI
ESG	0.620*** (0.049)	0.354*** (0.053)	0.274*** (0.046)	0.254*** (0.049)	0.242*** (0.049)
Controls	NO	NO	YES	YES	YES
Year	NO	YES	YES	YES	YES
City	NO	YES	YES	YES	YES
Constant	-0.625*** (0.191)	0.363* (0.206)	11.937*** (2.072)	10.967*** (2.131)	5.118* (2.761)
Observations	510	510	510	510	510
R-squared	0.242	0.627	0.709	0.714	0.728

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4.2 Mediation effect analysis

Table 2 presents the findings of the mediation effect analysis for dynamic capabilities. Column (1) displays the baseline regression results excluding R&D, revealing a statistically significant positive coefficient of 0.242. Column (2) indicates that the ESG performance coefficient stands at 0.761, which is also statistically significant and positive. Column (3) includes both R&D input and ESG performance as variables, with their regression coefficients both showing significant positive values at the 1% level. This finding implies that ESG performance facilitates the advancement of green innovation in construction firms through increased investment in research and development, thereby confirming Hypothesis 2.

Table 2. Mediation effect analysis results

VARIABLES	(1)GI	(2)RD	(3)H2-GI
ESG	0.242***	0.761***	0.164***
	(0.049)	(0.221)	(0.043)
RD			0.103***
			(0.012)
Controls	YES	YES	YES
Year/ City	YES	YES	YES
Constant	5.118*	37.995***	1.193
	(2.761)	(9.027)	(2.533)
Observations	510	510	510
R-squared	0.728	0.507	0.761

4.3 Moderation effect analysis

Table 3 exhibits the outcomes of the moderation effect analysis. The results reveal that the coefficient associated with the interaction term between ESG performance and government subsidies for construction enterprises (denoted as ESG × Gover) in Columns 1 and 2 is 0.074, achieving statistical significance at the 1% threshold. This result suggests that government subsidies can positively promote the improvement of green innovation levels by enhancing ESG performance. In essence, Hypothesis 3 is confirmed, indicating that in listed companies that receive greater government subsidies, the contribution of ESG performance to fostering green innovation holds greater significance.

Table 3 Moderation effect analysis results

VARIABLES	(1)GI	(2)H3-GI
ESG	0.176***	-1.026***
	(0.041)	(0.277)
Gover	0.317***	0.046
	(0.031)	(0.072)
ESG×Gover		0.074***
		(0.017)

Controls	YES	YES
Year/ City	YES	YES
Constant	-2.228 (2.447)	2.919 (2.707)
Observations	510	510
R-squared	0.778	0.788

4.4 Robustness test

(1) In order to substantiate the validity and reliability of the research findings, this study conducted a series of robustness tests as outlined below.

(2) Replace dependent variable. Instead of utilizing the count of granted green patents (GI) as the dependent variable, this study opted to employ the number of green patent applications (GI_1).

(3) Substitute the explanatory variables. In China, various institutions contribute to ESG ratings, drawing on authoritative data sources such as the Sino-Securities ESG Index, the Bloomberg ESG Index, and the CNRDS ESG Rating. To mitigate the influence of a single rating agency's data peculiarities on the research outcomes, this study further uses CNRDS ESG Rating data (ESG_1) for robustness testing.

(4) Instrumental variable approach. The ESG performance in the preceding period functions as an instrumental variable for the test. The instrumental variable exhibits a correlation with the ESG performance of listed firms within the same year, yet remains unaffected by the quantity of green patent applications submitted by the company during that year. Consequently, it fulfills the assumptions of correlation and exogeneity. Additionally, the rationality of the selected instrumental variable is tested. The Kleibergen-Paap rk LM statistic is 50.478 (p=0.000), indicating no unidentifiable instrumental variable. The Kleibergen-Paap rk Wald F statistic surpasses the 10% critical value of the Stock-Yogo weak instrument test, suggesting no presence of weak instrumental variables and confirming the rationality of the instrumental variable selection.

Table 4 shows the empirical results, demonstrating that the regression results of the three tests are statistically significant. Hypothesis 1 has been empirically validated.

Table 4. Robustness test results

VARIABLES	(1)GI	(2)GI	Phase I	Phase II
			(3)ESG	(4)GI
ESG	0.252*** (0.058)			0.209** (0.097)
ESG_1		0.014*** (0.005)		
IV_1			0.512*** (0.041)	
Controls	YES	YES	YES	YES
Year/ City	YES	YES	YES	YES

Constant	7.017** (2.945)	7.863*** (2.873)	3.473 (2.356)	5.511* (3.002)
Observations	510	510	510	510
R-squared	0.723	0.715	0.654	0.714
Kleibergen-Paaprk LM	-	-	50.478***	
Cragg-Donald Wald F	-	-	11.697	
Kleibergen-Paaprk Wald F	-	-	11.892	
Stock-Yogo(10%)	-	-	10.46	

4.5 Heterogeneity analysis

In various competitive environments, companies encounter different resources and conditions that can affect the driving force behind their ESG performance in green innovation. In the research, the sample firms are categorized according to the economic development and geographical location of Chinese cities into eastern, central, and western firms. Based on ownership structure, firms are further categorized into state-owned and non-state-owned enterprises. Table 5 presents the results of the heterogeneity analysis. Specifically, the sub-sample regression results in Columns 1 and 3 show that for enterprises located in central and western regions and state-owned enterprises, the effect of ESG performance on corporate green innovation is not significant. In contrast, Columns 2 and 4 demonstrate that ESG performance has a statistically significant positive effect on green innovation at the 1% level for eastern region enterprises and non-state-owned enterprises. This suggests that ESG performance plays a more critical role in promoting green innovation for these types of enterprises.

Table 5 Heterogeneity analysis results

VARIABLES	(1)Eastern	(2)Midwest	(3)Non-state-owned	(4)State-owned
ESG	0.276*** (0.050)	-0.078 (0.124)	0.126** (0.049)	-0.033 (0.070)
Controls	YES	YES	YES	YES
Year/ City	YES	YES	YES	YES
Constant	6.609** (3.017)	-13.692** (6.417)	12.872*** (3.316)	1.541 (3.793)
Observations	410	100	310	200
R-squared	0.741	0.759	0.627	0.869

5. Conclusion

Drawing on sustainable development and green technological innovation theories, this study analyzes data from 2013 to 2022 of Chinese listed construction firms on the Shanghai and Shenzhen A-share markets. This study empirically examines the impact of corporate ESG performance on green innovation. Regarding the effect of corporate ESG performance on green innovation, the results demonstrate that superior ESG performance significantly facilitates green innovation in construction enterprises. Additionally, the mediation effect test reveals that firms amplify the positive influence of ESG performance on green innovation by increasing research and development (R&D) investment. Furthermore, the moderation effect test indicates that government subsidies play a positive moderating role in the relationship between ESG performance and green innovation. Based on the above research findings, this study proposes the following policy recommendations:

(1) Enterprise level. First of all, enterprises should proactively engage in disclosing environmental, social, and corporate governance (ESG) information while ensuring the authenticity and effectiveness of such disclosures. Secondly, enterprises should establish and improve the green innovation and sustainable development system as soon as possible, take the initiative to shoulder the responsibilities of environmental protection and green development to attract high-quality value-based investment.

(2) The stakeholder leve. Investors should additionally place greater emphasis on a company's ESG performance and green innovation capabilities during the investment decision-making process. A higher ESG rating signifies not only stronger environmental, social, and governance (ESG) management but also indicates a more robust green innovation capability, potentially leading to greater economic benefits.

(3) Government level. First, efforts should be made to enhance the establishment of ESG information disclosure systems for listed companies, with a view to developing a set of widely applicable systems that align with China's national circumstances. Second, we should continue to strengthen the scale and intensity of government research and development subsidies, and provide necessary financial support for enterprises in urgent need of green innovation and transformation and upgrading.

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Research on Corporate Green Innovation from the Perspective of Red Culture

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Abstract. Corporate green innovation plays a crucial role in the strategic transformation and upgrading of firms. However, existing research on its relationship with informal institutions, especially red culture, is notably scarce. This study presents an empirical analysis based on a sample of A-share listed companies in China from 2012 to 2022. We find that red culture significantly enhances corporate green innovation performance, and this positive effect primarily manifests in substantive green innovation rather than strategic green innovation. We explore the influencing factors of corporate green innovation from a unique perspective of red culture, and the findings provide valuable insights for both government policy formulation and corporate strategic planning aimed at promoting green innovation.

Keywords. Red culture, green innovation, substantive green innovation, strategic green innovation

1. Introduction

Corporate green innovation serves as a key benchmark for assessing a firm's sustainable development performance. However, firms face significant challenges in implementing such innovation, and only a limited number have successfully adopted it in practice [1]. Identifying the factors that drive corporate green innovation is thus crucial for facilitating industrial transformation and upgrading. Prior research has examined the roles of government policies [2-3], corporate governance structures [4-6], and top executive characteristics [7-9], among other determinants of green innovation. Given the economic and public-interest attributes of corporate green innovation, examining firms' green innovation behaviors requires consideration of both formal and informal institutions, particularly in emerging markets like China where informal institutions play a prominent governance role. Therefore, when investigating the green transformation of Chinese firms, scholars must also consider the cultural influences on green innovation. This study offers unique theoretical and practical insights, focusing on the impact of red culture on corporate green innovation, with Chinese characteristics.

Unlike Confucian culture and nationalism, red culture represents a cultural spirit of breaking through external constraints and collectivism, which was cultivated during China's arduous revolutionary struggles. This cultural spirit encourages executives and

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employees to prioritize green development, continually innovate, and break free from limitations, thus accelerating the company's green innovation. Despite its profound societal significance, scholarly attention to red culture's impact on corporate innovation decisions remains scarce. Existing studies predominantly focus on its tourism-related economic value [10-11], with minimal exploration of its effects on business conduct or its deeper ideological connotations. Consequently, investigating how red culture shapes corporate green innovation and its role in firms' adoption of substantive versus strategic green innovation carries important theoretical and managerial implications.

This study empirically examines how red culture influences corporate green innovation using green patent data from the CNRDS database and manually collected red tourism site data, based on a panel of China's A-share listed firms from 2012 to 2022. The findings reveal that red culture significantly enhances corporate green innovation performance. Notably, this positive effect manifests specifically in substantive green innovation rather than strategic green innovation. These conclusions enrich the literature on red culture's impact on corporate innovation decisions, provide valuable insights for government policymaking, and offer practical implications for Chinese enterprises seeking to enhance their green innovation capabilities.

2. Hypotheses development

Drawing on institutional theory, this study posits that both formal institutions (e.g., laws) and informal institutions (e.g., culture, customs) shape corporate decision-making. As a distinctive Chinese cultural framework within informal institutions, red culture exerts positive influences on corporate green innovation through two primary mechanisms. First, the collectivist ethos embedded in red culture emphasizes aligning individual and organizational interests with broader societal welfare [12]. At the organizational level, this value orientation motivates firms to assume greater social responsibilities, including green development. Consequently, while pursuing economic benefits, firms demonstrate stronger commitments to sustainability through increased green investments and enhanced green innovation outputs. At the individual level, collectivism shapes both managerial decisions and employee behaviors. Within collectivism-oriented environments, employees exhibit greater willingness to contribute to collective goals and participate in green innovation initiatives. This cultivated social responsibility awareness helps employees recognize their work's significance beyond corporate profits, ultimately boosting work motivation and organizational loyalty. Second, the revolutionary spirit inherent in red culture advocates breaking conventions and pursuing innovative development [13], which aligns perfectly with green innovation principles. Under red culture's influence, firms demonstrate stronger innovation consciousness and practical spirit in exploring green technologies. Therefore, we propose the following H1:

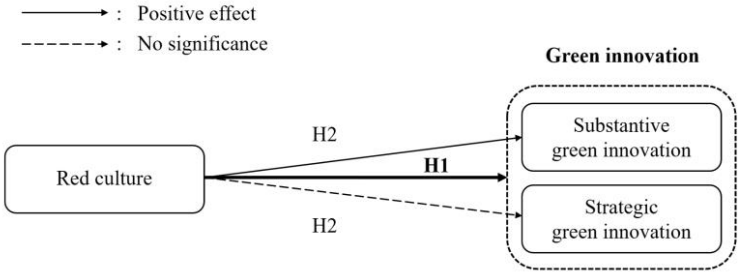
H1: Red culture has a positive influence on corporate green innovation.

Furthermore, the "seeking truth from facts" principle in red culture systematically shapes firms' strategic preferences in green innovation by instilling a results-oriented mindset. This pragmatic philosophy creates three distinct mechanisms that favor substantive green innovation over strategic approaches. First, it cultivates an evidence-based decision-making process where firms rigorously evaluate the actual environmental impact of innovations, naturally filtering out superficial modifications that fail to deliver measurable ecological improvements. Second, this principle embeds a cost-benefit analysis framework that prioritizes innovations with clear technological advantages and

commercialization potential, characteristics inherent to substantive green innovations like patented technologies. Third, it fosters a long-term orientation that views environmental challenges as fundamental issues requiring genuine solutions rather than temporary obstacles needing symbolic responses. Consequently, firms influenced by this tend to develop green capabilities through substantial R&D investments and core technology development, as these approaches better fulfill the principle's requirements for verifiable outcomes. This explains why such firms exhibit stronger preferences for substantive green innovations that offer both environmental integrity and competitive advantages through authentic technological progress. Overall, we propose the H2:

H2: Red culture has a positive influence on substantive green innovation in enterprises, rather than strategic green innovation

Therefore, the framework of the study in this paper is presented below.



Note: *This study divides green innovation into substantial green innovation (invention patents) and strategic green innovation (utility model patents). Of course, at the data level, it also includes green design patents.*

Figure 1 Research framework

3. Empirical design

3.1 Empirical design and data sources

This study selects China's Shanghai and Shenzhen A-share listed firms from 2012 to 2022 as the initial research sample. We exclude financial firms, observations with negative debt ratios, and samples with missing data for key variables. After these screening procedures, our final sample comprises 33,412 firm-year observations across 4,836 listed enterprises. Finally, to mitigate the influence of outliers, we winsorize all continuous variables at the 1st and 99th percentiles.

The data for this study come from the following sources: (1) Manually collect red culture data from the National List of Classic Red Tourism Scenic Spots; (2) corporate green innovation, including substantive green innovation and strategic green innovation, originates from the Chinese Research Data Services; (3) other firm-level financial data are obtained from the China Stock Market & Accounting Research database.

3.2 Variable Definition

Green Innovation. We measure corporate green innovation as the natural logarithm of the number of green patents applied by a firm plus one. Substantive green innovation is proxied by the number of invention patents, while strategic green innovation is measured by the number of utility model patents applied by the firm [14]. To mitigate potential

endogeneity concerns, all dependent variables are lagged by one period.

Red Culture. Following prior research [15], we adopt a distance-based approach to measure red culture exposure. The specific steps for measuring the variable of red culture are as follows: (1) Manually organize the specific names and addresses from the "National Red Tourism Scenic Area Directory" released by the National Development and Reform Commission; (2) Use Google Maps to collect the longitude and latitude coordinates of each red tourism site and listed company; (3) Calculate the geographic distance from the listed company to the red tourism site using the following distance formula. Specifically, we calculate the number of red tourism classic scenic spots within 20 km radii around a firm's headquarters. A higher count of such sites within these ranges indicates stronger exposure to red culture for the listed firm.

Control Variables. We include additional control variables to enhance robustness. A detailed description of these variables is provided in Table 1.

Table 1 Variable Measurement

Type	Variables	Symbol	Measurement
Dependent variables	Green innovation	Lngi	The number of total green patent applications plus 1 followed by logarithm
	Substantive green innovation	Sub_lngi	The number of green invention patent applications plus 1 followed by logarithm
	Strategic green innovation	Str_lngi	The number of green utility model patent applications plus 1 followed by logarithm
Independent variable	Red culture	Red20	The number of Red Tourism Classic Sites within a 20-kilometer radius of the company's registration location.
Controls	Firm size	*Size*	Natural logarithm of total assets
	Firm age	*Age*	Natural logarithm of current year minus the firm's year of establishment plus 1
	Return on assets	*Roa*	Net profit / total assets
	Leverage	*Lv*	Total liabilities / total assets
	Tobin Q	TQ	Market value/total assets
	State-Owned Enterprise	SOE	1 if the company is state-owned, 0 otherwise
	Dual	Dceo	1 if the chairman and CEO are the same, 0 otherwise

3.3 Model specification

This study employs the following model specification:

$$Lngi_{i,t+1} = \alpha + \beta_1 Red20_{i,t} + Controls_{i,t} + \sum Year + \sum Industry + \varepsilon_{i,t} \quad (1)$$

$$Sub_lngi_{i,t+1} = \alpha + \beta_1 Red20_{i,t} + Controls_{i,t} + \sum Year + \sum Industry + \varepsilon_{i,t} \quad (2)$$

$$Str_lngi_{i,t+1} = \alpha + \beta_1 Red20_{i,t} + Controls_{i,t} + \sum Year + \sum Industry + \varepsilon_{i,t} \quad (3)$$

In the model(1)-(3), $Lngi_{i,t+1}$, $Sub_lngi_{i,t+1}$ and $Str_lngi_{i,t+1}$ represent the dependent variables, measuring corporate green innovation, substantive and strategic green innovation, respectively; *Red* denotes the key explanatory variable capturing red culture; *Controls* refers to the vector of control variables; The model incorporates year and industry fixed effects (using 1-digit industry codes for non-manufacturing sectors and 3-digit codes for manufacturing sectors);ε signifies the stochastic error term.

4. Results

4.1 Descriptive Statistics

Table 2 presents the descriptive statistics of key variables. The corporate green innovation (Lngi) shows a mean value of 0.449 with a standard deviation of 0.865, ranging from 0 to 3.932, indicating substantial variation in corporate green innovation levels. Similarly, both substantive green innovation (Sub_lngi) and strategic green innovation (Str_lngi) exhibit considerable heterogeneity among firms. For red culture exposure, the mean value of Red20 is 2.094, suggesting that on average, sample firms are influenced by more than two red tourism sites within a 20km radius.

Table 2 Descriptive Statistics

VarName	Obs	Mean	SD	Min	Max	P25	Median	P75
Lngi	33412	0.449	0.865	0.000	3.932	0.000	0.000	0.693
Sub_lngi	33412	0.317	0.710	0.000	3.555	0.000	0.000	0.000
Str_lngi	33412	0.253	0.604	0.000	2.944	0.000	0.000	0.000
Red20	33412	2.094	3.459	0.000	13.000	0.000	0.000	2.000
Size	33412	22.201	1.300	19.881	26.273	21.265	22.004	22.935
Age	33412	2.932	0.321	1.946	3.555	2.708	2.996	3.178
Roa	33412	0.038	0.063	-0.258	0.198	0.014	0.039	0.069
Lv	33412	0.410	0.204	0.053	0.894	0.244	0.399	0.559
Tq	33412	2.035	1.321	0.845	8.670	1.243	1.607	2.298
SOE	33412	0.326	0.469	0.000	1.000	0.000	0.000	1.000
Dceo	33412	0.299	0.458	0.000	1.000	0.000	0.000	1.000

4.2 Baseline regression results

Table 3 presents the baseline regression results. Columns (1)-(3) report the outcomes for corporate green innovation, substantive green innovation, and strategic green innovation as dependent variables, respectively. All coefficient estimates show positive values. The significantly positive coefficient in Column 1 (significant at the 1% level) indicates that, the increase of 1 unit in red culture will lead to an increase of 0.008 units in green innovation which supports Hypothesis 1. Column 2 also demonstrates a positive coefficient significant at the 1% level, suggesting that red culture enhances substantive green innovation. However, while the coefficient in Column 3 remains positive, it lacks statistical significance, indicating that red culture has no significant effect on strategic green innovation, which validates Hypothesis 2.

Table 3 Baseline regression results

	(1)	(2)	(3)
	Lngi	Sub_lngi	Str_lngi
Red20	0.008***	0.009***	0.001
	(6.15)	(8.55)	(1.40)
Constant	-3.506***	-3.200***	-2.013***
	(-33.16)	(-36.34)	(-26.72)
Controls	YES	YES	YES
Industry	YES	YES	YES
Year	YES	YES	YES
Adjusted_R^2	0.211	0.188	0.177
N	33412	33412	33412

*p < 0.1, **p < 0.05, ***p < 0.01

4.3 Robustness checks

4.3.1 Instrumental variable analysis

To address endogeneity concerns, this study optimizes the methods used in previous research [16] by employing the number of national patriotism education bases (NPEB) in a firm's registered city as an instrumental variable. This selection satisfies two critical conditions: First, these designated bases effectively organize mass patriotism education activities that cultivate national spirit, inspire patriotic fervor, and promote red culture through collective mobilization. Second, the quantity of such bases in a city primarily reflects the local abundance of red cultural resources and regional implementation of patriotic education policies, rather than being directly influenced by corporate green innovation decisions. This ensures the exogeneity of our instrumental variable. The empirical results are presented in Table 4. Column (1) of Table 4 reports the first-stage regression results, demonstrating that the instrumental variable (NPEB) exhibits a statistically significant positive correlation with red culture (significant at the 1% level), with the first-stage F-statistic exceeding the threshold of 10. Columns (2)-(4) present the second-stage regression outcomes, confirming that red culture maintains its positive effect on both corporate green innovation and substantive green innovation, while showing no significant impact on strategic green innovation.

Table 4 Instrumental variable analysis

	(1) Red20	(2) Lngi	(3) Sub_lngi	(4) Str_lngi
Red20		0.004**	0.008***	-0.002
		(2.17)	(4.98)	(-1.29)
NPEB	0.190***			
	(167.19)			
Constant	-2.413***	-3.788***	-3.377***	-2.181***
	(-7.24)	(-34.66)	(-37.11)	(-28.01)
Controls	YES	YES	YES	YES
Industry	YES	YES	YES	YES
Year	YES	YES	YES	YES
Adjusted_R^2	0.538	0.212	0.190	0.179
N	33412	33412	33412	33412

*p < 0.1, **p < 0.05, ***p < 0.01

4.3.2 Alternative measure of key variables

The aforementioned findings may stem from the subjective selection of the distance model. To address this, this study re-measures red culture using the number of red tourist sites within 10-kilometer and 30-kilometer radii of listed firms' registered addresses (Red10, Red30). As Table 5 shows, the initial conclusions remain robust.

Furthermore, Green innovation is characterized by a notably high iteration cycle, as firms often undergo prolonged research and development phases to refine sustainable technologies. Given the extended nature of corporate green innovation cycles, this study incorporates a two-period lag for the dependent variable in the model. The robustness test is confirmed in Table 6, where the key findings remain statistically significant.

Table 5 Alternative measure of independent variable

	(1) Lngi	(2) Sub_lngi	(3) Str_lngi	(4) Lngi	(5) Sub_lngi	(6) Str_lngi
Red10	0.005**	0.008***	0.001			
	(2.36)	(4.04)	(0.74)			
Red30				0.006***	0.008***	0.001
				(5.75)	(8.57)	(0.85)
Constant	-3.528***	-3.221***	-2.016***	-3.514***	-3.207***	-2.016***

	(-33.33)	(-36.52)	(-26.73)	(-33.25)	(-36.44)	(-26.77)
Controls	YES	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Adjusted_R^2	0.210	0.187	0.177	0.211	0.188	0.177
N	33412	33412	33412	33412	33412	33412

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 6 Two-period lag of the dependent variable

	(1)	(2)	(3)
	Lngi	Sub_lngi	Str_lngi
Red20	0.007***	0.009***	0.001
	(5.04)	(7.33)	(0.88)
Constant	-3.673***	-3.379***	-2.069***
	(-31.46)	(-34.66)	(-24.89)
Controls	YES	YES	YES
Industry	YES	YES	YES
Year	YES	YES	YES
Adjusted_R^2	0.213	0.191	0.179
N	28688	28688	28688

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

5. Conclusion

This study systematically examines the impact of red culture on corporate green innovation using comprehensive data from Chinese A-share listed firms (2012-2022). The results demonstrate that red culture significantly promotes both overall green innovation and substantive green innovation, while showing no significant effect on strategic green innovation, confirming our hypotheses.

The study highlights the differential impact on innovation and provides empirical evidence for culture-based policy interventions. These findings have important implications for policymakers who aim to harness cultural factors as part of their efforts to promote authentic, impactful green innovation. The study suggests that policies should be tailored to recognize the unique contributions of cultural values like red culture in driving green innovation. Policymakers can leverage the cultural factors by fostering environments that align with local traditions, culture and ethical beliefs. By integrating cultural elements into sustainability strategies, governments can create more effective, context-specific interventions that enhance the potential for genuine, long-term green innovation. Future research should explore the mechanisms through executive ideology and corporate governance, as well as examine cross-country comparisons of political culture's role in sustainability transitions.

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The Impact of Abnormal Audit Fees and Accounting Information Transparency on Auditor Tone Manipulation in Key Audit Matters

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Abstract. Following the implementation of the CSA1504 Guideline by the Ministry of Finance on January 1, 2018, which mandates the disclosure of Key Audit Matters (hereinafter referred to as KAMs) by A-share listed companies in China, KAMs have enhanced the informational content of audit reports and granted auditors greater discretion in their drafting. Using a sample of public companies that disclosed KAMs from 2016 to 2021, this study employed Python software to calculate the tone of KAMs and applied Ordinary Least Squares (OLS) regression analysis to examine the impact of non-audit services on KAM tone, to investigate whether auditors manipulate the tone of KAMs for self-interested reasons. Our findings reveal that non-audit services amplify auditors' self-interest motives, prompting them to increase the proportion of positive wording in KAMs, thereby creating an overall optimistic tone, which is termed "auditor tone manipulation." Additionally, we find that excessively high abnormal audit fees and low accounting information transparency exacerbate this effect by strengthening alignment of interests between auditors and clients. This research provides novel insights into the textual tone of audit disclosures and offers valuable implications for the development and refinement of audit reporting liberalization policies, resulting in making contribution to audit reporting.

Keywords. "Auditor tone manipulation"; Abnormal audit fees; Accounting information transparency; Key audit matters

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1.Introduction

In December 2016, the Ministry of Finance issued the CSA1504 Guideline, mandating A-share listed companies in China to disclose Key Audit Matters (KAMs) from January 1, 2018. The emergence of KAM has transformed the way Chinese auditors write audit reports, increased auditors' discretion and the informational content of audit report, which is important. This development raises the possibility of "auditor tone manipulation", in other words, auditors may manipulate tone of KAMs (hereinafter referred to as Kam_tone) out of "self-interest motives". However, current studies have predominantly focused on the economic consequences of Kam_tone, such as leading to stock price crashes [1-4], few studies focused on its manipulation. As a result, this gap presents a significant research opportunity to explore the factors and mechanisms driving auditor tone manipulation.

Based on this gap, this study focuses on the manipulation of Kam_tone out of auditors' "self-interest motives", making contributions of as follows: Firstly, our research emphasizes the influencing factors and mechanisms of auditor tone manipulation rather than focusing on the economic consequences of Kam_tone, thereby enriching and expanding the research on tone of auditors. Secondly, this study provides valuable insights for the formulation and refinement of audit reporting "liberalization" policies by certifying that CSA1504 Guideline can increase the scope for auditors to freely write audit reports, resulting in tone manipulation. Thirdly, this study also finds that increased abnormal audit fees, higher levels of marketization, and reduced accounting information transparency will all exacerbate "auditor tone manipulation", thereby highlighting implications for audit practice and market regulation.

2.Literature Review, Theoretical Analysis and Hypothesis Development

2.1 Formation of "Auditor Tone Manipulation"

Existing research mainly focuses on tone of annual reports. Scholars define the tone of annual reports as the sentiment expressed by management within the Management's Discussion and Analysis (hereinafter referred to as MD&A) section, which has been shown to carry significant informational value [5-6]. Among which, MD&A is the section where management discloses their views on the future operating conditions of the company, existing studies indicate that the positive tone of MD&A may stem from management's self-interest motives to conceal negative information, such as misleading investors before stock sales [6] and embellishing firm performance [7-8]. These findings all suggest that management often embellishes the tone of annual reports driven by "self-interest motives" within the constraints of market regulations, which is referred to as "tone manipulation" of annual reports.

In December 2016, the Ministry of Finance officially issued the "Notice on the Issuance of the Auditing Standards of the Chinese Certified Public Accountants No. 1504 - Communicating Key Audit Matters in the Audit Report and Other 12 Standards", which is the so-called CSA1504 Guideline. This directive mandated that, starting from January 1, 2018, all domestic A-share listed companies must disclose key audit matters (KAMs) in their audit reports. According to the CSA1504 Guideline, key audit matters are defined as those matters that auditors, based on their professional judgment, deem to be the most significant for the current period's financial statement audit. The specific policy details

are outlined below.

Certified Public Accountants (CPAs) should identify key audit matters based on their professional judgment and communication with those charged with governance. In this process, CPAs should consider the following:

1.High-Risk Areas: Areas with a higher assessed risk of material misstatement, as outlined in the "Auditing Standards of the Chinese Certified Public Accountants No. 1211 - Identification and Assessment of the Risks of Material Misstatement."

2.Significant Judgments: Significant audit judgments related to significant management judgments in the financial statements, including those involving high estimation uncertainty.

3.Impact of Significant Transactions/Events: The impact of significant transactions or events of the current period on the audit.

The CSA1504 Standard mandates that auditors communicate KAMs with those charged with management and governance, which may inadvertently strengthen the alignment of interests between the two and lead to collusion. Existing research indicates that auditors, driven by self-interest to maintain long-term client relationships, may negotiate with clients to issue audit opinions that align with client preferences, a practice commonly referred to as "opinion shopping" [9-10]. Prior to the implementation of the CSA1504 Guideline, audit reports, were constrained to a fixed format, auditor-client collusion primarily manifests as "opinion shopping". However, with the recent strengthening of market regulatory systems, the illegal cost and litigation risk associated with "opinion shopping" have increased, deterring auditors from colluding with clients to manipulate audit reports out of self-interest.

After 2017, with the introduction of the CSA1504 Guideline, studies have revealed that auditors' intentional withholding of information can result in KAMs displaying features such as content similarity or insufficient informational value [11]. Furthermore, a more positive tone in KAMs has been shown to improve corporate investment efficiency [3-4]. These may indicate CSA1504 Guideline offer auditors the discretion to include matters they deem important in the audit report through communication with management and governance, allowing for more flexibility in report writing, which potentially providing auditors with the opportunity to manipulate the audit report, albeit within the bounds of regulatory compliance. Consequently, motivated by self-interest, auditors may incorporate information favorable to clients in the KAMs to sustain long-term client relationships and thereby increase revenue. Compared to the structured information in the textual content of KAMs, non-structured information such as tone is more subjective and harder to regulate than quantitative data, which makes Kam_tone manipulation a subtle yet effective means for auditors to achieve self-interest goals including relationship maintenance and revenue enhancement, rather than altering the explicit textual content.

Given that the provision of non-audit services can amplify auditors' self-interest, assisting them in maintaining long-term client relationships, generating knowledge premiums, and increasing the overall revenue of the firm [10-12], we select non-audit services as the starting point for examining "tone manipulation" and propose hypothesis H_1.

In summary, this study argues that when providing non-audit services, auditors may engage in "tone manipulation" out of "self-interest motives" by embellishing *Kam_tone* to make it more positive, namely, making "auditor tone manipulation", Based on this, the hypothesis H_1 is proposed.

H_1: Providing non-audit services will lead to "auditor tone manipulation," resulting in a more favorable tone in Key Audit Matters (KAMs).

2.2 Auditor's Perspective: The Impact of Abnormal Audit Fees on "Auditor Tone Manipulation"

From the auditor's perspective, this study firstly examines the impact of abnormal audit fees (hereinafter referred to as Ablnfee) on "tone manipulation". Existing research suggests that collusion between the client and the auditor will increase the auditor's workload and the risk of litigation, which inevitably leads to higher audit fees [12]. When audit fees exceed normal levels, Ablnfee arise. Subsequently, excessive Ablnfee will increase auditors' tolerance on earnings manipulation, reduce their auditor independence [9-10]. While strengthened market regulations have curtailed the practice of clients purchasing favorable audit opinions through high audit fees, clients may still compensate auditors through no independence, and promote auditor-client collusion as well as purchasing favorable audit opinions [13].

Prior research indicates that excessive audit fees can undermine n-audit services such as tax and consulting. This compensation can increase auditors' professional pressures and enhance their self-interest motivation. Consequently, auditors may "fine-tune" their reports within legal limits to meet client expectations, particularly by subtly adjusting less overt aspects like KAMs' tone. This practice allows auditors to secure higher fees and maintain long-term client relationships, ultimately leading to "auditor tone manipulation."

We hypothesize that higher abnormal audit fees paid through non-audit services intensify auditors' self-interest motivation, increasing their propensity for tone manipulation. Specifically, we propose:

H_2: There is a positive relationship between Abnormal Audit Fees (Ablnfee) and "auditor tone manipulation", such that higher Ablnfee is associated with a more Kam_tone.

2.3 Corporate Perspective: The Impact of Accounting Information Transparency on "Auditor Tone Manipulation"

From a corporate perspective, this study examines how Accounting Information Transparency (hereinafter referred to as Ta) affects "auditor tone manipulation." Prior studies have employed real earnings management (hereinafter referred to as REM) and earnings smoothing (hereinafter referred to as ES) to measure accounting information transparency (Section 3.3). In the existing research, higher transparency reduces information asymmetry between regulators and firms, enhancing regulatory scrutiny and increasing auditors' exposure to violation risks. This heightened risk compels auditors to be more diligent and makes collusion with clients more challenging [4].

Conversely, lower transparency exacerbates information asymmetry, weakening regulatory oversight. This has two implications: First, it diminishes the precision of key audit matter disclosures [14]. Second, it suggests inadequate corporate governance [15], which lowers auditors' litigation risk and violation costs. This makes auditors more daring and provides auditors with more room for maneuver, as a result, auditors are more likely to collude with clients and acquiesce to demands for "tone manipulation."

Based on this analysis, H_3 is proposed.

H_3:There is an inverse relationship between accounting information transparency (Ta) a nd auditor tone manipulation, such that lower Ta is associated with more pronounced a uditor tone manipulation.

3.Methods

3.1 Sample Data Sources

In this study, the research sample was selected to be A-share listed firms[3] that disclosed KAMs and allowed the calculation of Kam_tone from 2016 to 2021. Financial companies were excluded to prevent misinterpretation due to their distinct fin ancial statement disclosures, resulting in the removal of 220 observations. In addition, ST/*ST[4] companies were also excluded after removing 316 observations with missing data. The final sample consists of 18,393 firm-year observations and serves as the basis for this study.

3.2 Variable Definitions

Non-audit services and "auditor tone manipulation" are the primary variables in this study. Non-audit services are the main independent variable, and "auditor tone manipulation" measured by Kam_tone is the dependent variable. Non-audit services are measured as the ratio of the fees for non-audit services to the total fees for the audit (*Ratio*). "Auditor tone manipulation" is defined by *Kam_tone*. Following Cai Yandong et al. (2022) [2], this study uses Python to integrate the Chinese Financial Sentiment Dictionary (CFSD) [5]and apply the "Jieba" module for Chinese text segmentation to conduct word frequency analysis. The number of positive words and the number of negative words in KAMs are then counted. *Kam_tone* is calculated by calculating (Number of Positive Words - Number of Negative Words) / (Number of Positive Words + Number of Negative Words), where higher values indicate a more positive tone and higher degree of "auditor tone manipulation". Later, this study constructs an empirical model for verifying hypothesis by taking Firm Size *(Size),* Leverage Ratio (*Lev*), Asset Growth Rate (*Growth*), Loss Dummy (*Loss*), etc. as control variables.

3.3 Model Design

Model (1) is used to verify the hypothesis H_1, as shown in Model (1), The key focus here is on the coefficient α_1: a significantly positive α_1 suggests a higher proportion of non-audit services, a greater share of positive words in KAMs, and a more positive *Kam_tone*, thereby supporting Hypothesis 1 (H_1). Conversely, a significantly negative α_1 indicates

[3] An A-share listed company refers to a company that is registered in China and listed for trading on the Shanghai Stock Exchange or the Shenzhen Stock Exchange within China.

[4] ST (Special Treatment) and *ST (Delisting Risk Warning) are labels assigned by stock exchanges to alert investors to potential risks associated with listed companies facing financial distress or other irregularities. ST indicates significant concerns requiring special attention, while *ST signifies a heightened risk of delisting.

5 The Chinese Financial Sentiment Dictionary (CFSD) is a specialized lexicon tailored for sentiment analysis in financial contexts. Its use is justified by its domain-specific focus, which enhances the precision of sentiment detection in financial texts and mitigates the shortc omings of general dictionaries in capturing nuanced financial sentiments.

a higher proportion of non-audit services, fewer positive words in KAMs, and a more negative *Kam_tone*.Besides, an insignificant α_1 implies that providing non-audit services has no effect on Kam_tone. The latter two scenarios do not provide support for the hypothesis.

$$Kam_tone_{i,t}=\alpha_0+\alpha_1*Ratio_{i,t}+\alpha_2*Size_{i,t}+\alpha_3*Lev_{i,t}+\alpha_4*Growth_{i,t}+\alpha_5*Loss_{i,t}+\alpha_6*CFO_{i,t+}\alpha_7*First_{i,t}+\alpha_8*Mshare_{i,t+}\alpha_9*Indep_{i,t+}\alpha_{10}*Segment_{i,t+}\alpha_{11}*Big4dum_{i,t+}+\Sigma Yeardum+\Sigma Indudum+\varepsilon \quad (1)$$

To test the hypothesis H_2, Following Simunic (1984), normal audit fees are estimated controlling for *Size, Lev, Growth,* etc. Abnormal audit fees (*AbLnfee*) are the residual between logged actual fees and predicted normal fees.The interaction term of *Ablnfee* with the proportion of non-audit services is introduced into Model (1) to construct Model (2).

$$Kam_tone_{i,t}=\beta_0+\beta_1*Ratio_{i,t}+\beta_2*Ablnfee_{i,t}+\beta_3*Ablnfee_{i,t}*Ratio_{i,t}+\beta_4*Size_{i,t}+\beta_5*Lev_{i,t}+\beta_6*Growth_{i,t}+\beta_7*Loss_{i,t}+\beta_8*CFO_{i,t+}\beta_9*First_{i,t}+\beta_{10}*Mshare_{i,t+}\beta_{11}*Indep_{i,t+}\beta_{12}*Segment_{i,t+}\beta_{13}*Big4dum_{i,t}+\Sigma Yeardum+\Sigma Indudum+\varepsilon \quad (2)$$

Model (2) is used to verify the hypothesis H_2, In Model (2), the emphasis is on the coefficient β_3: a significantly positive β_3 suggests that, when non-audit services are provided, higher Ablnfeeare associated with a greater proportion of positive words in KAMs and a more positive tone, thus supporting Hypothesis 2 (H_2). Conversely, a significantly negative $\beta_3$indicates that, under the condition of providing non-audit services, higher Ablnfee are linked to a lower proportion of positive words in KAMs and a more negative tone. An insignificant β_3 implies that Ablnfee has no effect on Kam_tone. The latter two scenarios do not provide support for the hypothesis.

To verify the hypothesis H_3, this study calculates the degree of *REM* and *ES* based on existing research to measure *Ta*. Initially, this study estimated industry-specific normal levels of operating cash flow, expenses, and production costs on an annual basis. Abnormal values are then computed by deducting the firm's actual figures from these estimated norms. Real Earnings Management (*REM)* is quantified as the absolute difference between abnormal production costs and the aggregate of abnormal operating cash flow and abnormal expenses. Earnings Smoothness (*ES*) is measured as the ratio of the standard deviation of net operating cash flow to total assets over a three-year period to that of net income to total assets over the same timeframe. Elevated *REM* and *ES* values are indicative of reduced accounting information transparency (*Ta*). Subsequently, Ta is integrated into Model (1) as an interaction term to construct Model (3).

$$Kam_tone_{i,t}=\gamma_0+\gamma_1*Ratio_{i,t}+\gamma_2*Ta_{i,t}+\gamma_3*Ta_{i,t}*Ratio_{i,t}+\gamma_4*Size_{i,t}+\gamma_5*Lev_{i,t}+\gamma_6*Growth_{i,t}+\gamma_7*Loss_{i,t}+\gamma_8*CFO_{i,t+}\gamma_9*First_{i,t}+\gamma_{10}*Mshare_{i,t+}\gamma_{11}*Indep_{i,t+}\gamma_{12}*Segment_{i,t+}\gamma_{13}*Big4dum_{i,t+}+\Sigma Yeardum+\Sigma Indudum+\varepsilon \quad (3)$$

In Model (3), the focal point is the coefficient γ_3: a significantly positive γ_3 suggests that, within the context of providing non-audit services, lower accounting information transparency (*Ta*) is associated with a higher proportion of positive words in KAMs and a more favorable tone, thereby supporting Hypothesis 3 (H_3). Conversely, a significantly negative γ_3 indicates that, under the condition of providing non-audit services, higher Ta correlates with a lower proportion of positive words in KAMs and a more negative tone. An insignificant γ_3 implies that Ta has no effect on Kam_tone. The latter two scenarios do not provide support for the hypothesis.

4.Results & Discussion

4.1 Descriptive Statistical Analysis

Table 1. Descriptive Statistical Analysis

Variable	Obs	Mean	Std.Dev.	Min	Max
Kam_tone	18,393	0.486	0.260	-0.806	1
Ratio	18,393	0.111	0.133	0	0.337
Ablnfee	17,845	0.013	0.437	-2.293	7.270
REM	15,161	0.154	0.192	0.001	6.796
ES	15,161	4.091	9.180	0.015	306.2
Size	18,393	22.32	1.362	19.73	26.44
LEV	18,393	0.415	0.203	0.059	0.934
Growth	18,393	0.182	0.343	-0.360	2.050
Loss	18,393	0.116	0.320	0	1
CFO	18,393	0.049	0.068	-0.180	0.248
First	18,393	0.332	0.147	0.024	0.900
Mshare	18,393	0.159	0.330	0	20.17
Indep	18,393	0.378	0.056	0.143	0.800
Segment	18,393	19.23	34.87	0	780
Big4dum	18,393	0.067	0.251	0	1

Initially, a descriptive statistical analysis of the variables that are included in the Model (1) is conducted. All of the variables have been winsorized at the level of 1%. The results are shown in Table 2: (1) The mean value of *Ratio* is 0.111, indicating that, on average, non-audit service fees account for 11.1% of total audit fees in the sample. The minimum value is 0, and the maximum value is 0.337, suggesting that the highest proportion of non-audit service fees are relative to audit fees in the sample in 33.7%. (2) The minimum value of *Kam_tone* is -1, and the maximum value is 1, with a mean value of 0.486. This shows that the number of positive and negative words in KAMs is roughly balanced, and the overall tone is neutral. (3) The mean value of *Ablnfee* is 0.013, indicating that the average audit fees in the sample are slightly higher than normal audit fees. (4) The mean values of *REM* and *ES* are positive, suggesting that the *Ta* in the sample is relatively low.

4.2 Regression Analysis

Table 2 presents the regression analysis of "auditor tone manipulation." As shown in the "*Tone Manipulation*" column of Table 2, the proportion of *Ratio* is significantly positively correlated with *Kam_tone* at the level of 1%, and the coefficient is 0.030. This signifies a significant positive correlation between *Ratio* and *Kam_tone* at the 1% level, further suggesting that an increase in the proportion of fee of non-audit services is associated with a more pronounced tone in KAMs, implying that non-audit services may significantly increase the self-interest motives of auditors, leading to "tone manipulation", thereby validating the hypothesis H_1.

In the "*Ablnfee*" column of Table 2 the interaction term between *Ratio* and *Ablnfee* is significantly positively correlated with *Kam_tone* at the level of 5%, the coefficient is 0.047. This suggests that the interaction term *Ablnfee*Ratio* and the dependent variable *Kam_tone* are significantly positively correlated at the 5% level, further suggesting that when non-audit services are provided, higher Ablnfee may significantly increase the proportion of positive words in KAMs, thus leading to a more positive tone. Consequently, the hypothesis H_2 is validated.

Table 2. Regression Analysis of "Auditor Tone Manipulation"

	Tone Manipulation	***Ablnfee***	***REM***	***ES***
	Kam_tone	*Kam_tone*	*Kam_tone*	*Kam_tone*
Ratio	0.030**	0.032**	0.003	0.081***
	(2.01)	(2.10)	(0.16)	(2.75)
Ablnfee		-0.045***		
		(-8.00)		
*Ablnfee*Ratio*		0.047**		
		(2.00)		
REM			-0.008	
			(-0.59)	
*REM*Ratio*			0.142*	
			(1.65)	
ES				0.002
				(0.12)
*ES*Ratio*				0.357***
				(3.59)
Control Variable Industry and Year	Controlled Controlled	Controlled Controlled	Controlled Controlled	Controlled Controlled
cons	0.626***	0.509***	0.569***	0.512***
	(14.33)	(35.24)	(11.42)	(24.91)
VIF	1.14	1.15	1.14	1.12
N	17815[6]	17280	14692	14692
Adj.R^2	0.045	0.032	0.038	0.025

Notes: ***, **, and * denote significance at the levels of 1%, 5%, and 10% respectively. T-values are reported in brackets.

In the "*REM*" and "*ES*" columns of Table 2, the interaction term between *Ratio* and *REM* is significantly positively correlated with *Kam_tone* at the level of 10%, the coefficient is 0.142 and 0.357. Similarly, the interaction term between the proportion of *Ratio* and *ES* is significantly positively correlated with *Kam_tone* at the level of 1%. This indicates that when non-audit services are provided, higher levels of earnings management and *ES* will reduce the opacity of accounting information, which are associated with a more positive tone in KAMs, further reflecting "auditor tone manipulation." Hence, the hypothesis H_3 is validated.

To further substantiate the analysis, we conducted a multicollinearity test for each r esearch group, revealing a Variance Inflation Factor (VIF) coefficient of approximately 1.15, indicateing that multicollinearity is not a concern in the model.

4.3 Robustness Tests

To further validate the robustness of the research findings, this study conducted several additional tests, including Propensity Score Matching (PSM), controls for autocorrelation and heteroskedasticity, and alternative variable specifications. The main results remained consistent across all these robustness checks.

[6] Due to the control of industry and year effects in regression, some samples are missing, resulting in a total number smaller than the descriptive analysis sample.

5.Conclusion

Using a sample of A-share listed companies from 2016 to 2021, this study analyzes "auditor tone manipulation". According to the research, non-audit services will reinforce auditors' "self-interest motives", leading to align interests with clients and carry out auditor "tone manipulation". In other words, they increase the proportion of positive words when writing KAMs, so that *Kam_tone* will be whitewashed to make it positive. At the same time, excessive normal audit fees and low transparency of accounting information will also strengthen the auditor's motivation to conspire with the client, thus strengthening the "auditor tone manipulation".

This study recognizes limitations in relying on sentiment dictionaries for tone mea surement, which may not fully capture the complexities of auditor tone. The focus on C hinese firms which are listed on A-share market may restrict the generalizability of finding. Additionally, the limited temporal scope may not reflect long term trends influenced by economic cycles and policy changes. Future research could enhance understanding by conducting cross-country comparisons, exploring stakeholder perceptions of auditor tone, and examining its relationship with audit quality.

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A Study on the Coupling Relationship of the Integrated Development of Agricultural Product Wholesale Markets and E-Commerce: The Case of Beijing

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Abstract. Under the dual drive of the digital economy and the rural revitalization strategy, the digital transformation of the agricultural industry chain has become the core task of China's agricultural modernization. This study takes Beijing as an example to explore the coupling relationship between the integrated development of agricultural product wholesale markets and e-commerce. By using the projection pursuit method and an improved coupling coordination model, the development levels of Beijing's agricultural product wholesale markets and e-commerce from 2016 to 2022 were quantified, and the integration process and its influencing factors were analyzed. The study found a 1-unit increase in the development level of e-commerce leads to a significant 0.487-unit increase in the coupling coordination degree. In contrast, the development level of the agricultural product wholesale market has a negative impact on the coupling coordination degree, and its offline path dependence and interest solidification may inhibit the integration process. In addition, the integration process shows fragility and external sensitivity, and is greatly affected by external shocks (such as trade frictions, epidemics) and internal resistance of the agricultural product wholesale market.

Keywords. Agricultural product wholesale market; e-commerce; coupling coordination; projection pursuit method; digital transformation

1. Introduction

Under the dual drive of the digital economy and the rural revitalization strategy, the digital transformation of the agricultural industry chain has become the core task of China's agricultural modernization. In 2024, the Ministry of Agriculture and Rural Affairs of the People's Republic of China released the "National Smart Agriculture Action Plan (2024—2028)", which clearly proposed the need to promote the digital transformation of the entire agricultural industry chain and encouraged the construction of a collaborative ecosystem centered on "chain leader" enterprises. As a key link connecting production and consumption, the digital transformation of agricultural product wholesale markets is not only a policy requirement but also an inevitable choice to break through traditional circulation bottlenecks.

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Currently, China's agricultural product circulation system still faces multiple challenges. On the one hand, traditional agricultural product wholesale markets rely on offline transactions, which are characterized by information asymmetry, redundant intermediate links, and low supply-demand matching efficiency. On the other hand, consumers' demands for product traceability, immediacy, and diversity are continuously upgrading, forcing the innovation of circulation models. Against this backdrop, e-commerce has reconstructed the supply chain through digital technology, shortened the circulation chain through "disintermediation," and precisely matched supply and demand through "data-driven" approaches, providing a path for the transformation and upgrading of agricultural product wholesale markets. The integration of the two can not only alleviate the efficiency dilemma of agricultural product wholesale markets but also expand the supply chain resources of e-commerce, forming a new ecosystem of "online + offline" collaborative development.

As a megacity and policy pilot area, Beijing's agricultural product supply and demand contradictions are particularly prominent. Its agricultural product wholesale markets have both public welfare attributes and market-oriented characteristics, and they undertake core functions in ensuring urban supply. However, high operating costs, low information levels, and intense channel competition make it urgent for Beijing to enhance its competitiveness through the integration of e-commerce. This study focuses on the case of Beijing to reveal the integration mechanism of agricultural product wholesale markets and e-commerce through a quantitative model, providing a reference for the digital transformation of the national agricultural industry chain.

2. Coupling And Coordination Mechanism Analysis

The coupling relationship between agricultural product wholesale markets and e-commerce in the field of agricultural product circulation is not only reflected in their interdependent foundation but more importantly, there is a significant mutual promotion mechanism between them. They can bring positive feedback to each other through their respective development, integrating China's agricultural production, characterized mainly by "small-scale farming," into the "large market, large circulation" pattern of agricultural products. This integration improves the efficiency of the agricultural product supply chain rather than replacing the agricultural product wholesale markets as the hub of agricultural product distribution[1]. It also affects their functions and directions in price mechanisms, information transmission, and transaction settlement[2], ensuring that agricultural product wholesale markets will still have development space in China for the next 20-30 years[3].

(1) Complementary Business Synergy. Agricultural product wholesale markets, as traditional distribution centers, possess rich commodity resources, stable supplier systems, and mature logistics and distribution networks. These advantages provide a solid offline support for e-commerce platforms, enabling them to quickly access a large volume of high-quality agricultural products, enrich their product categories, and meet consumers' diverse needs, as well as the needs of emerging network platforms for merchants with market operation experience and capabilities[4]. Meanwhile, the development of e-commerce also brings new sales channels and customer groups to agricultural product wholesale markets. Through online platform promotion and sales, the trading scope of agricultural product wholesale markets can break through geographical restrictions and achieve broader market coverage. This helps to solve the

problem of saturation in Beijing's agricultural product wholesale markets[5], which have basically formed a spatial pattern characterized by "large-scale, comprehensive markets as the core, professional and origin markets as features, and small-scale regional markets as supplements"[6], injecting new vitality into the development of agricultural product wholesale markets.

(2) Information Sharing for Optimized Decision-Making. Agricultural product wholesale markets have accumulated a vast amount of transaction data, price information, and credit records of suppliers and purchasers. By integrating and sharing this information with e-commerce platforms, it can provide important decision-making basis for the operation of e-commerce platforms, helping them optimize product recommendation algorithms, formulate reasonable marketing strategies, and strengthen risk control. In return, e-commerce platforms, with their advanced information technology and big data analysis capabilities, can provide more precise market demand forecasts and consumer preference analyses to agricultural product wholesale markets. This guides the wholesale markets to adjust their product structures and optimize inventory management, enhancing market response speed and resource allocation efficiency. It promotes the effective connection between the supply and demand of fresh agricultural products, meeting upgraded demands[7], and simultaneously addresses the issue of traditional agricultural product wholesale markets, which, as typical traditional enterprises, lack effective channels for connecting with users and have failed to establish direct communication with users[8].

(3) Technological Innovation and Upgrading. The integration of agricultural product wholesale markets and e-commerce prompts both parties to increase their investment in technology and service innovation. To better adapt to the needs of e-commerce development, agricultural product wholesale markets actively introduce intelligent warehousing management systems, cold chain logistics technology, and quality traceability systems, enhancing their operational efficiency and service quality. Through the formation of a "large supply, large market, small distribution" circulation pattern, the traditional circulation system has been decomposed and restructured[9]. The application of these technologies not only improves the circulation conditions of agricultural products and reduces the loss rate but also enhances the supply chain management level of e-commerce platforms, providing consumers with higher quality and safer agricultural products. Meanwhile, technological innovations and optimizations in user experience, interface design, and payment settlement by e-commerce platforms also offer references and insights for agricultural product wholesale markets. The development of e-commerce can promote the transparency and standardization of the agricultural product supply chain[10], helping to solve the problems of traditional agricultural product wholesale markets that mainly rely on over-the-counter transactions, information asymmetry[11], unstable service quality, excessive middle links in the transaction process[12], and limited channels and options for consumers to understand products[13]. This integration further promotes innovation and upgrading in transaction methods and service models, enhancing the market competitiveness and attractiveness of agricultural product wholesale markets. However, an analysis from the perspective of competitive relationships reveals that an increase in online retail sales of agricultural products can hinder the improvement of operational efficiency in agricultural product wholesale markets by inhibiting their technological progress[14].

(4) Market Expansion and Brand Building. The coupling and coordination of agricultural product wholesale markets and e-commerce provide both parties with broader market space and brand promotion channels. Agricultural product wholesale

markets can leverage the network advantages and marketing resources of e-commerce platforms to promote local specialty agricultural products to the national and even global markets, meeting the demand of consumers who prefer geographically specific products[15]. This enhances the fame and market influence of agricultural products. Meanwhile, e-commerce platforms can better explore local specialty agricultural product resources through cooperation with wholesale markets, creating regionally distinctive agricultural product brands and enriching their platform's brand matrix to attract more consumer attention and purchases. In terms of brand building, both parties can jointly conduct brand promotion activities and integrate resources. Through internet and social media e-commerce platforms, agricultural products can reach consumers more widely, increasing sales volume and brand fame[16]. This enhances the overall image and value of agricultural product brands and addresses the current issue where most agricultural products entering wholesale markets are undifferentiated in terms of branding and quality standards, except for a few branded and packaged products[17].

In summary, there is a close mutual promotion relationship between agricultural product wholesale markets and e-commerce. The development of one can bring positive feedback to the other, forming a virtuous cycle. This mutually reinforcing coupling and coordination relationship not only helps to improve the operational efficiency and market competitiveness of both parties but also promotes the transformation and upgrading of the entire agricultural product circulation industry.

3. Research Methods And Indicator Construction

3.1 Research Methods

3.1.1 Projection pursuit method

The projection pursuit method is a non-parametric multivariate data analysis technique that projects high-dimensional data onto a low-dimensional space while preserving key information and revealing underlying structures and patterns. This method is suitable for both linear and non-linear data analysis and is particularly effective for handling complex, high-dimensional datasets. Its core idea is to optimize the projection direction so that the distribution of the data in that direction exhibits "interesting" characteristics (such as non-normality or sharp peaks), thereby achieving dimensionality reduction and extracting key features.

In the context of evaluating the development levels of agricultural product wholesale markets and the e-commerce industry, traditional linear dimensionality reduction methods (such as principal component analysis and entropy weight method) may fail to capture the non-linear characteristics of complex data, potentially leading to information loss. Therefore, the projection pursuit model emerges as a more effective alternative.

The simulated annealing algorithm is a global optimization algorithm that avoids getting trapped in local optima by simulating the annealing process of materials. It is well-suited for solving complex optimization problems with multiple peaks and local extrema. In this study, the simulated annealing algorithm is employed to solve the projection pursuit model, optimizing the projection index function to ensure the acquisition of the optimal projection direction, thereby enhancing the accuracy and reliability of the dimensionality reduction results.

To fully explore and reflect the data characteristics, an optimal projection vector is obtained by observing indicator data from multiple perspectives. Let $a = (a_1, a_2, \ldots, a_n)$ be an n-dimensional unit vector, representing the projection direction vector of n indicators. Then, the linear projection of the i-th sample in a one-dimensional space is:

$$Z_i = \sum_{i=1}^{n} x_{ij} a_j$$

Let the projection value of the data be Z_i, based on projection pursuit, the overall distribution characteristics of information and the local distribution characteristics of projection points are obtained by constructing a projection index function[cite: 54]. Generally, the overall distribution of information should be as dispersed as possible, while the local distribution of projection points should be as dense as possible. Finally, their maximum product is represented by the projection index function:

$$maxG(a) = Sa \cdot Ba$$

The local density of the projection value Zi is Ba, and the standard deviation of the projection value Zi is Ba. Therefore, Ba and Sa can be expressed as:

$$Ba = \sum_{i=1}^{n} \sum_{j=1}^{m} (R_{ij} - r_{ij}) u(R_{ij} - r_{ij})$$

$$Sa = \sqrt{\sum_{i=1}^{n} (Z_i - \bar{Z})/(n-1)}$$

In the above equation, u is the unit step function, which equals 1 when the value is greater than 0 and 0 when the value is less than 0. R is the window size for calculating local density, and the radius must include as many projection points as possible; otherwise, the sliding average deviation will be too large. The distance formula for r_{ij} is: $r_{ij} = Z_i - Z_j$.

3.1.2 Coupling and Coordination Model

The coupling degree is an indicator that measures the interdependence and interaction between multiple systems or factors. This concept originally emerged in physics and is typically used to measure the mutual influence of two or more systems.

The coupling coordination degree (CCD) further assesses the coordination between the various parts of a system based on the coupling degree. It measures the collaborative work efficiency of multiple subsystems. A higher value indicates that the various parts of the system are well-coordinated and the overall operation is more efficient. The coupling coordination degree not only considers the strength of coupling but also focuses on the overall benefits of the system, reflecting the coordination level and sustainable development capability of the system.

In the traditional coupling coordination degree distribution table, the coupling coordination degree is divided into grades with intervals of 10% (Table 1).

Table 1. Traditional Coupling Coordination Degree Distribution Table

Grade	Percentage Range	Stage	Stage Division
1	[0,10)		Extreme
2	[10,20)		Severe
3	[20,30)	Dysfunction	Moderate
4	[30,40)		Low
5	[40,50)		Weak
6	[50,60)		Weak
7	[60,70)		Low
8	[70,80)	Coordination	Moderate
9	[80,90)		High
10	[90,100]		Extreme

According to the research by Fan Dong jun, Ke Ling, and Cao Run min, the traditional coupling coordination degree model has three main issues: the unclear meaning of the coupling coordination degree, the unreasonable calculation of the coupling degree boundary values, and the low discriminative power of the coupling degree in the traditional model. The article elaborates on these issues and provides an improved model for calculating the coupling degree in social sciences. In this study, the following improved model is used for the binary coupling degree calculation.

$$C = 1 - \sqrt{(U_1 - U_2)^2} \quad (1)$$

This model separates the coordination degree from the coupling degree and enhances the discriminative power of the coupling degree by characterizing the deviation, thereby addressing the three issues of the traditional model.

Moreover, the traditional grading method has two problems. First, the coupling coordination degree is not uniformly distributed, and this grading method increases the probability of falling into the middle grade. Second, in social sciences, the more subsystems there are, the harder it is to couple, and the bias of using uniform grading becomes larger. Therefore, Fan proposed a new grading method, which is used in this study for the improved binary coupling coordination degree distribution table (Table 2).

Table 2. Improved Coupling Coordination Degree Distribution Table

Grade	Percentage Range	Stage	Stage Division
1	[0,0.341)		Extreme
2	[0.341,0.389)		Severe
3	[0.389,0.435)	Dysfunction	Moderate
4	[0.435,0.483)		Low
5	[0.483,0.533)		Weak
6	[0.533,0.587)		Weak
7	[0.587,0.646)		Low
8	[0.646,0.714)	Coordination	Moderate
9	[0.714,0.801)		High
10	[0.801,1]		Extreme

This study uses the coupling coordination degree to measure the degree of integrated development between agricultural product wholesale markets and e-commerce in Beijing. In this model, U_1 and U_2 represent the comprehensive development levels of Beijing's agricultural product wholesale markets and Beijing's e-commerce industry, respectively.

3.2 Indicator System Construction

3.2.1 Development Indicator System for Agricultural Product Wholesale Markets

Drawing on existing research, this study measures the development level of agricultural product wholesale markets through the following indicators. Sales efficiency per unit

and capital preservation rate per unit are used to measure operational performance. High operational efficiency can more effectively meet market demands, and its improvement signifies an enhancement in the market's ability to utilize resources, which is a key indicator of development level. Return on assets, marketing return on investment, and cost return rate are used to measure profitability. Profitability is the core competitiveness of a business and the foundation upon which it relies for survival. A high return on assets indicates that the market can maximize returns through optimized resource allocation. As a typical labor-intensive industry, agricultural product wholesale markets face increasing pressure from rising labor and logistics costs. An improvement in this indicator suggests that the market has achieved cost reduction and efficiency enhancement through process optimization or technological substitution. Industrial segmentation degree indicates the level of refinement in the development of agricultural product wholesale markets. The higher the degree of segmentation, the more choices available to different consumer groups, signifying more in-depth development of the agricultural product wholesale market.

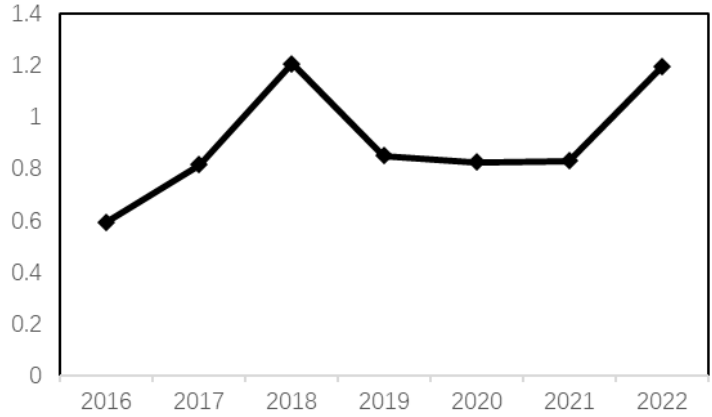
After organizing and processing the data, positive and negative indicators are respectively standardized using the range difference method to eliminate dimensional differences. Subsequently, the simulated annealing algorithm is used to solve the projection pursuit problem, yielding the optimal projection direction for each indicator on a one-dimensional scale, as shown in Table 3.

Table 3. Development Indicator System for Agricultural Product Wholesale Markets in Beijing

Indicator Name	Indicator Description	Optimal Projection Direction
Sales Efficiency per Unit	Sales per enterprise / Number of enterprises	0.0008
Capital Preservation Rate per Unit	Owner's equity / Number of enterprises	0.5074
Return on Assets	Net profit / Total assets	0.1962
Marketing Return on Investment	Operating income / Sales expenses	0.0094
Cost Return Rate	Sales / Operating costs	0.839
Industrial Segmentation Degree	Number of enterprises / (Number of comprehensive markets + Number of professional markets)	0.0119

The results indicate that the cost return rate and capital preservation rate per unit contribute the most to the comprehensive development level. Using the optimal projection direction, the scores for each year are obtained by multiplying with the normalized data of each indicator over the years. The results are as follows (Figure 1).

Figure 1. Scores of Beijing's Agricultural Product Wholesale Markets.



From the figure 1, it can be observed that Beijing's agricultural product wholesale markets developed steadily from 2016 to 2018. In 2019, the market began to decline, and in 2020 and 2021, due to the restrictive policies implemented in response to the COVID-19 pandemic, the development of the agricultural product wholesale markets stagnated. In 2022, with the normalization of pandemic control, the market returned to the level of 2018.

Using the same indicators, the scores for national agricultural product wholesale markets from 2016 to 2022 were calculated, as shown in Figure 2.

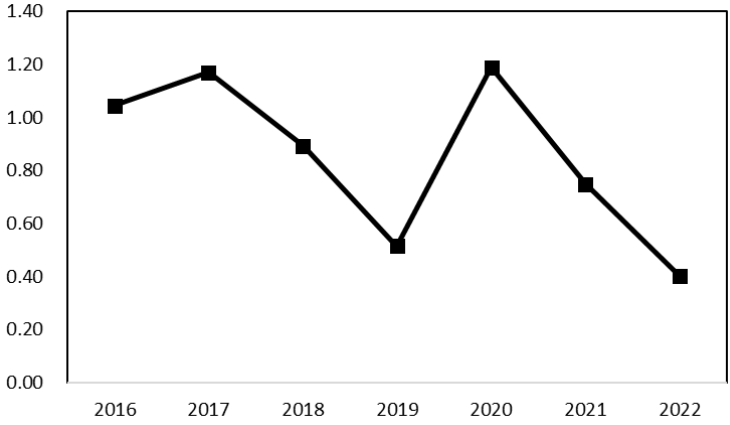


Figure 2. Scores of Agricultural Product Wholesale Markets Nationwide

Compared with the national scores, the development of Beijing's agricultural product wholesale markets exhibits significant uniqueness. First, overall, the average score for Beijing's agricultural product wholesale markets is 0.90, while the national average is 0.85. Second, in terms of trend, the development level of national agricultural product wholesale markets has shown a long-term downward trend, whereas Beijing's agricultural product wholesale markets show no clear trend. Finally, except for 2020, Beijing's agricultural product wholesale market development level has been higher than the national level since 2018.

3.2.2 E-commerce Development Indicator System

The mobile phone penetration rate and the reserve of information technology talent are used to represent the business foundation of e-commerce. These two indicators serve as the foundation for e-commerce operations. The mobile phone penetration rate, as the carrier of digital economy infrastructure, directly determines the user base and market penetration potential of e-commerce. The reserve of information technology talent indicates the development potential of the e-commerce industry and is the core driving force for technological innovation in e-commerce. Sales efficiency, management efficiency, return on assets, and profit per employee are used to represent the basic operational status of e-commerce. Sales efficiency measures the marketing capabilities of e-commerce platforms, revealing the traffic conversion ability and effectiveness of marketing strategies. Management efficiency measures the effectiveness of e-commerce operations. As a negative indicator, management efficiency reflects the internal governance level of the enterprise, and inefficient administrative processes can squeeze research and development investment. Return on assets measures the ability of e-commerce to convert investments into returns. E-commerce platforms can achieve economies of scale by using data assets to replace physical assets, and a high return on assets indicates that their business model has a stronger capital leverage effect. Profit per employee measures the profitability of e-commerce.

The data used in this study are sourced from the Beijing Municipal Bureau of Statistics and other relevant statistical publications. After organizing and processing the data, positive and negative indicators are respectively standardized using the range difference method to eliminate dimensional differences. Subsequently, the simulated annealing algorithm is used to solve the projection pursuit problem, yielding the optimal projection direction for each indicator on a one-dimensional scale, as shown in Table 4.

Table 4. Development Indicator System for E-commerce in Beijing

Indicator Name	Indicator Description	Optimal Projection Direction
Mobile Phone Penetration Rate	Mobile phone penetration rate	0.6058
Information Technology Talent Reserve	Information employment personnel / Total employed population	0.0392
Sales Efficiency	Operating income / Sales expenses	0.0045
Management Efficiency	Management expenses / Operating income	0.1303
Return on Assets	Profit / Total assets	0.7834
Profit per Employee	Total profit / Number of employees	0.027

The results show that return on assets and mobile phone penetration rate play a dominant role, indicating that capital operation efficiency and infrastructure level are the main drivers of current e-commerce development. It is worth noting that the weights of information technology talent reserve and profit per employee are relatively low, suggesting that the e-commerce industry in Beijing still has a structural imbalance of "emphasizing hardware over software."

Using the optimal projection direction, the normalized historical data of each indicator was multiplied to obtain the annual scores of Beijing's e-commerce development level from 2016 to 2022 (rounded to two decimal places), as shown in Figure 3 below.

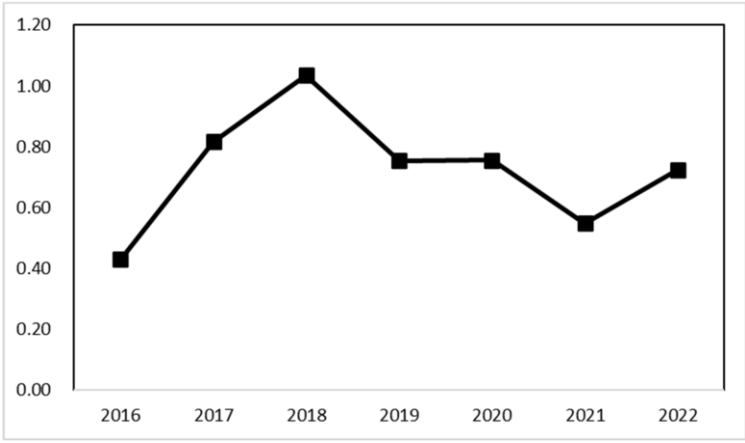


Figure 3. Scores of Beijing's E-commerce

The results indicate that the development of e-commerce in Beijing showed a rapid growth trend from 2016 to 2018. In 2019, it declined due to external shocks such as trade frictions, and then continued to remain at a low level due to the impact of the pandemic, without recovering to the level of 2017.

4 Empirical Analysis

The data used in this study are sourced from the National Bureau of Statistics, Beijing Municipal Bureau of Statistics, the "Main Data Bulletin of the Fourth National Economic Census in Beijing," the "Beijing Statistical Yearbook 2023," the "Third National Agricultural Census," and the "Fourth National Economic Census," covering the period from 2016 to 2022.

4.1 Measurement of the Coupling Coordination Degree between Agricultural Product Wholesale Markets and E-commerce in Beijing

In this section, the development scores of Beijing's agricultural product wholesale markets and e-commerce, calculated in the previous sections, are used as two subsystems. The coupling coordination degree is calculated to determine the level of integrated development between the two. Before calculation, the optimal projection directions are normalized to ensure that the scores are distributed within the [0,1] range, facilitating measurement. The final results of the coupling coordination degree are as follows (Table 5).

Table 5. Coupling Coordination Degree between Agricultural Product Wholesale Markets and E-commerce in Beijing

Year	Coupling Coordination Degree
2016	0.5333
2017	0.7164
2018	0.7873
2019	0.6855
2020	0.6876
2021	0.5902
2022	0.6411
Mean	0.6630

Based on the results, the coupling coordination degree between Beijing's agricultural product wholesale markets and e-commerce is as follows (Table 6).

Table 6. Coupling Coordination Degree between Agricultural Product Wholesale Markets and E-commerce in Beijing

Grade	Percentage Range	Stage	Stage Division
1	[0,10)		Extreme
2	[10,20)		Severe
3	[20,30)	Dysfunction	Moderate
4	[30,40)		Low
5	[40,50)		Weak
6	[50,60)		Weak
7	[60,70)		Low
8	[70,80)	Coordination	Moderate
9	[80,90)		High
10	[90,100]		Extreme

From table 6, it can be seen that the coupling development relationship between Beijing's agricultural product wholesale markets and e-commerce first increased and then decreased. From 2016 to 2018, the coupling coordination degree rose from 0.5333 to 0.7873, improving from weak coordination to high coordination. However, from 2019 to 2022, it fluctuated downward, eventually reaching a low coordination level of 0.6411 in 2022.

As shown in Figure 4, the trend of the coupling coordination degree is similar to that of the e-commerce development level, indicating that the development of the e-commerce industry has a significant impact on the coupling coordination degree, acting as a key driver for the integrated development of the two.

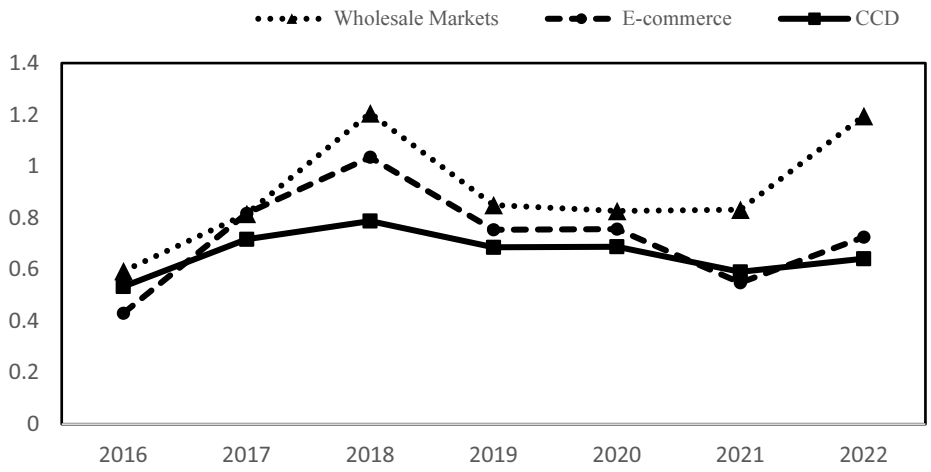


Figure 4. Agricultural Product Wholesale Markets, E-commerce, and Coupling Coordination Degree Scores

4.2 Grey Relational Analysis of Coupling Coordination Degree

Due to the small data volume, this study uses the grey relational analysis method to analyze small sample data. As it does not involve parameter estimation and hypothesis testing, this method avoids the pitfalls of regression analysis with small samples. This

method assesses the closeness of the association by comparing the similarity in the geometric shapes of data series. If the fluctuation trends (i.e., the shapes of the curves) of two series are more similar, their correlation is considered higher.

The coupling coordination degree is used as the reference series, and the development scores of agricultural product wholesale markets and e-commerce are used as the comparison series.

Table 7. Grey Relational Degree Calculation Table

YEAR	MAR	ECOM	CCD
2016	0.593143	0.429869	0.533295
2017	0.815225	0.816887	0.71638
2018	1.205477	1.034475	0.787319
2019	0.8494	0.753351	0.685467
2020	0.826337	0.756098	0.687615
2021	0.830987	0.547847	0.590182
2022	1.194889	0.724675	0.641075

After standardizing the initial values in the table to obtain dimensionless data, the difference sequence values are calculated. The maximum polar difference is 0.05107755, and the minimum polar difference is 0.001102073. Setting the resolution to 0.5, the grey relational coefficient and grey relational degree tables are obtained.

Table 8. Grey Relational Degree Coefficients and Grey Relational Degree

YEAR	coef_MAR	coef_ECOM
2016	0.572665	0.479674
2017	0.524399	0.818992
2018	0.569444	0.442398
2019	0.687847	1
2020	0.621787	0.997021
2021	0.889189	0.598738
2022	0.347718	0.872284
r	0.601864	0.744158

The grey relational degree between e-commerce and the coupling coordination degree is 0.744, while that between agricultural product wholesale markets and the coupling coordination degree is 0.602. Based on the comprehensive analysis of these calculation results, it can be concluded that the development of e-commerce has the closest relationship with the integrated and coordinated development of the two, followed by agricultural product wholesale markets.

4.3 Research Conclusions and Discussion

Based on the projection pursuit method and the improved coupling coordination model, this study measured the integration process and its influencing factors of agricultural product wholesale markets and e-commerce in Beijing from 2016 to 2022, and the following conclusions were drawn:

(1) The dominant role of e-commerce development in the integration process. The coupling development relationship between e-commerce and agricultural product

wholesale markets is primarily influenced by the development of e-commerce, and secondarily by the development of agricultural product wholesale markets.

(2) The fragility and external sensitivity of the integration process. From 2016 to 2018, the coupling coordination degree rose from a weak coordination level of 0.5333 to a high coordination level of 0.7873, driven by the rapid expansion of e-commerce. However, after 2019, due to external shocks such as trade frictions and the pandemic, as well as internal resistance from agricultural product wholesale markets, the coordination level fell back to a low coordination level of 0.6411 in 2022, reflecting the fragility of the integration development.

This study quantifies the dynamic relationship between agricultural product wholesale markets and e-commerce integration in Beijing, with findings that both engage in dialogue with existing research and offer new insights.

This study reveals that the development of e-commerce plays a dominant role in the integration process, a conclusion that deepens the general understanding from previous research. Most literature posits that e-commerce can provide a transformative pathway for traditional wholesale markets through "disintermediation" and "data-driven" approaches, addressing issues such as information asymmetry and redundant links. The grey relational analysis in this study (e-commerce correlation 0.744, agricultural wholesale market correlation 0.602) clearly quantifies this dominant role from a data perspective, confirming that e-commerce serves as a crucial engine for initiating and deepening integration.

The study also reveals the "fragility and external sensitivity" of the integration process. Data show that after 2019, external shocks such as trade frictions and the COVID-19 pandemic led to a significant decline in coordination levels. This indicates that the current "online + offline" collaborative ecosystem is still unstable, and its development highly depends on the certainty of the macro environment. Previous research has often focused on the models and benefits of integration, with less attention paid to its development resilience. Through data fluctuation analysis, this study visually demonstrates this fragility, reminding policymakers to establish risk buffering mechanisms when promoting integration.

5 Policy Recommendations for Enhancing the Integration

Based on the research findings, the following policy recommendations are proposed to enhance the integration of agricultural product wholesale markets and e-commerce:

(1) Strengthen the Investment in Digital Infrastructure of Agricultural Product Wholesale Markets. The government should increase its support for the construction of digital infrastructure in agricultural product wholesale markets by establishing special funds to provide financial security for their digital transformation and upgrading. Specifically, support can be given to build intelligent warehousing systems in agricultural product wholesale markets, using Internet of Things technology to achieve precise monitoring and management of inventory, improve warehousing efficiency, and reduce losses. Additionally, traceability systems can be constructed using blockchain technology to ensure that every link of agricultural products from the origin to the consumer is traceable, enhancing consumer confidence in the quality and safety of agricultural products. Finally, data platforms can be established to integrate various data resources within the market, providing data support for market operation decisions and promoting the integration of online and offline transactions.

(2) Formulate Standards for Agricultural Product Grading and Packaging. Standardizing the grading basis and packaging requirements of agricultural products can provide a unified interface for e-commerce connections. This will not only help improve the standardization of agricultural products and reduce e-commerce procurement costs but also enhance the display effect and sales competitiveness of agricultural products on e-commerce platforms, thereby lowering the technical barriers for integration and promoting the deep integration of agricultural product wholesale markets and e-commerce.

(3) Implement Digital Transformation in Layers. Different scales and types of agricultural product wholesale markets should adopt a layered approach to digital transformation. For core markets, such as the large agricultural product wholesale markets like XinFaDi, the government should take the lead in constructing "Smart Agricultural Wholesale Complexes." These complexes should integrate blockchain traceability, intelligent sorting, and cloud warehouse management systems to achieve full-process traceability, rapid sorting, and efficient storage of agricultural products. At the same time, first-tier wholesalers should be required to connect to a unified data center to break down information silos and achieve real-time sharing and interaction of transaction data, thereby improving the overall operational efficiency and management level of the market. For medium and small markets, policies such as tax incentives can be used to encourage their transformation into regional service nodes for e-commerce. For example, policies like exempting value-added tax for the first three years can be implemented to reduce their transformation costs and stimulate their motivation for transformation. These medium and small markets can undertake supporting functions such as origin pre-processing and customized distribution, forming a complementary advantage with e-commerce platforms and jointly building a new ecosystem for agricultural product circulation. By implementing a layered approach to digital transformation, the path dependence of agricultural product wholesale markets can be broken, and their synergistic development with e-commerce platforms can be promoted.

(4) Establish an Interest Sharing Mechanism to Break Down Path Dependence. To break down the path dependence between agricultural product wholesale markets and e-commerce platforms, an interest sharing mechanism should be established. Agricultural product wholesale markets and e-commerce platforms are encouraged to form joint operation entities through equity cooperation or profit-sharing, balancing the interests of offline and online operations. Specifically, the two parties can jointly establish an operation company, sharing profits and bearing risks according to their equity proportions, achieving interest sharing and risk co-sharing. At the same time, market entities that actively carry out digital transformation should be given tax reductions or rent subsidies to stimulate their transformation motivation and promote the deep integration of agricultural product wholesale markets and e-commerce platforms. Additionally, the government should strengthen the guidance and supervision of the interest sharing mechanism to ensure the fairness and rationality of interest distribution, prevent improper competition and monopolistic behaviors, maintain market order, protect the legal rights and interests of all parties, and promote the long-term and stable cooperation between agricultural product wholesale markets and e-commerce platforms.

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Digital Leadership and Sustainability in Manufacturing: The Mediating Role of Green Innovation

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Abstract. In the context of the rapid development of the digital economy and the digital transformation of enterprises, this study empirically analyzes 352 questionnaires from manufacturing companies. The results show that digital leadership positively affects green innovation and sustainability performance. Green innovation mediates between digital leadership and sustainability performance. Digital sustainability orientation strengthens the impact of digital leadership on green innovation. This study provides strong support for promoting the sustainable development of manufacturing companies and realizing low-carbon and environmental protection transformation.

Keywords. Digital Leadership, Sustainable Performance, Green Innovation, Digital Sustainability Orientation

1. Introduction

The Third Plenary Session of the 20th CPC Central Committee proposed to accelerate the process of shaping the new quality productivity forces, to promote the new type of industrialization, to cultivate and grow advanced manufacturing clusters, and to promote the high-end, intelligent, and green development of the manufacturing industry. However, the traditional productivity model is gradually difficult to meet the increasingly stringent needs of modern society for environmental protection and rational use of resources. Manufacturing companies are facing the dual challenge of achieving digital transformation and green innovation.

Leadership traits, as one of the key resources within an organization, play an important role in advancing organizational change and innovation. Digital Leadership emphasizes the critical role of leaders in the digitalization process, who are change-oriented, adaptable, and have a "transformative vision and forward-looking perspective," which is key to working on transformation and driving cultural change in a volatile environment[1][2]. In the digital era, business leaders must actively cultivate Digital Leadership that aligns with contemporary development trends, facilitating technological upgrades while addressing environmental imperatives, thus unlocking the potential of Green Innovation. According to the resource-based view, Green Innovation is a fundamental mechanism for corporate development, enabling the dual achievement of

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environmental protection and economic growth, and ultimately enhancing Sustainability Performance.

The concept of digital sustainability is emerging at the intersection of digitization and sustainability[3]. Manu and Sriram define strategic orientation as an organization's intention to use strategy to adapt and change its environment to effect change[4]. According to the Strategic Orientation Theory, the Digital Sustainability Orientation advocates for organizations to achieve synergy between digital transformation and sustainability, and serves as a behavioral principle that guides their overall business activities. Under the macro framework of sustainability strategy, digital sustainability orientation, as an emerging research direction, emphasizes the synergistic development between digital transformation and sustainability, which has become a core guide for enterprise business development, providing a new perspective for in-depth research on how enterprises can achieve sustainable performance.

Based on this, this study will explore how to utilize digital leadership to enhance the sustainable performance of enterprises in order to promote the transformation and upgrading of China's economic structure and realize the strategic goal of sustainable development. This will not only enrich the theoretical results of digital leadership and enterprise sustainable development performance, but also provide useful references for enterprise managers to improve enterprise sustainable performance.

2. The Theoretical Framework and Research Hypotheses

2.1 Digital Leadership and Sustainability Performance

Digital leadership is different from transformational leadership's focus on organizational change breakthroughs[5]and visionary leadership's focus on vision, consensus and cultural cohesion[6], and it is better suited to the complex challenges of the digital era through the deep integration of digital technology, strategic thinking, and sustainability concepts. As a fusion of leadership theory and digital technology, Digital Leadership represents a novel managerial approach and serves as a key enabler of digital transformation within enterprises[7]. Leaders with strong Digital Leadership are more receptive to innovative ideas and adept at leveraging digital technologies to reduce costs, improve efficiency, and enhance environmental governance. According to upper echelons theory, executives' traits and experiences influence their cognition and behavior, which in turn shape corporate performance[1]. Digitally-oriented leaders tend to be forward-looking and proactive, facilitating the formulation of digital business strategies and improving the efficiency of digital resource utilization, thereby strengthening Sustainability Performance[8]. Based on this reasoning, the following hypothesis is proposed:

H1: Digital Leadership has a positive effect on corporate Sustainability Performance.

2.2 Digital Leadership and Green Innovation

Unlike traditional leadership, digital leadership emphasizes adaptability, comprehension, inclusiveness, and supportiveness[9]. From the resource-based view, digital leaders enable firms to identify and acquire key resources such as digital technologies and data, thereby providing critical support for green innovation. Moreover, digital leadership

fosters the construction of digital communication platforms, breaking down interdepartmental information silos, facilitating knowledge sharing and cross-functional collaboration, and cultivating an organizational environment conducive to green innovation. From a decision-making perspective, digital leadership integrates the core traits of transformational leadership with heightened ethical standards and values, motivating firms to prioritize social responsibility and environmental sustainability. Thus guiding manufacturing companies to shift to a greener direction aligned with societal needs and to exhibit higher green innovation behavior[10]. Strategically, digital leaders possess forward-looking market insights, enabling them to anticipate trends in green technologies, better understand user value propositions, and respond effectively to environmentally driven market shifts, thereby advancing green innovation efforts[11].

H2: Digital Leadership has a significant positive effect on Green Innovation in manufacturing enterprises.

2.3 Green Innovation and Sustainability Performance

Green innovation refers to the innovative activities carried out by enterprises to achieve the dual goals of economic and environmental benefits by focusing on the introduction of new technologies and ideas, and through the development or improvement of product design, process flow, and organizational management[12]. Advanced clean technologies significantly improve the processes, systems, production, and management practices of the industry and mitigate the adverse impacts of the enterprise on the environment[13]. Under the double constraints of resources and environment, the manufacturing industry is facing increasingly severe environmental pressure, and green innovation has become a key path to break the dilemma. Through green innovation, enterprises can not only create a greener production process and improve environmental performance[14], but also meet consumer demand for environmental protection, enhance product differentiation advantages, and then enhance market share and economic benefits. Therefore, green innovation is of great significance to enhance the sustainable performance of the industry. Based on this, the following hypotheses are proposed[15]:

H3: Green Innovation has a significant positive effect on the Sustainability Performance of manufacturing enterprises.

2.4 The Mediating Role of Green Innovation

According to the resource-based view, the sustained competitive advantage of an enterprise stems from its unique and hard-to-replicate resource endowment, and resource-rich enterprises often have “resource positioning barriers” [16]. By creating a culture of innovation and optimizing resource allocation, digital leadership inspires enterprises to deeply integrate digital technology with green concepts and promote the development of green products, processes, and services. At the same time, digital leadership helps to identify green market opportunities, provides insight into consumer environmental needs, and then guides enterprises to carry out targeted green innovation practices, continuously strengthening their green innovation capabilities, forming a virtuous cycle. Green innovation plays a key intermediary role between digital leadership and enterprise sustainable development, serving as a bridge and link connecting function. Based on this, the following hypotheses are proposed:

H4: Green Innovation mediates between Digital Leadership and Sustainability Performance.

2.5 The Moderating Role of Digital Sustainability Orientation

George and other scholars first proposed the concept of digital sustainability, advocating that enterprises synergize digital transformation with sustainable development orientation as a guiding principle for overall business actions[17]. At the strategic level, the concept provides clear value guidelines for enterprises, helping them to formulate forward-looking innovation plans around green development, and at the same time creating an organizational culture and institutional environment that encourages green innovation and strengthens synergistic support. In terms of the external environment, the digital sustainability approach makes it easier for companies to gain government policy support, consumer recognition, and investor support for green innovations driven by digital leadership. In terms of internal driving force, digital sustainability orientation encourages enterprises to deeply integrate digital transformation and sustainability goals, forming a positive feedback mechanism to continuously promote green innovation practices.

H5a: Digital Sustainability Orientation moderates the relationship between Digital Leadership and Green Innovation.

With the continuous development of digital technology, enterprises are faced with the challenge of how to simultaneously achieve sustainable development in the process of digital transformation. Digital sustainability orientation, as a strategic guiding principle for enterprises, can promote the synergy between digitalization and sustainable development goals. The stronger the digital sustainability orientation, the more business executives can focus on the environmental benefits and social values of technology when promoting green innovation, thus strengthening the role of green innovation in promoting sustainable performance. Thus, the following hypothesis is proposed:

H5b: Digital Sustainability Orientation positively moderates the mediating effect of Green Innovation between Digital Leadership and corporate Sustainability Performance.

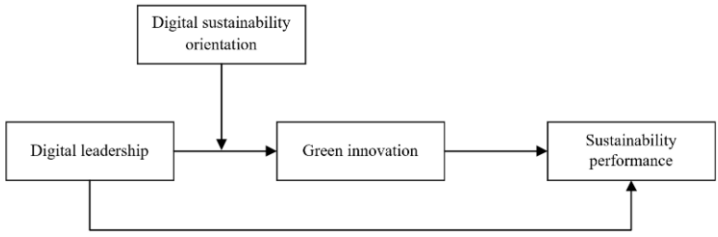


Figure 1. Theoretical model.

3. Data Collection and Analysis

Data for this study were collected through an online survey. The questionnaire was designed using a five-point Likert scale, where "1" indicates "strongly disagree" and "5" indicates "strongly agree." The survey consisted of two parts. The first part gathered respondents' demographic and organizational information, including age, gender, educational background, industry type, firm size, years of tenure, and ownership type of the organization. The second part focused on the measurement of key constructs. Digital leadership, based on the scale developed by Yanping Li et al.[18],using 5 items such as "Company leaders have a strong ability to think strategically and digitally". Green

innovation, based on the scale developed by Chang and Delmas & Toffel[19][20], using 8 items such as "The company often develops new products that can be recycled and reused". Sustainability Performance based on the scale developed by Huang et al.[21], using 6 items such as "The company pays a lot of attention to environmental protection". Digital Sustainability Orientation, based on the scale developed by Wang[22], using 18 items such as 'The company advocates the introduction, learning, and use of digital technology to solve the efficiency problems of enterprises.' A total of 386 questionnaires were distributed, and 352 valid responses were collected, yielding an effective response rate of 91.2%. It has been shown that age, education, and years of working experience are the key factors affecting digital leadership[23].In addition, the size of the firm[24], the nature of the firm, and the industry in which it is located are also related to the sustainability performance of the firm[25]. Therefore, in this study, age, education, firm size, years of experience, nature of the firm, and the industry in which the firm is located are used as control variables. Among the executive respondents, 51.7% were male and 48.3% female. The majority of executives were between the ages of 31 and 40 (38.5%). In terms of ownership structure, private enterprises accounted for the largest proportion (40.63%). Firms with more than 16 years of operational history made up 31.25% of the sample. Industries with the highest representation included machinery manufacturing (21.88%) and furniture manufacturing (26.99%). For reliability and validity testing, SPSS 27.0 was used to assess internal consistency and construct adequacy. All constructs demonstrated high reliability, with Cronbach's α values ranging from 0.879 to 0.965. The Kaiser-Meyer-Olkin (KMO) values ranged from 0.883 to 0.981, indicating suitability for factor analysis. Confirmatory factor analysis (CFA) was conducted using MPLUS 8.3. As shown in Table 1, the four-factor model exhibited superior fit compared to alternative models (χ^2 = 661.754, df = 623, χ^2/df = 1.062, RMSEA = 0.013, SRMR = 0.030, CFI = 0.995, TLI = 0.996), confirming satisfactory discriminant validity among constructs.

Table 1. Validatory factor analysis

Model	χ^2	df	χ^2/df	RMSEA	SRMR	CFI	TLI
Single-factor model	3448.261	629	5.482	0.113	0.128	0.662	0.642
Two-factor model	2107.274	628	3.355	0.082	0.093	0.823	0.812
Three-factor model	1451.264	626	2.318	0.061	0.081	0.901	0.895
Four-factor model	661.754	623	1.062	0.013	0.030	0.995	0.996

To assess potential common method bias and multicollinearity, Harman's one-factor test was conducted. The variance explained by the first unrotated factor was 38.649%, below the 40% threshold, suggesting that common method bias is not a serious concern.

Hierarchical regression analysis was employed to test the hypothesized model. As shown in Table 2, Model 5 reveals that Digital Leadership significantly and positively influences Sustainability Performance (β=0.344, p<0.01), supporting H1. Model 2 confirms a significant positive effect of Digital Leadership on Green Innovation (β= 0.353, p<0.01), supporting H2. Model 6 indicates that Green Innovation significantly contributes to Sustainability Performance (β=0.376, p<0.01), supporting H3. A bootstrap test with 5,000 resamples was conducted to examine mediation. The indirect effect of Digital Leadership on Sustainability Performance via Green Innovation was significant (95% CI [0.0658, 0.1581]), supporting H4. Model 3 introduced the interaction between Digital Leadership and Digital Sustainability Orientation. The interaction term was significant (β=0.244, p<0.01), indicating a positive moderating effect and supporting H5a.

Further moderated mediation analysis showed that under high Digital Sustainability Orientation (M+1SD), the indirect effect of Digital Leadership on Sustainability Performance through Green Innovation was significant (effect = 0.1325, 95% CI [0.084, 0.189]). The difference between high and low levels was also significant (95% CI [0.034, 0.105]), supporting H5b.

In summary, all six hypotheses were supported. The results demonstrate that Digital Leadership positively influences both Green Innovation and Sustainability Performance. Green Innovation serves as a significant mediator, and Digital Sustainability Orientation amplifies both the direct and indirect effects of Digital Leadership.

Table 2. Regression analysis results

	Green innovation			Sustainability performance			
Varibles	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Age	0.054	0.086	0.062	0.029	0.061	0.009	0.036
Academic qualifications	0.012	-0.021	0.001	0.005	-0.027	0.001	-0.021
Enterprise Scale	-0.054	-0.059	-0.029	-0.081	-0.085	-0.061	-0.069
Enterprise years of experience	0.04	0.018	-0.002	0.025	0.004	0.011	-0.001
Nature of enterprise	0.059	0.056	0.038	0.047	0.045	0.025	0.029
Type of enterprise	-0.023	-0.034	-0.029	-0.001	-0.011	0.007	-0.002
Gender	-0.049	-0.058	-0.045	-0.258	-0.267**	-0.241**	-0.251**
Digital leadership		0.353***	0.234***		0.344***		0.244***
Green innovation						0.376***	0.283***
Digital sustainability orientation			0.266***				
Digital sustainability orientation* Digital leadership			0.244***				
R2	0.009	0.142	0.254	0.029	0.162	0.176	0.233
Adjusted R2	-0.011	0.122	0.232	0.011	0.142	0.156	0.213
F	0.441	7.122***	11.585***	1.491	8.266***	9.131***	11.555***

Note: *** denotes statistical significance at the 0.001 level ($p < 0.001$),** denotes statistical significance at the 0.01 level ($p < 0.01$), and * denotes significance at the 0.05 level ($p < 0.05$).

4. Conclusion

4.1 Research Findings

This study explores the mechanism of digital leadership's influence on manufacturing firms' sustainability performance through green innovation and tests the moderating role of digital sustainability orientation. The results of the study show that: First, digital leadership has a positive impact on corporate sustainability performance, which enriches the scope of application of the upper echelon theory from the perspective of digital leadership, and highlights the importance of integrating digital strategy into sustainability planning. Second, although digital leadership is widely regarded as a booster for corporate performance, its mechanism of sustainability through green innovation still lacks systematic research, and this study fills this research gap by validating the mediating role of green innovation. Third, digital sustainability orientation not only strengthens the relationship between digital leadership and green innovation but also enhances its indirect impact on sustainable performance, enriching the research on the moderating role of corporate strategic orientation in the synergistic path of green and digital transformation. Previous studies have rarely examined the specific role of digital leadership in advancing green innovation and sustainable development, and this study broadens the path of previous research on corporate sustainable performance in the context of digitalization, enriches the transmission mechanism between relevant

variables, and provides deeper insights into the embedding of corporate sustainability goals into digital strategies.

In addition, most of the existing studies are based on the Western marketized environment, focusing on the synergistic effect of digital technology and green innovation. China's unique "dual-carbon" goals and policy-led governance model pose localization challenges. Based on the Chinese context, this paper proposes a framework for digital leadership to influence sustainable performance, which not only responds to the strategic requirement of "new quality productivity" but also provides a complementary approach for application in the Chinese context.

4.2 Managerial Implications

This study has important management implications for manufacturing enterprises to enhance sustainable development. First, enterprises should elevate the cultivation of digital leadership to a strategic level, improve digital management capabilities, identify green market opportunities, assess environmental risks, and promote green transformation with the help of digital technology, so as to promote the in-depth integration of digitalization and sustainability goals. Secondly, enterprises should build a dual orientation that takes into account both technological progress and environmental management, strengthen the full implementation of the concept of digital sustainability in their operations, promote the construction of green information systems and ESG disclosure mechanisms, and convey sustainability commitments through digital green reports to enhance brand reputation and long-term competitiveness. At the policy level, regulators should fully recognize the key role of digital leadership in the green transformation of the manufacturing industry and guide enterprises to incorporate sustainable development into their digital strategies by means of tax exemptions, technology subsidies, and green credit. At the same time, executive training programs focusing on green and digital capabilities should be established. Sound policy support and institutional systems will help accelerate the synergistic development of a high-quality, green, and digital manufacturing industry.

4.3 Limitations and Future Directions

This paper has some limitations and shortcomings in the study. First, this paper uses cross-sectional survey data, but the external environment is constantly changing, and the use of more objective secondary data to construct longitudinal panel data can be considered in the future to further validate the research conclusions. Second, the sample data of this paper comes from manufacturing enterprises; the sample coverage and capacity are limited, and the generalizability of the research conclusions in different contexts needs to be further demonstrated. Moreover, this paper only investigates the mediating variables of green innovation, and the mediating variables of digital leadership on sustainability performance still deserve further exploration. In addition, cross-country comparative studies can be considered to explore whether there are differences in the mechanisms of digital leadership and green innovation in the institutional, cultural, and economic environments of different countries, so as to further enhance the external applicability and replication value of the research findings.

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Research on the Impact of Digital Transformation on Financial Sustainable Growth—Based on the Perspective of Green Technological Innovation

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Abstract. Based on the data sample of China's Shanghai and Shenzhen A-share listed companies from 2013 to 2023, this study empirically examines the impact mechanism of enterprise digital transformation on sustainable financial growth. The results show that: firstly, the digital transformation of enterprises has a significant role in promoting sustainable financial growth. Second, digital transformation has significantly driven the improvement of green technology innovation. More importantly, green technology innovation plays a significant role in mediating between digital transformation and sustainable financial growth. This study provides new empirical evidence for an in-depth understanding of the path and effect of enterprise digital transformation to empower sustainable financial growth.

Keywords. Digital transformation; green technology innovation; Financially sustainable growth

1. Introduction

As the core proposition of enterprise survival and development, sustainable financial growth (sgr) not only requires stable short-term profitability, but also emphasizes the long-term development of resource efficiency. Xi Longsheng and Zhao Hui (2022) [1]believe that Green Technology Innovation (GTI) is the core driving force for high-quality development. From the perspective of accounting, whether digital transformation can improve the resource utilization efficiency, environmental performance and long-term financial resilience of enterprises by enabling green technology innovation, and ultimately achieve sustainable financial growth is an important topic that needs to be explored urgently.

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2. Theoretical analysis and research hypotheses

2.1 The impact of enterprise digital transformation on sustainable financial growth

Based on the Resource Base Theory (RBV), digital transformation reconstructs the value creation path by optimizing the unique resources (such as data assets and digital technologies) and dynamic capabilities of enterprises, ultimately driving sustainable financial growth. Wang et al. (2022)[2] believe the digital transformation(dt) can affect the improvement of sales net profit margin and earnings per share. Yang Yin and Chen Feier (2024)[3] believe that digital transformation(dt) can increase the total asset turnover rate to a certain extent. Li et al. (2023) [4]believe that digital transformation will reduce cash dividend distribution. Xu Chaohui and Wang Mansi (2022)[5] believe the digital transformation(dt) reduces transaction costs, improves internal cash flow. Formulate a research hypothesis:

H1: The digital transformation will improve sustainable financial growth.

2.2 Digital transformation of enterprises, Green Technological Innovation and sustainable financial growth

Based on the theory of innovation diffusion, digital transformation accelerates the diffusion of green technology innovation. This process reduces the cost of environmental compliance, and ultimately enhances the ability of financial sustainability. Digital transformation can drive companies to invest in innovation at the technology level. For example, Saqib et al. (2025)[6] believe that enterprises will increase investment in development of digital technologies. If they improve sustainable financial growth, enterprises must build advantages through green technology innovation[7][8]. By combing through the above literature, Formulate a research hypothesis:

H2: digital transformation promotes the innovation of green technology, which in turn achieves financially sustainable growth.

3. Sample selection and research design

3.1 Sample Selection and Data Sources

This paper takes the A-share listed companies in Shanghai and Shenzhen from 2013 to 2023 as the research sample, and the relevant data are mainly from the China National Security Financial Database (CSMAR).

3.2 Variable Definition

3.2.1 Explained variables

The explained variable is financially sustainable growth (sgr). For the measurement of f inancial sustainable growth, drawing on the practices of Wang Jianwen and Zhang Yueji n (2022)[9], and the specific formula is as follows:

$$SGR = \frac{NPMS \times RR \times (1 + ER)}{\left[\frac{1}{TAT} - NPMS \times RR \times (1 + ER)\right]} \quad (1)$$

3.2.2 Explanatory variables

The explanatory variable is the digital transformation(dt), based on the practice of Wu Fei et al. (2021)[10].

3.2.3 Mediator and control variables

The mediating variable is green technology innovation, and the total number of green invention and utility model patents is measured by the logarithm of +1. The control variables include: company size (size), age of companies (age), growth of the company (growth), asset-liability ratio (lev), current ratio (cr), book market value (bm), cash flow ratio (cf), and shareholding ratio of the largest shareholder (top1).

3.3 Model

The following fixed-effect model is constructed:

$$SGR_{it} = \beta_0 + \beta_1 dt_{it} + \sum_j \beta_j Controls + \sum Industry + \sum year + \varepsilon_{it} \quad (2)$$

The mediating effect model is as follows:

$$SGR_{it} = a_1 + \beta_1 dt_{it} + \Sigma_j \beta_j Controls + \sum Industry + \sum year + \varepsilon_{it} \quad (3)$$

$$inter = a_2 + \beta_2 dt_{it} + \Sigma_j \beta_j Controls \sum Industry + \sum year + \varepsilon_{it} \quad (4)$$

$$SGR_{it} = a_3 + \gamma_3 inter + \beta_3 dt_{it} + \Sigma_j \beta_j Controls + \sum Industry + \sum year + \varepsilon_{it} \quad (5)$$

4. Empirical analysis

4.1 Regression analysis

In Table 1. Column (1) shows that coefficient for sgr and dt is 0.032 without any control variables, and dt can improve sgr. Column (2) in the table shows that after adding a series of control variables, and the regression coefficient of sgr and dt is 0.027, indicating that enterprises can improve sgr by deepening dt, supporting hypothesis 1.

Table 1 Regression results of dt and sgr

	sgr	sgr
dt	0.032***	0.027***
	(12.557)	(11.208)
controls	no	yes
year	yes	yes
industry	yes	yes
N	24119	24119

***p<0.01, **p<0.05, *p<0.10

4.2 Intermediary mechanism check

In Table 2, column (2) shows coefficient of dt to green technology innovation(gti) is 0.059, confirming that dt has a positive effect on gti. In column (3) show the regression coefficient of gti to sgr is 0.007, indicating that the impact of dt on sgr is partially mediated by gti, and the results support hypothesis H2.

Table 2 Mediator effect check

	sgr	gti	sgr
dt	0.027***	0.059***	0.026***
	(11.208)	(11.285)	(11.012)
gti			0.007**
			(2.294)
controls	yes	yes	yes
year	yes	yes	yes
industry	yes	yes	yes
N	24119	24119	24119

***p<0.01, **p<0.05, *p<0.10

4.3 Robustness check

The mean (mean_dt) of the degree of digital transformation(dt) in the same region, industry and year was selected as the instrumental variable. Table 3 show that coefficient of mean_dt in the first stage is 0.587, indicating that mean_dt is related to the original explanatory variable. The coefficient of the second stage is 0.06, indicating that the endogeneity problem does not affect the robustness of the conclusions of this paper.

Table 3 Test results of instrumental variable method

	dt	sgr
mean_dt	0.587***	
	(43.321)	
dt		0.060***
		(6.285)
controls	yes	yes
year	yes	yes
industry	yes	yes
N	24119	24119

***p<0.01, **p<0.05, *p<0.10

5. Conclusion

The empirical results show digital transformation(dt) can improve sustainable financial growth(sgr), and green technology innovation (gti) plays a key intermediary role in it. Specifically, digital transformation (dt) effectively improves the resource utilization efficiency by empowering green technology research and development, thereby enhancing their long-term financial resilience and sustainable growth capabilities. This study provides an important theoretical basis and practical enlightenment for enterprises to achieve a financially sustainable growth path of economic benefits through the synergy of digitalization and green innovation in the era of digital economy.

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The Impact of Supply Chain Textual Information Disclosure on Analysts' Earnings Forecasts

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Abstract. As the core link of efficient operation of enterprises, supply chain directly affects competitiveness, customer satisfaction and production and operation efficiency, and supply chain information can intuitively respond to the operation status of enterprises and market expectations. This paper employs data from A-share listed companies from 2012 to 2023 to conduct an empirical study on the impact of supply chain textual information disclosure on analyst earnings forecasts. This paper finds that the disclosure of supply chain information by enterprises has a significant effect on improving the accuracy of analysts' earnings forecasts through the machine learning text analysis method. The mechanism test finds that there is a partial mediating effect of analysts' attention in it. The findings of this paper help enrich the literature on supply chain, disclosure and analyst earnings forecasting, and are useful for information users to better understand the supply chain information disclosed by listed companies.

Keywords. Supply chain; textual disclosure; analyst earnings forecasting; text analysis

1. Introduction

In today's globalized economy, it has become increasingly important to build an autonomous, controllable, safe and efficient supply chain. In recent years, the demand for information disclosure by relevant stakeholders is no longer confined to a single enterprise, but has been extended to the entire supply chain, especially the demand for disclosure of the relationship and details of the transactions with the suppliers, and the regulators are constantly upgrading the disclosure requirements for the customers' and suppliers' information. On the one hand, this move aims to enhance the transparency of financial information in the annual reports of listed companies; on the other hand, the detailed disclosure of supply chain information by enterprises can enable stakeholders to have a more comprehensive knowledge of the enterprise.

However, the existing data show that the disclosure of quantitative supply chain information by listed companies is not satisfactory, there exists a large amount of textual supply chain information in the MD&A section of the annual report, and it is not difficult to find out that there are more diverse forms of presenting supply chain information in the annual report. As a kind of non-financial information, whether supply chain textual information has information value and whether it can be used by analysts and

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stakeholders and other information users has not yet been answered by relevant studies. As an important participant in the capital market and a bridge for information communication, analysts can obtain and analyze information more professionally and reducing information asymmetry between investors and listed companies (Geng et al., 2024) [1] This paper focuses on the perspective of supply chain textual information disclosure on analysts' earnings forecasts.

2. Literature review

Supply chain information has a certain impact on the business performance and development prospects of enterprises and is an important concern for enterprises and their stakeholders, which has a direct impact on the profits of enterprises. In their study, Li Dan and Wang Dan (2016) [2] reveal that the transparent behavior of supply chain customer information disclosure providing a richer information base for decision-making in the capital market. In addition, Ledoux et al. (2014) [3] study pointed out that in a market environment with high uncertainty, enterprises can reduce information asymmetry and enhance market trust in enterprises by proactively disclosing customer value information, and enhance consensus among analysts, providing analysts with a more accurate basis for earnings forecasts.

It has been argued that the primary function of securities analysts is to analyze and research information and give investors professional advice on investment decisions. Francis (1997) [4] argues that, assuming analysts' optimism bias is not intentional but rather due to insufficient processing of available information, analysts may issue favorable reports because of cognitive limitations. The information disclosed by listed companies is a key source of information that analysts refer to when making earnings forecasts (Ledoux et al., 2014) [3]. The content of information disclosed by companies can have an impact on analysts' forecast accuracy. Some scholars have pointed out that the disclosure of supply chain information covers information interactions between suppliers and industry peers, as well as information exchanges between suppliers' major customers and other companies within the analyst's focus (Jia & Wu, 2023)[5], and Luo & Nagarajan (2015)[6] argued that by disclosing supply chain information, it can reveal a company's competitive advantage, help analysts to better assess supply chain risks, thus improving market efficiency.

Existing domestic and international literature has achieved abundant results in the field of supply chain information disclosure. However, the current literature on supply chain information disclosure mostly focuses on the quantitative disclosure of customer/supplier names and business information, with few studies considering the textual information in the MD&A section regarding supply chain relationships, forecasts of supply chain development, and assessments of potential risks. In addition, at present, there is limited research on the impact of information disclosure on analysts' earnings forecasts, especially regarding supply chain - related textual information.

3. Research design

3.1. Data sources

In this paper, the data of Chinese A-share listed companies during 2012-2023 are selected as the research sample. Financial listed companies and companies listed in the current year are excluded; meanwhile, ST, *ST companies and companies with missing data problems in the sample interval are excluded to obtain 18007 company-year observations. In addition, this paper implements the shrinking treatment of 1% and 99% quantile points for continuous variables.

3.2. Variable setting

Explained variable (FERROR): analysts' earnings forecast accuracy. It is measured using the earnings forecast bias.

Explanatory variable (SCTI): This paper uses a large amount of financial report text data disclosed by listed companies as the training source and employs the "seed words + Word2Vec expansion of similar words" method to construct a dictionary for measuring supply chain information disclosure. The sources of seed words include authoritative literature, professional books, government policy documents, and manual reading and screening. The specific steps are as follows:①Referring to the topic classification and corresponding vocabulary proposed in the study by Muslu et al. (2015) [7], we screened out supply chain - related keywords and translated them into Chinese expressions. ② We randomly selected 300 MD&A texts and extracted keywords in the field of supply chain through manual reading of each text. We then collected a large number of financial reports disclosed by listed companies, summarized them, and performed word segmentation using the jieba library. With the help of Python code, we called the Word2Vec deep - learning - based model to establish a semantic similarity model for words. ③ Finally, we input each supply chain seed word into the semantic similarity model to obtain their corresponding similar words. To balance the accuracy and comprehensiveness of the screening results, we sorted the similar words for each supply chain seed word by similarity in descending order and retained the top 50 similar words. The ratio of the number of sentences related to the supply chain to the total number of sentences in the MD&A section is used as the measure of supply chain textual information disclosure level.

Mediating variable (Analyst): analyst attention, which is taken as the natural logarithm of the number of analysts who issued earnings forecasts for the firm from the disclosure of the firm's annual report in year t until the disclosure of the annual report in year t+1, plus one. Other variables are defined as shown in Table 1.

Table 1. Definition of variable

Variable type	Variable symbol	Variable name
Explained Variable	FERROR	Earnings forecast deviation
Explanatory Variable	SCTI	Number of Supply Chain Text Sentences/Total MD&A Sentences
Control Variables	SIZE	Natural logarithms of total assets
	BM	Book value/market value
	ROE	Net profit/average balance of owners' equity

4. Empirical results and analyses

4.1. Benchmark regression results

Table 2. Descriptive statistical characteristics of the main variables

Variant	N	Mean	Median	S.D.	Min	Max
FERROR	18007	1.090	0.560	1.630	0	22.57
SCTI	18192	0.141	0.126	0.0860	0	0.400
Analyst	18192	1.710	1.610	1.430	0	4.470

Table 3 reports the effect of supply chain textual disclosure on the accuracy of analysts' earnings forecasts. SCTI is significant at the 1% level, and the coefficient is negative. In terms of economic significance, a 1% increase in supply chain textual information disclosure is associated with a 0.78% improvement in the accuracy of analysts' forecasts. When the level of supply chain textual information disclosure increases by one standard deviation (0.0860), the accuracy of analysts' earnings forecasts increases by 6.708%. The above results all confirm Hypothesis of this paper.

Table 3. Baseline regression results

	FERROR	FERROR-1
SCTI_S	-2.082***	-0.780***
	(0.217)	(0.185)
Controls	YES	YES
Constant	1.380***	-1.369***
	(0.0418)	(0.522)
Observations	18007	18007
Adj. R2	0.084	0.186

4.2. Endogeneity test

Table 4. Endogeneity test and robustness test

	FERROR	FERROR-1
SCTI_S	-0.766***	-0.417***
	(0.185)	(0.160)
Controls	YES	YES
Constant	-1.274**	1.069***
	(0.524)	(0.333)
Observations	17,890	18192

This paper employs Propensity Score Matching (PSM) to assign values of 1 and 0 to supply chain textual information disclosure based on whether it is above the median or less than or equal to the median, respectively. As shown in the second column of Table 4, the research conclusions remain unchanged after addressing the sample selection bias.

4.3. Robustness test

As shown in the Third column of Table 4, to eliminate the impact of the measurement method of the dependent variable, we replaced the original dependent variable with the absolute value of the difference between analysts' earnings per share (EPS) forecasts and the actual EPS, divided by the actual EPS. The conclusions drawn from this alternative measurement are consistent with the benchmark regression results.

5. Heterogeneity analysis

The regression results in Table 3 show that the disclosure of supply chain textual information can improve the accuracy of analysts' earnings forecasts. This may be because such disclosure provides more valuable incremental information. Therefore, different characteristics of text information may have differential impacts on this result. We further analyze this from two perspectives: text readability and text similarity.

5.1. Readability analysis

This paper further examines the impact of the readability of annual report disclosures on the research conclusions. Based on the Flesch Reading Ease formula, the readability of the text is assessed, and the samples are naturally divided into high - readability and low - readability groups using the median readability within each industry - year. Table 5 reports the results of the heterogeneity analysis of readability levels, which suggests that supply chain textual disclosures can play a greater role when the readability of textual information in annual report disclosures is high.

5.2. Similarity analysis

When the text similarity of a company's annual report is relatively low compared to other companies in the same industry, it is considered that the company provides more heterogeneous and incremental information Therefore, this paper uses cosine similarity to calculate text similarity, the samples are naturally divided into low - similarity and high - similarity groups using the median similarity within each industry - year. As shown in Table 5, when the text similarity is lower, the supply chain textual disclosure plays a more significant role.

Table 5. Heterogeneity test results

	FERROR			
	Highly readability	Low readability	Low similarity	High similarity
SCTI	-0.749** (0.364)	-0.278 (0.527)	-1.118*** (0.407)	-0.259 (0.432)
Controls	YES	YES	YES	YES
Constant	-5.678** (2.796)	-3.489 (2.489)	-2.953 (2.595)	-4.739* (2.604)

6. Effect further analysis

6.1. Analysis of moderating

Star analysts have better resources and capabilities. Therefore, this paper further investigates whether the potential advantages of star analysts play a moderating role. As shown in Table 6, star analysts exert a significant positive moderating effect in the mechanism.

Table 6. Star analyst moderating effect

	FERROR		FERROR	
SCTI_S	-0.940***		-1.405***	

	(0.194)		(0.253)	
SCTI_S×Star	-0.290** (0.132)		-0.00105*** (0.000332)	
Star	0.0554 (0.0744)	0.0552 (0.0744)		
Controls	YES	YES	YES	YES
Constant	-1.430*** (0.544)	-1.414*** (0.544)	-1.316** (0.517)	-1.301** (0.517)

6.2. Analysis of intermediary mechanisms

The results of the mediation effect test are shown in Table 7. The higher the level of supply chain textual information disclosure, the greater the attention from analysts, and consequently, the higher the accuracy of their earnings forecasts.

Table 7. Analysis of Intermediary Mechanisms

	Analyst	FERROR
SCTI	0.833*** (0.158)	-0.746*** (0.185)
Analyst		-0.0411*** (0.0154)
Controls	YES	YES
Constant	-8.091*** (0.341)	-2.2804*** (-12.88)

7. Conclusion

This paper examines the impact of supply chain textual information disclosure on the accuracy of analysts' earnings forecasts among Chinese A-share listed companies from 2012 to 2023 using machine - learning - based text analysis methods. The results show that there is a significant positive correlation between supply chain textual information disclosure and the accuracy of analysts' earnings forecasts. Moreover, both the readability and similarity of text information have an impact on analysts' earnings forecasts.

Based on the above conclusions, the following suggestions are put forward: Listed companies should fully recognize the economic impact of supply chain textual information disclosure and avoid making the content of information disclosure too complicated or template based. For regulatory authorities, it is necessary to further strengthen relevant policies on supply chain information disclosure, improve the quality of supply chain information disclosure by listed companies, and provide reliable and easily accessible information for analysts and other information users. Future research can further explore the moderating role of different industry characteristics on the relationship between supply chain textual information disclosure and analysts' earnings forecasts, as well as combine big data and artificial intelligence technologies to deeply mine the key elements in supply chain textual information to more accurately reveal the impact mechanism on analysts' forecasting behavior.

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The Impact of Digital Transformation on Regional Green Innovation Efficiency

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Abstract. In research on how digital transformation affects green innovation efficiency, human capital, government transparency, technology market development, and green-low carbon awareness are key variables shaping its operational path and effect. To find out the internal mechanism and transmission path of how this affects regional green innovation efficiency, this study uses panel data from 30 provinces between 2012 and 2022. It uses the undesirable-output Super-EBM model and entropy method. It tests panel fixed effects, mediating effects, and threshold effects. Results show: (1) Digital transformation greatly raises green innovation efficiency. There is regional difference, and it is "Central China > Eastern China >> Western China". (2) It raises this efficiency by increasing human capital and improving government transparency. (3) Both technology market development and green-low carbon awareness have a single threshold effect in this impact. When they cross the threshold, the effect of digital transformation becomes much stronger.Promoting digital transformation can speed up innovative iterations. It can help spread technology. And it can achieve green technological innovations. These innovations have low costs, high efficiency and use very few resources.

Keywords. Digital transformation, regional green innovation efficiency, mediating effect, threshold effect

1. Introduction

Digitization and greenization represent key trends in the new technological and industrial revolution, underscoring the urgency of long-term green development [1]. Existing research has not sufficiently studied the threshold effect of digital transformation on the efficiency of regional green innovations and reveals gaps in optimizing the measurement of this efficiency. For instance, Zhang Bo [2] examined the moderating role of human capital, technology integration, and absorption capabilities in their relationship; Liu Chang [3] measured innovation efficiency using the natural logarithm of green invention patents (plus 1) and analyzed its influencing factors. Although these studies cover various factors, they do not pay sufficient attention to a thorough analysis of threshold effects, and the accuracy of results obtained from their measurement methods is relatively limited. To address this gap, this paper employs the Super-EBM model to measure innovation efficiency and conducts threshold effect tests to supplement existing research.

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2. Related Works

Current studies on the impact of digitalisation on green innovation in regions focus little on the macro level and adopt mainly a micro perspective. For example, Zhou Huihui analyzed digitization's effect on manufacturing enterprises' green innovation performance via its moderating role [4]; Song Deyong measured enterprise digitization with intangible asset data and explored its promotion of green technological innovation [5]. However, macro-level regional studies are scarce (e.g., Wang Fengzheng et al. [6]), so this paper aims to supplement such research. Second, existing green innovation studies focus on efficiency measurement and mechanism testing. In measurement, SFA and DEA are main methods. Wei Mei used DEA to analyze provincial energy efficiency [7], but traditional DEA cannot handle variables with both radial and non-radial characteristics. To address this, Tone and Tsutsui [8] proposed the EBM model, integrating both types and dividing indicator improvement into radial and slack improvement. Thus, this paper uses the super-efficiency EBM model to measure green innovation efficiency, enhancing accuracy. In mechanism testing, existing studies (e.g., Zhang Xiaojuan [9]) mainly analyze mediating or moderating effects separately. Therefore, this paper supplements the research by examining threshold effects and regional heterogeneity analysis.

3. Theoretical Analysis and Research Hypothesis

3.1 Digital transformation and regional green innovation efficiency

The development of digitization can efficiently integrate demand information and supply information. The efficient allocation of resources can minimize energy consumption and environmental pollution, thereby improving the efficiency of achievement transformation [10].
Based on this, this paper proposes:

Hypothesis 1: Digital transformation can promote regional green innovation efficiency.

3.2 Mechanisms of digital transformation on regional green innovation efficiency

High-quality human capital rebuilds green value, pushes forward green consumption revolution and promotes the continuation of green innovation through rapid popularization of green products in dual-performance enterprises. Jiang Fuxin et al. [11] confirmed that human capital exerts a significant positive impact on green innovation. Based on this, this paper proposes:

Hypothesis 2: Human capital functions as a mediating variable in the relationship between digital transformation and regional green innovation performance.

Government measures on data opening and sharing have enabled platforms to open key channels for societal data circulation, breaking information barriers to enterprises' disruptive digital transformation [12]. Based on this, this paper proposes:

Hypothesis 3: Government transparency has a mediating role in the relationship between digital transformation and regional green innovation efficiency.

The feedback effect of the technology market further incentivizes enterprises' green innovation, while a sound technology market system enhances market competition and promotes green innovation [13]. Based on this, this paper proposes:

Hypothesis 4: The impact of digital transformation on the effectiveness of green innovation includes threshold effects related to the level of development of the technology market.

The green focus on low carbon reflects the political support and oversight provided by governments, markets and the public in the context of low carbon development. Higher attention makes policies more targeted, guiding digital transformation resources toward green innovation [14]. Based on this, this paper proposes:

Hypothesis 5: The impact of digital transformation on green innovation efficiency involves a threshold effect of green low-carbon concern.

Based on the above assumptions, construct the following conceptual diagram.

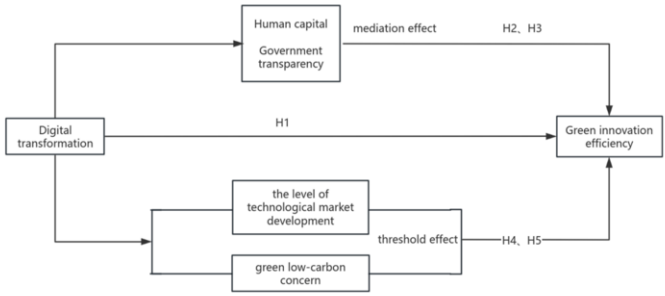


Figure 1: Conceptual diagram

4. Research Methods and Data Sources

4.1 Basic regression model

In this paper, a fixed effects model is used to construct the benchmark regression, which is shown below:

$$GE_{i,t}=\alpha_0+\alpha_1 DIG_{i,t}+\alpha_2 X_{i,t}+\mu_t+\lambda_i+\varepsilon_{i,t}$$

α_0 is a constant term;α_1 and α_2 are variable coefficients; $GE_{i,t}$ is the green innovation efficiency of province i in year t; $DIG_{i,t}$ is the digital transformation level of province i in year t;$X_{i,t}$ is a series of control variables for year t in province i; μ_t and λ_i represent the fixed effects of year and province in panel data

4.2 Entropy method

In this paper, the entropy method was employed to calculate the weight of each indicator, and the method of standardization of the extreme difference was used to standardize the data. The standardized data were then added uniformly.

4.3 Super-efficient EBM model

In this paper, the super-efficient EBM model with variable returns to scale is used to evaluate the performance of green innovations in 30 provinces from 2012 to 2022:

$$\gamma^* = \min \theta - \varepsilon_x \sum_{i=1}^{m} \frac{W_i^- S_i^-}{x_{ik}}$$

$$s.t. \begin{cases} \sum_{j=1}^{n} x_{ij} \lambda_j - \theta\, x_{ik} + s_i^- = 0 & i = 1,2,\ldots m \\ \sum_{j=1}^{n} y_{rj} \lambda_j \geq y_{rk} & r = 1,2,\ldots,s \\ \lambda_j \geq 0, s_i^- \geq 0 \end{cases}$$

Assuming the decision unit to be measured is DMU, where γ^* represents the optimal efficiency under variable returns to scale; S_i^- is the slack variable of input factor i; j is the decision-making unit; n is the total number of decision-making units; W_i^- is the importance level of the input indicator, satisfying x_{ij} and y_{rj} as the i-th input and r-th output of decision unit j, respectively; X_{ik} and y_{rk} are the i-th input and r-th output of decision unit k, respectively; m and s are the quantities of input and output, respectively; θ is the planning parameter for the radial part; λ_j is the linear combination coefficient; ε_x is the key parameter, satisfying $0 \leq \varepsilon_x \leq 1$

Extend the above model into a non-desired output based, unoriented EBM model as in the following equation:

$$\gamma^* = \min \sum_{i=1}^{m} \frac{\theta - \varepsilon_x \sum_{i=1}^{m} \frac{W_i^- S_i^-}{x_{ik}}}{\varphi + \varepsilon_y \sum_{r=1}^{s} \frac{W_r^+ S_r^+}{y_{rk}} + \varepsilon_b \sum_{p=1}^{q} \frac{W_p^{b-} S_p^{b-}}{b_{pk}} +}$$

$$s.t. \begin{cases} \sum_{j=1}^{n} x_{ij} \lambda_j + s_i^- = \theta\, x_0 & i = 1,2,\ldots m \\ \sum_{j=1}^{n} y_{rj} \lambda_j - s_r^+ = \varphi\, y_{rk} & r = 1,2,\ldots,s \\ \sum_{p=1}^{n} b_{pj} \lambda_j + s_p^{b-} = \varphi\, b_{pk} & p = 1,2,\ldots,q \\ \lambda_j \geq 0, s_i^- \geq 0, s_r^+ \geq 0, s_p^{b-} \geq 0 \end{cases}$$

4.4 Data sources

To reduce sample heterogeneity and facilitate comparison with existing literature, this study uses data from 30 Chinese provinces (excluding Tibet, Hong Kong, Macao and Taiwan) over 2012–2022. These provinces, accounting for approximately 97.8% of the national population, are largely representative of the total population. Original data come from the China Statistical Yearbook (various years) [15] and CSMAR [16], with minor missing values supplemented via linear interpolation.

5. Variable Selection

Digital transformation (DIG): this paper measures the level of digital transformation by integrating four dimensions: digital infrastructure, digital industrialisation, industrial

digitization, and digital innovation capability.
Green innovation efficiency (GE): In this paper, we refer to the study of Lv Yanwei et al. [17] to construct the evaluation index system as shown in Table 1.

Table 1 Green innovation efficiency evaluation indicator system

Typology	Indicators (units)
Innovative inputs	Full-time equivalent of R&D personnel (person-years) Internal Expenditures on R&D Funding (million of yuan)
Expected outputs	Value added of industry (billions of yuan) Number of invention patents authorized (items) Technology market turnover (billions of yuan)
Non-expected outputs	Industrial solid waste generation (tons) Sulfur dioxide emissions (tons) Industrial wastewater discharge (tons)

We selected the following variables: degree of openness to the outside world (OPEN), financial support (FIN), intellectual property protection (IPP), and industrialization (IP). The measures of the variables are referred to the studies of Wei Hao [18], Zhang Hu [19], and Liu Rongzeng [20].

We selected the following variables: human capital (HUM) is based on the number of students in the general higher education institutions in the region; and government transparency (GT), measured by the government transparency index of each province.

The following mediating variables were selected: the level of development of the technology market (TRL), expressed as the proportion of technology market sales to regional gross domestic product; green and low-carbon concern(GLC), which is obtained through the statistics of word frequency of the provincial government's work report, and screened for the “green”, “environment protection” and so on. The number of occurrences of keywords is measured.

6. Results and Discussion

6.1 Correlation analysis

Table 2 shows that digital transformation has a significant positive correlation with the efficiency of green innovation by province, while other variables are also correlated, confirming the explanatory validity of the selected variables.

Table 2 Correlation analysis results

GREEN	DIG	GT	HUM	OPEN	FIN	IPP	
GREEN	1						
DIG	0.523***	1					
GT	0.399***	0.486***	1				
HUM	0.345***	0.549***	0.312***	1			
OPEN	0.371***	0.622***	0.279***	0.672***	1		
FIN	0.143***	0.270***	0.201***	0.431***	0.348***	1	
IPP	0.522***	0.595***	0.465***	0.367***	0.548***	-0.0450	1
IP	0.162***	0.422***	0.291***	0.683***	0.483***	0.534***	0.094*
TRL	0.300***	0.498***	0.286***	0.739***	0.483***	0.487***	0.273***
GLC	0.139**	0.0900	0.134**	0.0330	-0.0240	0.302***	0.0230
	IP	TRL	GLC				
IP	1						
TRL	0.766***	1					
GLC	0.146***	0.123**	1				

To avoid multicollinearity in the empirical model, a VIF test was performed. Table 3 shows all VIF values (max 3.24) are below 10, indicating no multicollinearity and a sound model structure.

Table 3 VIF test results

Variable	VIF	1/VIF
TRL	3.24	0.308510
HUM	3.11	0.321773
IP	3.07	0.325329
OPEN	2.7	0.362531
IPP	2.48	0.403140
DIG	2.30	0.435649
FIN	0.73	0.577417
GT	1.55	0.644390
GLC	1.17	0.855000
Mean VIF	2.38	

6.2 Analysis of baseline regression results

As Table 4 shows, R^2 rises with stepwise inclusion of control variables. Columns (1)–(5) all confirm that digital transformation significantly boosts green innovation efficiency, verifying Hypothesis 1 by indicating its facilitation of regional green innovation.

Table 4 Benchmark regression results

	（1）	（2）	（3）	（4）	（5）
	GE	GE	GE	GE	GE
DIG	1.170*** (0.174)	1.380*** (0.204)	0.791*** (0.258)	0.844*** (0.244)	0.893*** (0.251)
OPEN		0.338* (0.174)	0.245 (0.172)	0.096 (0.165)	0.046 (0.176)
FIN			0.228*** (0.063)	0.153** (0.061)	0.181** (0.070)
IPP				0.673*** (0.110)	0.662*** (0.111)
IP					-0.054 (0.066)
Constant	0.493*** (0.023)	0.378*** (0.063)	0.122 (0.094)	-0.178* (0.102)	-0.133 (0.116)
固定效应	YES	YES	YES	YES	YES
Observations	330	330	330	330	330
R^2	0.045	0.054	0.090	0.190	0.191

6.3 Robustness check

Following Fan Hejun & Wu Ting (2021) [21], this paper uses provincial website counts (DIGin) as a proxy for digital transformation and green patent applications (GEin) for green innovation efficiency. Core explanatory variables are lagged by one period for robustness tests; provincial fixed effects (id) are controlled (after Yakun et al., 2022 [22]) to mitigate endogeneity.

Table 5 shows that robustness test results align with the benchmark regression, confirming the validity of this study's conclusions.

Table 5 Robustness test results

	(1)	(2)	(3)	(4)
	GE	GE_{in}	GE_{in}	GE
DIG_{in}	0.008*** (0.002)		439.240*** (40.947)	
DIG		85290.971*** (3799.092)		
L.DIG				0.639** (0.266)
Constant	-0.197* (0.114)	8624.752*** (1752.108)	2378.827 (2413.250)	-0.162 (0.134)
Observations	330	330	330	330
R^2	0.284	0.790	0.590	0.282
year	YES	YES	YES	YES
id	NO	NO	NO	NO

6.4 Endogeneity test

Following Guo and Luo [23] in addressing endogeneity from reciprocal causality, we use the first-order lag of DIG as its instrumental variable and adopt the 2SLS model for regression.

Table 6 Endogeneity test results

Variables	Phase I	Phase II
DIG_iv	0.0238*** (10.88)	
OPEN	0.0426 (1.16)	-0.0343 (-1.13)
FIN	0.5148*** (4.88)	0.1792** (2.02)
IPP	1.7721*** (6.95)	1.0069*** (3.52)
IP	-0.0069 (-0.16)	-0.0150 (-0.43)
DIG		0.1946*** (2.67)
Kleibergen-Paap rk LM		88.307 [0.0000]
Cragg-Donald Wald F		118.38 {16.38}
Constant	-4.0692*** (-18.75)	-0.8503** (-2.28)
Observations	330	330
R^2	0.0267	0.330

Table 6 shows: First-stage results confirm DIG_IV correlates significantly positively with the core explanatory variable (satisfying relevance). Kleibergen-Paap rk LM statistic (p=0.0000, 1% significant) rejects underidentification. Weak IV tests for endogeneity reveal second-stage DIG is 1% significant positive; Cragg-Donald Wald F exceeds 10% Stock-Yogo critical value. This validates the IV, supporting prior conclusions' robustness.

6.5 Mediation effect test

The results of the mediated effects regressions in this paper are shown in Tables 7 and 8

Table 7 Mediation effect test results

Variables	(1) HUM	(2) GREEN	(3) GT	(4) GREEN
DIG	2.321*** (0.169)	0.003 (0.311)	1.741 (8.568)	0.886*** (0.250)
OPEN	0.342*** (0.118)	-0.086 (0.172)	-21.161*** (5.987)	0.130 (0.178)
FIN	0.214*** (0.047)	0.099 (0.070)	15.992*** (2.400)	0.118 (0.075)
IPP	1.500*** (0.075)	0.082 (0.165)	21.749*** (3.784)	0.575*** (0.116)
IP	0.241*** (0.045)	-0.146** (0.067)	3.581 (2.258)	-0.068 (0.066)
HUM		0.386*** (0.084)		
GT				0.004** (0.002)
Constant	7.317*** (0.078)	-2.959*** (0.622)	29.806*** (3.947)	-0.252** (0.126)
Fixed effect	YES	YES	YES	YES
Observations	330	330	330	330
R^2	0.823	0.241	0.419	0.201

In Column (2), HUM has a positive significant coefficient ($p<0.01$) while DIG is positive but insignificant, prompting a Sobel test. Table 8 shows $Z=4.14$ ($p=0.00003$, $p<0.01$) with 41% mediating effect, confirming HUM's mediating role in enhancing green innovation efficiency, validating Hypothesis 2. In Column (4), DIG is positive significant ($p<0.01$). In Column (3), GT is positive but insignificant, requiring a Sobel test: $Z=2.61$ ($p=0.0081$, $p<0.01$) with 16% mediating effect, confirming GT's role via transparency, validating Hypothesis 3.

Table 8. Results of the Sobel test for mediation effects

Intermediary variable	Z	P	Percentage of intermediary effects
HUM	4.14	0.00003	41%
GT	2.61	0.0081	16%

6.6 Threshold effect test

500 bootstrap samples tested thresholds; results in Table 9.

Table 9. Threshold effect test results

Variables	TRL	GLC
First threshold	0.0015**	71.00**
DIG（TRL≤α）	-2.288*** (0.726)	
DIG（TRL>α）	0.805*** (0.244)	
DIG（GLC≤α）		0.461* (0.278)
DIG（GLC>α）		1.037*** (0.250)
control variable	YES	YES

year	YES	YES
id	YES	YES
observations	330	330
R^2	0.323	0.301

Below the technology market threshold (0.0015), digital transformation significantly inhibits green innovation efficiency (coefficient=-2.288, $p<0.01$); above it, the effect turns positive (0.805, $p<0.01$), supporting H4.Below the green-low-carbon attention threshold (71.00), digital transformation promotes efficiency (0.461, $p<0.1$); above it, the effect strengthens (1.037, $p<0.01$), confirming H5.

6.7 Tests for regional heterogeneity

The sample is divided into eastern, central and western regions. Table 10 shows digital transformation significantly enhances green innovation efficiency in eastern and central regions (insignificant in the west). DIG coefficients indicate a stronger promotion effect in the central region than the eastern—likely due to the east's higher digital transformation level (diminishing marginal benefits) versus the central's digital popularization stage (more room for improvement). The insignificant effect in the west may stem from weak subjective demand for green innovation.

Table 10. Results of the regional heterogeneity test

	eastern region	central region	western region
DIG	0.8796*** (4.6909)	1.2956*** (2.9537)	0.6480 (1.3513)
OPEN	0.0686 (0.8063)	-0.6690 (-1.3780)	1.0513*** (4.0130)
FIN	0.1107** (2.1030)	0.0496 (0.7008)	0.1708*** (3.0069)
IPP	0.5249** (2.4306)	0.6858*** (4.1190)	0.6562*** (3.7318)
IP	-0.0320 (-1.5100)	0.1913** (2.3812)	-0.2066** (-2.1095)
Constant	-0.0340 (-0.1945)	-0.1146 (-0.7783)	-0.0174 (-0.1113)
Fixed effect	YES	YES	YES
Observations	330	330	330
R^2	0.433	0.416	0.288

7. Research Conclusions and Policy Recommendations

7.1 Research conclusions

(1) Digital transformation directly boosts regional green innovation efficiency, empirically supporting its role in sustainable development. It acts via enhancing government transparency (optimizing resource allocation) and accumulating human capital (strengthening R&D capacity), deepening understanding of its mechanism in empowering green innovation and filling gaps in mediating pathway research.
(2) The validation of thresholds has shown that the positive impact of digital transformation on the efficiency of green innovation will only improve significantly if

the development of the technology market and interest in green low carbon exceed the thresholds. It reflects its "context dependence."
(3) The impact of digital transformation on green innovation efficiency exhibits regional heterogeneity, presenting a gradient of "Central > Eastern > Western". This reflects how regional development foundations and digital adaptability constrain the driving forces of green innovation.

7.2 Policy recommendations

(1) Strengthen new digital infrastructure, advance industrial structure upgrading, improve talent training systems, and accelerate human capital accumulation.
(2) Strengthen data opening and sharing mechanisms and track the real-time correlation between digital technology application and environmental performance.
(3) Government must take into account the real development of the regions and put in place a system of targeted policies to ensure coordinated development of the regions and a constant improvement of the digital transformation.

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Section II

Track on “Applied-Education and Applied-Research in AI, Data Science, and Web6.0”

Digitalization and Management Innovation IV
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Challenges of Using Generative AI in Entrepreneurship

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Abstract. Generative Artificial Intelligence (GenAI) is becoming a powerful tool in modern entrepreneurship, providing new opportunities for automation, personalization, and the creation of innovative products and services. Through emerging technologies such as language models, image and audio generation systems, entrepreneurs can significantly accelerate their workflows and reduce costs. However, the implementation of GenAI is associated with a number of significant challenges. The technological barriers include high requirements for computing resources, complexity in integration, and the need for specialized knowledge. The lack of trained personnel and resistance to technological changes are another obstacle in its sustainable implementation. From a business perspective, the unpredictability of the GenAI results and the lack of trust among users can slow down the growth. The emerging global legal regulations impose additional responsibilities on the entrepreneurs. The aim of this conceptual paper is to analyze these multi-layered challenges and offer guidelines for the responsible and effective use of GenAI in entrepreneurship. A framework for using GenAI in entrepreneurship is proposed too.

Keywords. Entrepreneurship, Innovation, Digitalization, Generative Artificial Intelligence

1. Introduction

Entrepreneurship is a major driver of economic progress, innovation and social development. It is a process by which individuals or groups of individuals identify opportunities, generate new ideas, organize resources, and implement projects with the aim of creating economic, social or cultural value [1]. At the core of entrepreneurship is the figure of the entrepreneur, who is a person that takes risks, seeks solutions to real problems and generates innovations that change the market and society. Entrepreneurship can be defined as an activity involving the discovery, evaluation and exploitation of opportunities to create new products, services or enterprises, by using available resources under uncertainty to create value.

The key elements in this definition are [2, 3]:

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- **Opportunity identification** - the entrepreneur can recognize niches in the market.
- **Innovation** - the entrepreneur can design or improve a product, process or business model.
- **Risk** - includes financial uncertainty, market unpredictability and technological challenges.
- **Value** - the entrepreneur can not create for himself only, but also for consumers, society and the economy.

1.1. Entrepreneurship Architecture

The entrepreneurship architecture combines all elements, participants and interactions that make up the entrepreneurial system. It includes the following main components [4, 5]:

Entrepreneur - is the main pillar of the process. Motivation, knowledge, personal characteristics (such as creativity, resilience, flexibility), as well as the social capital of the entrepreneur are decisive for success.

Idea - every entrepreneurship starts with an idea which can be a product, service, social initiative, technological innovation or a new organizational model.

Resources – they include financial capital (investments, loans, grants), human capital (team, experts, mentors), intellectual capital (patents, know-how), social capital (networks of contacts, partnerships).

Market – an environment in which the idea must be realized and accepted by consumers. Market need and demand are fundamental to success.

Business model - the way in which the idea will be implemented - how value will be delivered, what will be the revenues and costs, how logistics are carried out, etc.

Environment - legislative frameworks, cultural context, economic conditions, technological trends and competition the all influence entrepreneurship.

1.2. Functions of Entrepreneurship

Entrepreneurship is responsible for a set of important functions in the economy and society [6, 7, 8]:

Innovation function - entrepreneurship is a main driver of technological progress and innovation. This function is responsible for the creation of new products, services, production methods and ways of working.

Economic function - by creating new businesses, production increases, jobs are created and economic activity expands.

Social function - entrepreneurship can address social problems through the social entrepreneurship with the aim of improving living conditions, education, healthcare and ecology.

Risk-taking function - entrepreneurs take risks that others avoid, which allows them to create new paths and opportunities for growth.

Coordination function - the entrepreneur coordinates resources, such as capital, labor, technology, and directs them for the implementation of a specific goal, often in conditions of uncertainty and rapid change.

Regional development - by creating small and medium-sized businesses, entrepreneurship stimulates the development of less developed regions, reduces migration and promotes the local economy.

1.3. Purpose of Entrepreneurship

Entrepreneurship has both an individual and a social purpose. It includes the following aspects [9, 10]:

Personal fulfillment - entrepreneurship for many individuals is a way to achieve independence, express creativity and realize dreams. It allows personal development, freedom of activity and satisfaction.

Value creation - the main goal of entrepreneurship is to create value - economic (profit), social (benefit to society) or cultural (change in thinking, attitudes, aesthetics).

Change and transformation - entrepreneurs do not just do business, but they also change rules, create new realities and transform entire industries.

Adaptation to change - entrepreneurship offers a appropriate way for flexible adaptation and sustainability in the conditions of global uncertainty, technological changes and social dynamics.

Sustainable development - the entrepreneurship aims not only at profit, but also at ecological, social and economic sustainability. Modern start-ups focus on sustainable business models, circular economy, ethical practices, etc.

Modern entrepreneurship needs the use of emerging technologies such as artificial intelligence, language models, image and audio generation systems for a substantial digital innovation, significant acceleration of workflows and cost reduction [11, 12, 13]. The aim of this conceptual paper is to analyze these multi-layered challenges and offer guidelines for the responsible and effective use of GenAI in the entrepreneurship. A framework for using GenAI in entrepreneurship is proposed too.

2. Technological and Information Barriers to the Entrepreneurship Development

The development of entrepreneurship in the modern world is closely related to technological progress and access to information resources. Although technologies promise enormous opportunities for optimization, automation and increasing competitiveness, they can also become serious barriers. Information and technological barriers affect the efficiency, growth and ability of entrepreneurs to implement their ideas. In this regard, we will consider the main obstacles that can hinder entrepreneurship from the point of view of information technology [14, 15, 16].

Insufficient information infrastructure is the first and perhaps the most significant obstacle is the lack of a sufficiently developed technological infrastructure. In many areas of the world, especially in developing countries and remote regions, access to high-speed Internet, quality communication networks and modern technological services remains limited. Weak infrastructure hinders the ability of entrepreneurs to actively participate in the global economy, to use cloud services, online platforms and e-commerce. Limited access to a reliable internet connection makes it impossible to conduct online business, especially in the context of the ever-widening digitalization of consumer behavior.

High costs of technological equipment and software is often a challenge for small and medium-sized entrepreneurs to invest in modern information technologies. The high costs of quality hardware, specialized software, cloud services, and technological support

are serious obstacles, especially when starting a business with limited financial resources. As a result, many companies fail to make the necessary investments and remain technologically behind.

Difficulties in managing and analyzing large data sets since data is considered one of the most valuable resources for businesses. However, many entrepreneurs face difficulties in processing, analyzing, and using such data. This is due to both the lack of appropriate technologies and the lack of competencies. As a result, companies miss out on important opportunities to improve their services, optimize costs, or identify new market opportunities.

Lack of integration between different IT systems is another serious technological failure. Small companies usually use different software solutions for their activity, such as accounting, marketing, warehouse management, etc. The lack of integration between these systems can result in loss of efficiency, errors, inability to analyze data properly..

Cybersecurity and data protection in processing large amounts of sensitive information, such as customer personal data, financial transactions, sensitive corporate documents and intellectual property. Vulnerability to cyber attacks is one of the major technological obstacles facing entrepreneurship. Small and medium-sized businesses, which often lack the resources for expensive security systems and specialized teams, are the most vulnerable.

Technological lag and slow adaptation to innovation pose a constant challenge for entrepreneurs to follow current trends. For small companies, rapid adaptation to new technologies can be extremely difficult. Slow integration of new solutions – such as artificial intelligence, machine learning, automation, and cloud services – can lead to a significant technological lag compared to competitors who adapt innovations faster.

Lack of access to technology and information resources in remote areas, where, entrepreneurs cannot use critical technology data centers, cloud services, high-speed internet, professional IT services. This limits their ability to develop competitive businesses and seize opportunities in the global marketplace.

Lack of digital literacy and technological competences since many entrepreneurs, especially in small and medium-sized enterprises, do not have the necessary training to work with modern digital tools such as analytical software, customer management systems, automated marketing platforms and business analytics. This leads to poor performance, limiting growth potential and failing in competitiveness against more technologically advanced business adversaries.

3. Using Generative AI in Entrepreneurship

Generative Artificial Intelligence (GenAI) is emerging as a new opportunity in entrepreneurship, focusing on how these advanced AI technologies can enhance productivity, creativity and decision-making processes for entrepreneurs [17, 18, 19]. GenAI has the potential to revolutionize entrepreneurial practices and business models. GenAI is a set of technologies that can create original and new content, such as text, images, videos, audio and code, based on the data on which they have been trained.

The main technologies in generative artificial intelligence are based on several powerful algorithms and models that allow systems to generate original content :[20, 21]

Generative Adversarial Networks (GANs) use two neural models – a generator and a discriminator that compete with each other in order to create high-quality images and videos that are indistinguishable from the real thing.

Large Language Models (LLMs), such as ChatGPT, LlaMA, Gemini, and others, based on transformer architectures, are capable of creating text content, holding conversations, writing code and solving complex tasks.

Diffusion Models generate images by gradually adding and removing noise, which leads to the creation of extremely realistic and detailed images.

Variational Autoencoders (VAEs) can encode data in a compressed form and then reconstruct it or generate new, similar patterns.

These technologies provide vast opportunities for innovation in entrepreneurship and the current paper will discuss the five most important solutions of GenAI [22].

3.1. GenAI in Entrepreneurship for Generation and Implementation of Business Ideas

GenAI supports the brainstorming process through its ability to process vast amounts of information, identify trends and propose innovative solutions based on data and context. Entrepreneurs can use language models to ask questions like "What are the potential applications of GenAI in education?" or "What business models can be implemented in social entrepreneurship?", and to receive meaningful, original and structured answers to serve as a starting point [23, 24, 25].

The analysis and validation phase follow the idea generation. GenAI can help formulate business plans, create SWOT analyses, competitive assessments, market behavior simulations. This allows entrepreneurs to assess the potential of their idea before they have invested significant resources. GenAI can also assist in the preparation of product concepts and suggest different ways to test the idea in the real market.

GenAI is useful at the stage of generating an idea as a tool for creating specific content, such as websites, investor presentations, marketing materials, campaign texts, emails, product descriptions, etc. GenAI supports also creative communication with potential partners and investors by automating email communication, creating personalized presentations, and adapting messages to the audience. This allows entrepreneurs to appear more professional and confident even in the early stages of their development.

Through continuous feedback and analysis of results, GenAI supports the optimization and iterative development of business ideas, which is of a special importance in a dynamic and competitive environment. Entrepreneurs can quickly adapt their concept to market needs by using GenAI to analyze user behavior and reaction.

3.2. GenAI in Entrepreneurship for Creation New Professional Roles and Market Niches

The GenAI creates entirely innovative entrepreneurial ecosystems, that can include new professional roles, market niches, micro-entrepreneurship and freelancing, human-GenAI collaboration, regional economic development potential [26, 27, 28, 29].

New professional roles are feasible with the advent of GenAI models such as ChatGPT, DALL·E, Midjourney, etc. These roles require a new combination of creativity, technological skills and understanding of the behavior of AI systems. Most popular new professions are:

- **AI Prompt Engineer** is a specialist who knows how to formulate precise and effective prompts to extract the best results from GenAI systems. This profile is in demand in marketing, design, programming, education.

- **AI Content Curator** is a professional who knows how to filter, edit and adapt content created by GenAI to meet certain requirements for style, tone, accuracy and target audience.
- **AI Product Designer** focuses on integrating AI into product solutions. These professionals develop interfaces that allow users to interact with GenAI in an easy and efficient way.

These new professions not create jobs only, but also shape new areas of expertise, which in turn opens opportunities for consulting, training, freelance projects, abuilding personal brands.

New market niches are possible by GenAI through the creation of completely new services and products. Wide-spread examples include:

- **GenAI-based Content-as-a-Service** with agencies and platforms creating personalized content (text, images, video) for small businesses using GenAI. This is extremely useful for companies without an in-house marketing team.
- **GenAI templates and resources** for ready-made prompts, chatbot templates, storyboard structures or visual styles that save other users' time and effort.
- **GenAI training and certification** through creation of educational platforms and courses that teach how to effectively use generative tools in various industries.

Micro-entrepreneurship and freelancing becomes easier since GenAI eliminates the need for large teams and significant investments to create quality products. This opens the possibility of emerging micro-entrepreneurs – people who build profitable businesses around their skills and interests through GenAI. Examples can include:

- A freelancer can create and sell digital books created with the help of GenAI.
- A graphic designer can use Midjourney to create original designs for t-shirts, posters or brand identities.
- A copywriter can use ChatGPT to create marketing texts, SEO articles or product descriptions for clients around the world.

Human-GenAI collaboration as a new work model is a new business opportunity. GenAI will not completely replace human labor, but rather augments it. Humans focus on strategic thinking, creativity, emotional intelligence, and critical analysis, while GenAI takes over repetitive or technical tasks. In result new job roles, such as:

- **GenAI co-designer** is a person who collaborates with GenAI to create visual or textual content.
- **GenAI strategist** is focused on how businesses can effectively use GenAI for growth, optimization, and scaling.

Regional economic development potential creates new market niches based on GenAI offers broader social and economic implications. Regions that have not previously been part of the digital economy can now build ecosystems around GenAI entrepreneurship. Educational programs, incubators, shared workspaces and online hubs can stimulate local economic activity by training AI professionals and creating new businesses.

3.3. GenAI in Entrepreneurship for Expanded Access to Global Entrepreneurial Opportunities

GenAI creates global entrepreneurship opportunities [30, 31, 32, 33]:

Access to knowledge and expertise is one of the biggest challenges for budding entrepreneurship, especially in developing countries, due to the lack of access to business knowledge, mentorship, and professional advice. GenAI through established platforms, such as ChatGPT, Claude, DeepSeek and others, provides instant access to business information, terminology explanations, business plan writing guidelines, market analysis tips, and business model simulations. In this way GenAI becomes a kind of virtual mentor in multiple languages, and without high costs.

Lowering barriers to entry is especially important since starting a business traditionally requires significant resources, such as money, expertise, teams, networks of contacts. GenAI significantly reduces the need for many of these resources. Through GenAI tools Website or application creation can be feasible without the need for a heavy-paid programmers. On the other hand, GenAI-based content generation allows for product descriptions, blog posts, marketing copy, emails, presentations. GenAI-based prototyping allows for rapid visualization of product concepts and designs. These capabilities significantly reduce the cost and time required to start a business, making entrepreneurship more accessible to people with limited resources.

Support for multilingual and multicultural markets is feasible with GenAI for entrepreneurs who want to operate outside their native language or market. GenAI language models can translate high-quality content, adapt communication to a specific cultural environment, and suggest appropriate wording according to the target audience. This makes it easier to enter the global market and overcome language barriers.

Accelerating innovation and experimentation is enhanced by GenAI, since it helps entrepreneurs to generate new ideas, simulate market scenarios, create multiple product versions, and experiment with business models in a short amount of time and with minimal cost. This is especially valuable for social entrepreneurs who are looking to solve specific problems in their communities, such as access to healthcare, education, or sustainable agriculture. GenAI delivers the tools to think creatively and act quickly.

Global economy without intermediaries is made possible with GenAI, which allows entrepreneurs from anywhere in the world to create and offer digital products, such as e-books, online courses, graphics, templates, software, etc. They can sell directly through well-established platforms, Shopify and other, without the need for intermediaries, agencies or external infrastructure. GenAI makes it easier to create content, communicate with customers, process orders, provide support. This creates new income streams and economic independence for people in regions with limited job or growth opportunities.

Sustainability and inclusion through GenAI enables the creation of sustainable micro-businesses that do not require large investments or complicated logistics. This is especially important in the context of climate change, economic crises and global conflicts that limit the opportunities for physical businesses. GenAI allows for publicity of communities that would remain on the periphery of the entrepreneurial map.

Equality in entrepreneurship has often been limited by gender, ethnicity, social class or geographic region. GenAI has the potential to reduce these inequalities by

providing the same tools to anyone with access to the internet. Women in conservative societies can start online businesses with the help of GenAI without relying on external teams or investment; young people without a university education can create digital products using GenAI for training, development, and marketing; small ethnic communities can create content and products in their own language and culture without having to adapt to mainstream templates.In this way GenAI contributes to more equal participation in the global entrepreneurial ecosystem.

3.4. GenAI in Entrepreneurship for the Routine and Time-consuming Task Automation

One of the main areas where GenAI is widely used is in the creation of marketing content. Using language models, such as ChatGPT and others, companies can automatically generate social media posts, blog posts, product descriptions, email campaigns. This significantly reduces the time it takes to plan and execute marketing strategies, while maintaining consistency in customer communication [34, 35, 36, 37].

Another key area is customer service. GenAI is used to create intelligent chatbots that can answer queries, solve common problems, direct users to the right resources. This reduces the need for large support teams and allows for a continuous support, which is especially valuable for online-based businesses and international companies.

In the administrative part, GenAI can automate the creation of reports, document summaries, letters, and internal communication. An entrepreneur can use GenAI to generate summaries of business meetings, analyze market data, and prepare presentations. This not only saves time, but also increases the accuracy and consistency of internal documents.

In the field of product development and programming, GenAI can help automatically write code, detect errors, create technical documentation, and generate interfaces. This makes it easier for technology startups, which often have small teams of developers.

GenAI helps personalize the customer experience by generating individualized recommendations, offers, and content based on behavior and preferences. This increases customer loyalty and sales efficiency.

3.5. GenAI in Entrepreneurship for Testing and Development Processes Acceleration

One of the most key roles of GenAI is rapid prototyping. Through the use of GenAI tools entrepreneurs can generate initial versions of websites, mobile applications, interfaces or product designs [38, 39]. This allows for a quick visualization of the concept and its presentation to potential customers, partners or investors. GenAI can suggest an initial structure for a specific product, generate text content and suggest UX solutions that can be directly tested. In the field of user testing, GenAI can simulate different scenarios of product or service usage, as well as generate realistic responses and behavior on behalf of virtual users. This allows entrepreneurs to test functionality, navigation, and interface understandability or communication effectiveness even before they have a real user base. GenAI can analyze data from real test users, automatically detect patterns, problems or opportunities for improvement.

4. A Framework for using GenAI in Entrepreneurship

Despite the great opportunities that GenAI offers for the entrepreneurship development, there are significant obstacles in its implementation. Entrepreneurs can encounter difficulties in identifying the exact applications of GenAI while choosing the right technologies, as well as in structuring effective processes for integration and management of the risks associated with its use.

Key questions can demand specific attention:

- What are the most relevant areas of application of generative AI in entrepreneurship?
- Which specific technologies and tools are most useful for different entrepreneurial goals?
- What are the potential risks associated with the use of generative AI, and how can they be effectively managed?
- What are the best practices and clear steps for integrating generative AI into existing and new business models?

This clear statement of the problem draws attention to the need for a structured framework and specific strategies through which entrepreneurs can effectively and responsibly use GenAI to achieve sustainable development and competitiveness in the market.

A framework for using GenAI in entrepreneurship is proposed, which is based on the following stages [40, 41, 42, 43, 44]. The framework is shown in Fig.1.

Stage 1. Identifying opportunities for integrating generative AI, responsible for:

- Generating ideas and innovations (creating new product concepts, discovering new market opportunities, identifying competitive advantages through GenAI)
- Automating repetitive tasks (creating content, customer service and technical support, analyzing market and user data)
- Improving product development and design (generating prototypes and test versions, automatic creation of UX/UI designs, technological validation of ideas)

Stage 2. Selecting appropriate GenAI tools and technologies for

- Text generative tools (ChatGPT, Claude, Google Gemini, etc.)
- Generative tools for visual content (Midjourney, DALL·E, Adobe Firefly, Canva AI)
- GenAI platforms for prototyping (Framer AI, Figma AI, Sketch AI)
- GenAI automation systems and data analytics (Zapier, Microsoft Power Automate, Airtable AI, Notion AI)

Stage 3. Structuring the GenAI implementation process, responsible for

- Defining business goals what is expected from GenAI.
- Technical integration by using GenAI tools into existing business processes and systems.
- Staff training of teams for effective use of GenAI tools.

Stage 4. Risk management and ethical issues, responsible for

- Cybersecurity and data protection by creating privacy and security policies and Using secure GenAI platforms and providers.
- Copyright and intellectual property by clarifying rights to GenAI-generated content.
- Ethical use of GenAI by avoiding the generation of misleading content and reducing the risks of bias.

Stage 5. Measuring results and optimizing by

- Key Performance Indicators (KPIs) by defining clear criteria for the success of GenAI applications.
- Continuous improvement by regular analysis and optimization of the results generated by GenAI.
- Iterative feedback from users and teams to improve GenAI applications.

Stage 6. Scaling and expanding the use of GenAI with

- Creating new business models by developing products or services based entirely on GenAI.
- Expanding solutions to new markets by using GenAI to adapt content and communication to international audiences.
- Building competencies as a competitive advantage by creating internal expertise for working with GenAI and training new specialists in the field.



Figure 1. A Framework for using GenAI in Entrepreneurship.

5. Conclusion

Generative Artificial Intelligence (GenAI) is a transformation force in modern entrepreneurship and innovation. With its ability to create original content, such as text, images, audio and video, the GenAI provides new opportunities for automation, personalization and optimization of business processes [45]. It accelerates the generation and validation of new ideas, creates new professional roles and opens new market niches. This conceptual paper has clarified the role of GenAI in the entrepreneurship development, focusing on the main opportunities, challenges and prospects for its application. The key contributions consist in defining a clear framework for integrating GenAI into entrepreneurial practice, as well as in identifying specific technologies. The paper has examined in detail the new professional roles and market niches that arise as a result of GenAI integration, including the acceleration of the innovation cycle and the automation of processes. The potential risks, such as ethical dilemmas, copyright protection and cybersecurity, have also been clearly identified, and specific approaches to their management have been proposed. The paper offers a practical guide for entrepreneurs, allowing them not only to effectively use GenAI, but also to minimize the risks associated with it. All this said makes GenAI a powerful tool for increasing competitiveness, innovation and global accessibility of entrepreneurial opportunities.

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Convergence of Generative Artificial Intelligence and Extended Reality for Real Estate Business Innovation

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Abstract. The combination of Generative Artificial Intelligence (GenAI) and augmented reality (XR) technologies opens up new opportunities for innovation in the real estate business. GenAI provides automated predictions and personalized recommendations, while XR provides interactive virtual experiences. These technologies are revolutionizing old business models and offering new ways to connect with customers, manage properties, and optimize investments. These innovations will create new business opportunities, but will also require new approaches to governance, data protection, and social impacts. The purpose of this conceptual paper is to explore the issues of the convergence of GenAI and XR and to propose a conceptual framework for real estate business innovation.

Keywords. Real Estate, Innovation, Business, Generative AI, Extended Reality

1. Introduction

Real estate is one of the oldest investment sectors, playing a central role in economic development and socio-cultural processes. Real estate can be residential, commercial, industrial or agricultural and it includes a wide range of activities: purchase, sale, rental, management and investment in properties [1]. Real estate is always perceived as a stable and conservative investment, associated with long-term assets and slow market cycles [2, 3]. However, globalization, urbanization and digitalization are changing the dynamics of the market. Customers today expect greater transparency, flexibility and immediate satisfaction of their needs. They are looking for digitalized processes, access to virtual tours, automated financial assessments and the ability to conclude deals remotely.

The real estate industry has traditionally been slow to introduce innovations, but in recent years, we have witnessed significant technological advances. Startups, partly supported by new technologies, have begun to introduce virtual tours, automated property valuations, and analytics based on big data [4]. As consumer demands for faster, more personalized and more intuitive experiences grow, the real estate industry is

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gradually introducing innovations such as artificial intelligence, augmented and augmented reality, and automated property management systems. These processes are laying the foundations for new business models that are expected to dominate the future.

A new generation of companies is developing automated property management platforms, blockchain-based solutions for ownership transparency, smart leases, and dynamic pricing systems. All of this leads to more efficient business processes and better satisfaction of customer needs. At the same time, large investors and institutions are starting to apply sophisticated analytical models to predict property value and risk, using data from multiple sources - demographic, economic, and environmental. This is leading to an increasing demand for technologies like GenAI and XR, which can create detailed simulations and predictions [5, 6].

Despite the rapid development of GenAI and XR, there is a lack of in-depth research on their joint integration in the real estate business. Most existing studies focus separately on technological aspects or customer experiences, but do not analyze how these technologies work together in a real estate environment. The effects business models, operations, and long-term sustainability that have not been sufficiently studied. This gap limits the strategic adoption of the convergence between GenAI and XR and the opportunities for innovation in the industry.The purpose of this conceptual paper is to explore the issues of the convergence of GenAI and XR and to propose a conceptual framework for real estate business innovation.

2. Introduction to Generative Artificial Intelligence and Extended Reality

Generative Artificial Intelligence (GenAI) and Extended Reality (XR) are two of the most promising technological trends that are radically transforming various industries, including real estate [7]. To understand their potential, it is necessary to examine the foundations of these technologies and way they work.

GenAI is a field of artificial intelligence that focuses on creating new content based on trained models and analysis of existing data. GenAI can efficiently create texts, images, music, code, designs, 3D environments. This can be original and adaptive output. The technologies that make up GenAI include [8, 9]:

- Deep Learning — especially neural networks such as transformers, which allow processing of huge amounts of data.
- Generative Adversarial Networks (GANs) — an architecture consisting of two competing models – a generator" and a - that create extremely realistic content.
- Variational autoencoders (VAEs) and other deep models for reconstructing and creating new data.
- Large Language Models (LLMs) such as GPT, which generate text that mimics human writing.

The key components of Generative AI include [10]:

- Data Modeling: GenAI learns from large amounts of data by analyzing and identifying patterns in that data.
- Content Generation - Once AI is trained to understand patterns in data, it can generate new content.

- Forecasting and Optimization - by generating predictions of future market trends, GenAI can help investors make more informed decisions by providing them with predictions of property values in specific areas.
- Personalization of Experiences - GenAI can create personalized recommendations for users, based on their past actions, interests, and their online behavior.
- GPT models (Generative Pre-trained Transformers), which are used to process text information and GANs, which create realistic images, find can practical applications in many industries.

Extended Reality(XR) brings together a variety of technologies that combine physical and virtual reality, giving users the ability to interact with existing and created virtual elements in engaging formats. XR includes Virtual Reality (VR) and ExtendedReality (AR) [11, 12].

VR creates a fully artificial environment that is simulated by a computer [13]. Users can immerse themselves in this environment through VR headsets and interact with the elements within, giving them the feeling of being physically present in a given space.

AR combines the real world with virtual elements that are superimposed on the physical environment [13, 14]. The ability to visualize digital elements in real space is changing the way users perceive and interact with the surrounding environment.

3. The Convergence of Generative AI and XR in Real Estate Business

GenAI and XR are forming the foundation of a new epoch in real estate business. Their convergence opens countless possibilities for innovation, which can create new ways to interact with the market, improve user experiences and optimize business processes. Some of the most innovative models include [15]:

Personalized Recommendations and Virtual Tours - One of the main benefits of using GenAI in real estate is the ability to analyze huge volumes of data and generate personalized property recommendations based on user preferences and behavior [16, 17]. GenAI can take into account factors such as budget, location, property size, residential or commercial property type and other specific requirements to generate a list of properties that best match the client's needs. XR can add a new dimension to these recommendations by allowing users to explore selected properties through immersive virtual experiences. When GenAI generates a list of recommended properties, a user can use VR tours to view the properties remotely without having to physically visit them. These virtual tours provide a sense of reality by allowing users to walk through the properties and get a detailed look at the interiors and exteriors. Users, by using AR, can add digital elements to the real space, such as furniture or decorative elements, allowing them to visualize how different interior design styles would look in specific properties. This creates a personalized experience that increases user engagement and satisfaction.

Automated generation of design solutions - GenAI can analyze data about user preferences, such as color schemes, furniture styles, space layouts, and automatically generate multiple design suggestions that match specific requirements [18, 19]. These generated designs can be visualized through XR in real time in 3D, allowing users to interact with them. User, by using AR, can see how different furniture or decorations would look in their real home simply by pointing their mobile device at a specific room

or space. All this allows users to make informed decisions about the visualization and arrangement of the space before making the final choice. GenAI can also suggest new design options based on trends in interior design, automatically adapting the styles and colors of the property, taking into account the latest fashion trends or the user's preferences. XR can help those suggestions be visualized and tested in real conditions, while providing feedback and suggestions for improvements.

Visualizing future trends and market forecasts - GenAI can play an important role in predicting market trends by analyzing historical data on property prices, rental levels, economic indicators in different regions [20]. GenAI can generate forecasts for the future development of real estate markets, which is a valuable information for investors, buyers and tenants. These forecasts are used to make informed decisions about buying or renting properties, as well as to assess the long-term potential of specific areas. On the other hand, XR can add a visual dimension to these forecasts by showing users what specific areas or sites will look like in the future, after undergoing the changes predicted by Generative AI. Users, by using AR, can see how a given neighborhood will develop in the coming years, as new buildings or infrastructure projects are added. This provides a visual representation of the future of a given location and helps users make better-informed choices about buying or renting a property.

Price Predictions and Smart Pricing - GenAI can be used for dynamic property pricing too. By analyzing data on demand, supply, and market conditions, GenAI can predict how property prices will change across different geographic regions or market segments [21]. These predictions can help investors and real estate agents make more informed decisions about pricing strategies and optimize their listings. With the help of XR these price predictions can be visualized in an interactive way, such as in 3D property visualizations that show how prices for specific properties change over time or how various external factors may affect the value of a property. These visualizations help users understand the complexity of market conditions and make decisions based on predictions that provide them with a better understanding of the future.

Interactive Real Estate Buying and Renting Platforms – there exists an opportunity to create new interactive real estate platforms that leverage both GenAI and XR technologies [22]. GenAI can create personalized property listings based on user preferences, while XR can enable interactive virtual tours and visualizations of those properties. Platforms can offer users the ability to browse properties, customize them, and receive automated suggestions for improved deal terms, with GenAI analyzing market demand and supply data.

Shift to Flexible Leases and Co-working - Virtualization and automation technologies are also driving changes in the rental and use models of spaces. The trend for flexible leases and co-working spaces is starting to gain popularity as part of this shift in real estate business models [23]. GenAI and XR offer new opportunities to create flexible lease models, where tenants can choose different terms, such as lease terms, number of workstations, furnishings, etc. These technologies can help property owners analyze what terms attract the most customers and what are the most effective solutions for optimizing spaces. Co-working spaces are becoming increasingly popular and XR can play a key role in creating virtual spaces that provide the opportunity for remote collaboration and interaction between tenants. The GenAI and XR can offer virtual meetings and work sessions that create a sense of physical presence and interaction, while reducing the need for a physical presence in the workplace.

Digital Twins and Predictive Analytics - Digital twins of buildings and infrastructure projects will become standard due to GenAI and XR [24, 25]. They will allow simulations of future use, risk assessment, energy consumption and long-term maintenance. These analyses will be an indispensable tool in evaluating investment opportunities.

4. Challenges and Limitations of the Convergence between Gen AI and XR

The convergence of GenAI and XR provides new opportunities for the real estate business, while also posing new questions and challenges that need to be overcome. While the technologies themselves offer significant benefits, their synergy may encounter certain barriers and limitations in the process of integration, adaptation and use. Lowering these obstacles requires strategic thinking, innovation and optimization in a number of aspects of technology and organizational processes.

High initial implementation and maintenance costs are the main challenges in implementing GenAI and XR in the real estate business [26]. In order to integrate these technologies into business operations, companies must invest in modern computer systems, as well as in staff training, which is time-consuming and expensive. Companies must allocate funds to create specialized XR platforms and GenAI algorithms that meet their specific needs. GenAI requires large volumes of data and powerful processors that can handle these calculations. Developing personalized models that generate accurate predictions and recommendations for properties requires significant investments in data analysts, machine learning engineers, etc. On the other hand, implementing XR requires the purchase of devices such as VR helmets, AR technologies, 3D scanners and cameras, which are also expensive and require regular maintenance. These implementation costs can be a major barrier for small and medium-sized businesses that do not have sufficient budget for long-term investments in new technologies. For many companies in the real estate business, there is a risk that they will not be able to restore the initial investment if the implementation of these technologies does not lead to significant short-term gains.

Technological limitations and integration complexity can hinder the successful integration of both technologies in the real estate business. GenAI, as mentioned already, requires huge volumes of data and can have difficulties in processing irregular or incomplete data [27]. If data about a given property or market conditions is insufficient or inaccurate, algorithms can generate inaccurate forecasts or recommendations, leading to errors in decision-making processes. XR also faces a number of technological challenges since it requires the use of high-end hardware and software that provide smooth visualizations and realistic 3D tours of properties. Some of these devices can be unsuitable, which can lead to dissatisfaction among users who are not used to such technologies. The creation of quality XR applications requires a significant level of specialization and extreme precision in graphic design and programming. The convergence of GenAI with XR in real estate requires both expertise and time. Many companies still use old technologies and processes that are difficult to be compatible with innovations. This leads to additional technical difficulties when trying to synchronize different systems, which slows down processes and increases the risks of errors.

Data confidentiality and security issues - can include issues about information about previous property transactions, personal data of users, rental and sales history, forecasts of future market trends [28]. While this data can provide valuable insights, its

collection and processing raises serious questions about the confidentiality and security of personal information. Real estate includes sensitive data about customers, property owners, and other stakeholders, which, if not properly protected, can be at risk of misuse. Cyber threats and hacker attacks can compromise both the data itself and the entire infrastructure of the business [29, 30, 31] Therefore, companies must implement modern data protection technologies and ensure full compliance with local and international data protection laws, such as GDPR. On the other hand, the virtualization and 3D visualization processes of properties can require high-quality images and information about spaces, which can also fall into the category of sensitive data. If not managed properly, these images and data can be used improperly, such as to create false advertisements or fraudulent practices.

Compatibility and Standardization Issues could pose other problems in the convergence of GenAI and XR [32]. The virtualization technologies still lack unified standards for content creation and property presentation, leading to differences in the quality of virtual tours and interactive experiences. These differences can create confusion among users and make it difficult to compare different properties.

5. A Conceptual Framework for the Convergence of Generative AI and XR in Real Estate Business

A conceptual framework for the convergence of GenAI and XR for innovation in real estate business is proposed [33, 34, 35, 36]. It represents an integrated system of technologies that connects data collection, automatic analysis and 3D visualization to create new business models in the real estate sector. Fig. 1 shows the conceptual framework.

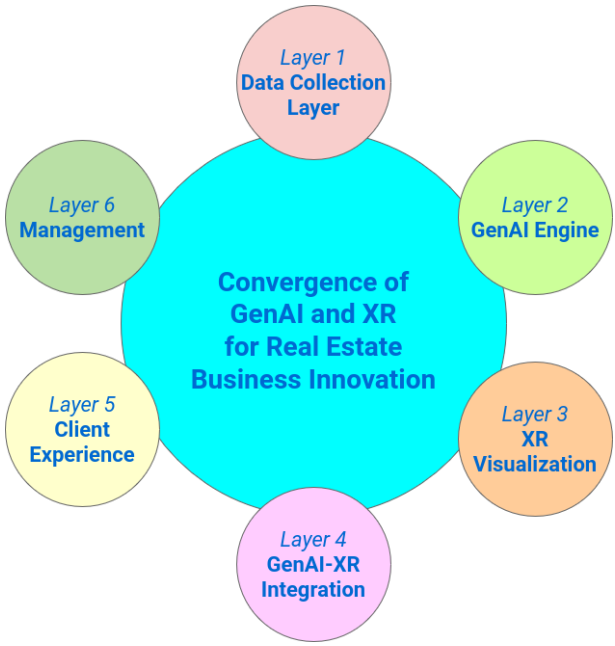


Figure 1. A conceptual framework for the convergence of GenAI and XR

The key components of the model include the following layers:

Layer 1: Data Collection - GenAI collects property data (descriptions, plans, photos, video, market data), while sensors and XR devices collect spatial data about objects in real time.

Layer 2: GenAI Engine - Generates personalized property visualizations, predictive price and sustainability analyses, virtual reconstruction scenarios. It trains on real transactions and user behavior.

Layer 3: XR Visualization - Creates 3D virtual tours, virtual reconstructions, modeling of future projects. It enables interaction in real or mixed environments.

Layer 4: GenAI-XR Integration Core - connects GenAI to XR environments in real time and adapts visualizations based on customer behavior and reactions.

Layer 5: Client Experience Silo - Personalized customer choices, such as virtual selection, automated recommendations, and renovation simulations. It also collects feedback to improve the model.

Layer 6: Management - Displays real-world customer engagement data, market forecasts, property performance.

Such a framework can help achieve a better personalized user experience, rapid automation of investment decisions, real estate optimization, dynamic market forecasting, and sustainable digital real estate development.

6. Conclusion

The convergence of GenAI and XR marks new opportunities for innovation in real estate business. These technologies are not only digitizing traditional processes, but also creating entirely new business models that meet modern customer needs for personalization, speed, and interactivity. Personalized virtual tours, GenAI-based investment forecasting, digitalized property management, and virtual sustainable construction projects are the beginning. Businesses that successfully integrate GenAI and XR into their strategies will gain a competitive advantage and be able to offer services on a higher level to the market. Nevertheless, this transformation requires active adaptation, technological investments and strict adherence to ethical standards. The convergence of GenAI and XR paths the way to innovations to create better customer experiences, optimize operations, and a sustainable foundation for growth in an increasingly competitive world.

The results of the study can be summarized as:

- Key findings in the convergence of GenAI and XR state a significant technological shift for the real estate industry. It is transforming the customer experience, improving the efficiency of business operations, and creating new opportunities for personalization and automation.
- The management implications state that leaders in the sector should strategically invest in building digital infrastructure, training staff and developing GenAI-XR platforms. Implementing this type of technology requires a visionary approach, adaptability and cross-functional collaboration.
- The study limitations are that the current analysis is conceptual and based on secondary sources. Empirical data from real business cases and practical

implementations are lacking, which limits conclusions about the effectiveness and applicability of the framework in different market contexts.

- The future research directions state that empirical research on real projects for converging GenAI and XR in the real estate sector is needed. The economic, social and ethical aspects of this transformation should be explored and methodologies developed to measure its impact on business value and customer satisfaction.

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From Data Silos to FAIR Research: Interoperability and Integration in European CRIS

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Abstract. Current Research Information Systems (CRIS) play a pivotal role in the management, storage, and dissemination of research data, serving as key components within both national and international research infrastructures. Scientific and academic libraries, with their established expertise in resource description, access facilitation, and the long-term stewardship of digital assets, are instrumental in the implementation and operation of CRIS systems. This article examines the integration of the FAIR principles—Findability, Accessibility, Interoperability, and Reusability—within CRIS systems, emphasizing their contribution to supporting Open Science. Through case studies from both Slovakia and Germany, we investigate the implementation of FAIR principles in the national SK CRIS and the German CRIS systems. The article also addresses the critical importance of data source integration, the adoption of Persistent Identifiers (PIDs), and the implementation of robust data management practices as essential elements for advancing Open Science and ensuring the effective application of FAIR principles at the national level. This analysis underscores the crucial role of libraries and CRIS systems in enhancing the accessibility and interoperability of research data, fostering international collaboration, and ensuring the long-term sustainability of scientific outputs.

Keywords. CRIS, FAIR principles, interoperability, open science, data integration, persistent identifiers (PIDs), data management, libraries, national research infrastructures, case study.

1. Introduction

The effective management and dissemination of research data are crucial for scientific progress. A current research information system (CRIS) is a database or other

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information system to store, manage and exchange contextual metadata for the research activity funded by a research funder and/or conducted at a research-performing organisation [1]. The CRIS comprise software solutions that merge research information from different sources and databases in order to describe and report on research.

CRIS serve as essential components in research information infrastructures by enabling the systematic collection, organization, and accessibility of research outputs. These systems function as local and national nodes within broader research ecosystems, ensuring structured and interoperable access to scientific information [2,3]. In the context of Open Science, CRIS play a vital role in facilitating transparency, reproducibility, and knowledge exchange [4].

Academic and research libraries have traditionally been responsible for metadata curation, resource description, and long-term digital stewardship [5]. Given this expertise, libraries are instrumental in managing CRIS and ensuring adherence to best practices for research data management. The implementation of the FAIR (Findability, Accessibility, Interoperability, and Reusability) principles [6] within CRIS is fundamental to improving data discoverability, accessibility, and usability on national and international levels. However, achieving FAIR compliance in CRIS requires robust data governance, integration of Persistent Identifiers (PIDs), and the harmonization of metadata standards across institutional and national boundaries [7].

In Europe, several national CRIS initiatives have been developed to align with FAIR principles and support Open Science policies. The Slovak Current Research Information System (SK CRIS) provides a national framework for research data integration, focusing on metadata standardization and persistent identifiers to enhance interoperability. Similarly, Germany has implemented FAIR-aligned infrastructures within the National Research Data Infrastructure (NFDI), particularly in domains such as health and social sciences [8]. These efforts reflect a broader movement toward structured research data management at the national level, supporting both institutional reporting and international collaborations.

This paper aims to examine the role of FAIR principles in CRIS implementation, emphasizing the necessity of data integration, metadata interoperability, and persistent identifiers in supporting Open Science. To achieve this, we employ comparative case studies of CRIS implementations in Slovakia and Germany:

- Case Study: Slovakia – Analyzing the integration of FAIR principles in SK CRIS, particularly in terms of persistent identifiers, metadata alignment, and national Open Science policies.
- Case Study: Germany – Examining FAIR adoption within German CRIS frameworks, focusing on the NFDI initiative, data stewardship practices, and interoperability with European Open Science Cloud (EOSC).
- Comparative Analysis – Identifying best practices, challenges, and lessons learned from both national implementations to provide recommendations for FAIR-compliant CRIS development.

2. Interoperability in CRIS Systems: Foundations, Dimensions, and Strategic Implications

Interoperability is a fundamental requirement for the effectiveness, scalability, and sustainability of CRIS, particularly in the context of Open Science and data-driven

research policy. As CRIS platforms serve as integrative nodes within a fragmented research information ecosystem, their ability to interoperate with both internal and external data sources is critical for ensuring consistent, reliable, and reusable research metadata [5,9]. Achieving such interoperability, however, is contingent upon the fulfilment of several interrelated technical, semantic, and organizational conditions, each of which contributes to the broader objective of systemic coherence across heterogeneous infrastructures.

A cornerstone of interoperability in CRIS systems is the implementation and resolution of Persistent Identifiers (PIDs). PIDs such as DOIs (Digital Object Identifiers) for publications and datasets, ORCID iDs for researchers, and RORs (Research Organization Registry) for institutions serve as globally unique identifiers that anchor CRIS metadata in an ecosystem of linked open data [10,11]. The consistent and mandatory use of such identifiers ensures that entities within the CRIS—authors, institutions, outputs—can be unambiguously referenced across systems, thereby enabling findability, data deduplication, and cross-platform data reuse. Without this infrastructural layer of machine-resolvable identifiers, semantic alignment and reliable data federation across CRIS and external services would be significantly impeded.

Another foundational element of CRIS interoperability lies in the creation and maintenance of authoritative records, also referred to as "gold records" or authority files. These are curated, validated, and disambiguated metadata records that serve as canonical representations of key research entities (e.g., individual researchers, organizational units, research outputs). Authority records are essential not only for internal consistency within a CRIS but also for enabling semantic interoperability with external systems [12]. For instance, a disambiguated researcher profile in a national CRIS can be automatically reconciled with records in ORCID or Crossref via standardized metadata fields and PIDs. This reduces data fragmentation and strengthens trust in the provenance and accuracy of research information across platforms.

Beyond identifiers and authority records, interoperability also demands semantic and syntactic alignment with external reference registries and classification schemes. This includes the alignment of CRIS data models with widely accepted ontologies and schemas, such as CERIF (Common European Research Information Format) or schema.org, as well as mappings to domain-specific vocabularies. Such alignment enables CRIS platforms to exchange data with reference registries, particularly in the domains of organizations, projects, and persons, where shared classification systems (e.g., ISCED, NACE) enhance data harmonization across national and disciplinary boundaries [13,14].

A particularly critical layer of interoperability involves content-related systems, notably publication and citation databases (e.g., Scopus, Web of Science), full-text repositories (e.g., institutional repositories, arXiv), and research data repositories (e.g., Zenodo, Figshare). CRIS platforms must be able to both ingest data from and export data to these systems via standard interfaces such as OAI-PMH, RESTful APIs, and Linked Data endpoints. Bidirectional integration enables not only the enrichment of CRIS metadata with citation counts, usage statistics, and full-text access links but also supports the export of curated CRIS data to external aggregators, thus reinforcing Open Access dissemination and research impact monitoring.

A comprehensive approach to interoperability in CRIS systems, therefore, involves more than just technical compatibility. It demands a strategic alignment of infrastructures, standards, and policies to facilitate seamless, sustainable, and trustworthy data exchange. Only through such alignment can CRIS fulfill their role as reliable intermediaries in the

global research information landscape and support emerging frameworks such as the European Open Science Cloud (EOSC) or national research assessment exercises.

3. Integration of Data Sources in CRIS

The effective integration of heterogeneous data sources into CRIS is a foundational requirement for achieving both operational efficiency and compliance with the FAIR principles (Findable, Accessible, Interoperable, Reusable). In practice, data integration refers to the systematic collection, harmonization, and continuous updating of research-related information from a diverse range of institutional, national, and international sources. These sources include internal university repositories, project management systems, external bibliographic and citation databases (e.g., Scopus, Web of Science), funding agency databases, and research infrastructure services such as ORCID, ROR, and Crossref [2,15].

A central aim of this integration process is the establishment of authoritative "single points of truth" — high-quality, validated, and de-duplicated information records that minimize inconsistencies and redundancies across systems. This is achieved through the use of authority files, controlled vocabularies, and PIDs, which are essential for the unambiguous identification and linking of research entities such as people, organizations, publications, and datasets. The most widely adopted PIDs include DOIs for publications and datasets (DataCite, Crossref), ORCID iDs for individual researchers, and ROR IDs for research-performing institutions [16].

Figure 1 illustrates how various sources—such as institutional repositories, bibliographic databases, funding agency platforms, and PID services—interface with a central CRIS system using standardized protocols (e.g., OAI-PMH, REST APIs). Persistent identifiers act as connective tissue between distinct entities.

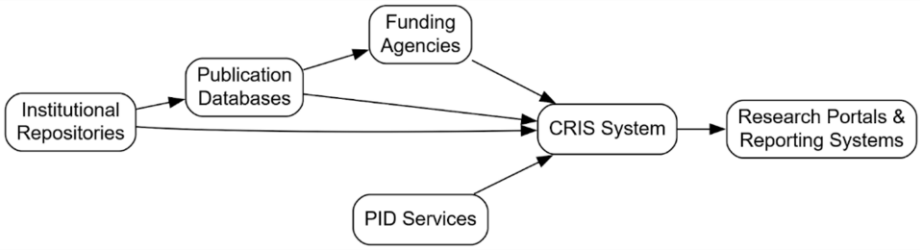


Figure 1. Example of Data Flow into a National CRIS System.

Integrating these data sources into a CRIS not only enables a comprehensive and reliable aggregation of research outputs, but also facilitates advanced functionalities such as automated reporting, Open Science monitoring, and participation in supra-national infrastructures such as the EOSC. Harmonization with external systems through standard data models (e.g., CERIF) and metadata schemas ensures semantic interoperability, which is vital for cross-system data reuse and analytics [17,18].

Despite these clear benefits, the integration of data sources into CRIS environments remains a complex and challenging endeavor. One of the foremost issues is the variability in metadata quality and formatting across data sources. Institutional repositories, bibliographic databases, and national registries often use divergent metadata schemas and terminologies, making semantic alignment and data normalization a non-

trivial task. This heterogeneity can significantly hinder interoperability and reduce the overall reliability of aggregated data [19].

A further complication arises from legal and technical restrictions on data sharing, especially in the case of commercial data providers such as Scopus and Web of Science. Licensing agreements may limit the extent to which data can be ingested into CRIS systems or re-used in other contexts, posing a substantial barrier to openness and data sovereignty. Moreover, technical restrictions, such as the absence of standardized APIs or limitations on harvesting frequency, further complicate automated integration workflows.

Another persistent challenge is the inconsistent adoption of persistent identifiers and metadata standards across institutions and regions. While initiatives like ORCID, DataCite, and ROR have made significant strides toward universal adoption, gaps remain—particularly among smaller institutions or in certain disciplinary fields. Without the systematic application of PIDs, linking and deduplicating entities becomes error-prone and inefficient, undermining the promise of data unification across systems [16].

Finally, CRIS systems face high demands for data curation and validation, especially at the point of ingestion. The integration process is rarely automatic or fully error-free; instead, it requires ongoing human intervention to resolve ambiguities, correct metadata errors, and ensure consistency with internal standards. This manual effort is resource-intensive and may be underestimated during CRIS implementation planning [19]. Consequently, institutions must invest in both technical infrastructure and skilled personnel to support high-quality data integration processes.

In light of these challenges, successful CRIS integration strategies often rely on a combination of technological interoperability, institutional collaboration, and policy alignment. National CRIS initiatives, such as SK CRIS in Slovakia or Germany's involvement in the NFDI, demonstrate that overcoming these barriers is possible through coordinated governance frameworks, adoption of shared metadata standards, and investment in long-term sustainability mechanisms.

4. FAIR-by-Design: Integrating FAIR Principles Natively into CRIS Architectures

While the integration of FAIR (Findable, Accessible, Interoperable, Reusable) principles into CRIS has been broadly acknowledged as essential for advancing Open Science [6,20], existing approaches predominantly focus on retrofitting FAIR compliance onto legacy systems and existing data structures. This reactive approach often requires significant human and technical resources for metadata curation, mapping, and validation, and is inherently constrained by legacy formats and system limitations [7]. In contrast, the concept of FAIR-by-Design advocates for a proactive and systemic integration of FAIR principles directly into the architectural and functional foundations of CRIS platforms [21]. Rather than treating FAIRness as an external or evaluative layer, this paradigm proposes embedding FAIR compliance mechanisms into the core workflows and data ingestion pathways of CRIS.

The FAIR-by-Design approach redefines CRIS not as passive aggregators of research metadata, but as active agents in the production of FAIR-compliant research ecosystems. Concretely, this involves the implementation of structured metadata templates that dynamically adapt based on the type of research object (e.g., publication, dataset, project, infrastructure), disciplinary standards, and repository-specific

requirements. These templates enforce minimum metadata quality thresholds at the point of entry and promote the use of PIDs such as ORCID iDs, DOIs, and RORs through automated validation and resolution services embedded within the CRIS infrastructure. By making FAIRness a condition of successful data registration, CRIS systems become engines for data quality rather than consumers of external quality assurance tools [7]. A Figure 2 illustrating this FAIR-by-Design architecture is shown below, emphasizing the role of real-time feedback and automated metadata templates in ensuring FAIRness throughout the CRIS system.

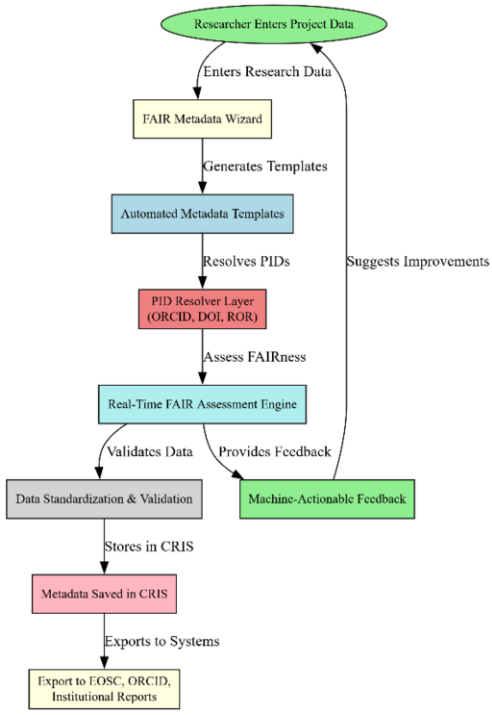


Figure 2. FAIR-by-Design Architecture for CRIS Integration.

Furthermore, a FAIR-by-Design CRIS architecture includes real-time FAIRness assessment mechanisms that offer immediate, machine-actionable feedback to data providers. Such systems may implement visual scoring indicators or automated diagnostics to identify missing metadata elements, incompatible formats, or licensing gaps. This not only supports better metadata practices among researchers but also enables institutions to monitor and benchmark FAIR compliance across departments and disciplines over time. Additionally, machine-actionable metadata facilitates seamless interoperability with transnational infrastructures such as the EOSC and enables CRIS systems to act as certified data providers within wider research data commons.

The implications of this architectural shift are significant. Firstly, it reduces the downstream workload of data curators and CRIS administrators, as compliance is achieved upstream. Secondly, it promotes metadata completeness and standardization at scale, enhancing the discoverability and reusability of research outputs. Lastly, it positions CRIS systems as key enablers of policy-driven Open Science, capable of supporting national and institutional mandates for FAIR data stewardship. While the concept of FAIR-by-Design is still in its infancy and largely absent from current

academic discourse, its theoretical promise lies in its ability to operationalize FAIR principles as system logic rather than aspirational goals.

A future research agenda must address the technical and organizational preconditions for implementing FAIR-by-Design CRIS, including the development of discipline-specific metadata ontologies, automated PID resolution layers, and machine-learning models for metadata suggestion and validation. Moreover, ethical considerations surrounding mandatory metadata completeness and researcher autonomy must be critically evaluated. Nevertheless, the transition from FAIR-compliant to FAIR-native CRIS infrastructures may constitute a pivotal step toward sustainable, scalable, and policy-aligned research data ecosystems.

5. Challenges and Opportunities for Open Science

The transition toward Open Science is not merely a technical transformation—it is a systemic shift that requires cultural, institutional, and policy-level realignments. One of the major challenges lies in the fragmentation of accountability and responsibility across stakeholders in the research ecosystem. While PIDs have become standard for individuals, publications, and institutions, the granular and consistent linkage of research projects to their respective outputs and contributors remains incomplete in many systems. Without reliable attribution at the project level, assessing societal impact or calculating "value for money" becomes difficult. This gap presents an opportunity: by embedding project-level PIDs and metadata into national and institutional workflows, a more complete and transparent view of the research lifecycle can be achieved.

Another systemic challenge is the lack of harmonized workflows across institutions when it comes to data curation and metadata management. Even where technical interoperability exists, divergent practices regarding metadata quality, completeness, and validation impede effective data reuse and policy monitoring. Instead of focusing solely on unifying standards, incentivizing local practices that align with shared reference models—and making tools for metadata generation more usable—could accelerate convergence organically. Particularly underexplored is the potential of automated metadata enrichment, driven by AI tools, to bridge local variations and improve standard compliance without increasing researcher workload.

At the institutional level, a further opportunity lies in embedding Open Science goals into research evaluation and funding mechanisms. Too often, open data practices are treated as optional or auxiliary to traditional publication outputs. By integrating Open Science criteria into grant assessments, promotion criteria, and institutional audits, compliance can evolve into commitment. This, however, requires not just policy reform but also capacity-building—especially in smaller institutions that may lack the resources to develop advanced CRIS or data stewardship teams.

Lastly, Open Science efforts are often constrained by asymmetric access to infrastructure. Countries and institutions with limited digital infrastructure face disproportionate challenges in implementing FAIR principles or maintaining interoperable CRIS systems. A coordinated European effort—similar to existing models in the EOSC—could focus on shared service centers that provide technical back-ends, training, and certification services to under-resourced institutions, thereby reducing the digital divide in research information management.

In sum, while the conceptual framework for Open Science is well articulated, its operationalization depends on overcoming structural, social, and economic barriers. The

integration of PIDs, better metadata workflows, and equitable access to infrastructure are not just technical enhancements—they are foundational to achieving the inclusive, transparent, and reproducible research ecosystem that Open Science envisions.

6. Case Studies from Slovakia and Germany: SK CRIS and German CRIS Systems

In Slovakia, we are aware that the concept of the CRIS system is to provide comprehensive information about science and research at the national, departmental, and institutional levels. As part of the research, we sought answers to several questions:

- Why is a scientific/academic library a suitable operator of science support systems, including the CRIS system?
- What conditions have to be met to integrate information systems for science support?
- How do we address the issue of science support in Slovakia, with an emphasis on the integration of resources (science support systems) and the implementation of FAIR principles?

Research information comprises data on a research institution's (scientific) staff and structure, projects, third-party funding, publications, patents, etc. The efficient processing of institutional research information in higher education and research institutions is a complex task, which involves the implementation and use of the CRIS system [22]. High-quality data about research activities and processes (research information) are of strategic relevance for both science communication and for research governance and policy.

The CRIS system is often operated by scientific and academic libraries. The role of libraries in this area is based on the fact that libraries have a strong tradition in describing resources, providing access and building collections, and providing support for the long-term stewardship of digital resources [23].

The Slovak Centre of Scientific and Technical Information (SCSTI) is a subsidiary organization (public body) of the Ministry of Education, Research, Development, and Youth of the Slovak Republic. SCSTI is the national information center for science, technology, innovation, and education, and a specialized scientific library of the Slovak Republic. It coordinates activities and ensures the operation of interdisciplinary R&D centers and national infrastructures for research, development, innovation, and education.

The SCSTI's main roles and activities are as follows:

- National information center and specialized scientific library of the Slovak Republic
- Operation of specialized portals and systems for research and higher education
- Promotion of technology transfer and innovation
- Popularization of science and technology
- Support of Slovakia in international research cooperation
- Implementation of national and international projects in research, development, and education

Comprehensive experience in supporting science and education with an emphasis on operating information systems at the national level, including data curation, predetermines SCSTI to play the role of an implementer of the FAIR and open science principles in the processing of research information.

In Slovakia, we focus on the implementation of unique identifiers, data management, and metadata quality control, as well as the integration of various data sources into larger infrastructures with the character of research infrastructures. The goal is to use the collected data not only at the national level but also to provide it for international comparison as part of research infrastructures.

Several significant milestones in this area have been achieved in the recent past:

(1) Deployment of the new Information System for Research and Development SK CRIS
(2) Deployment of a Comprehensive Information System for Acquiring, Processing, Storing, and Making Available Scientific and Bibliometric Data and Publications and Ensuring Access to Tools and Applications for Supporting Science and Research (KOMIS)
(3) Joining the EOSC network as a national EOSC Node

6.1. SK CRIS Information System

The information system SK CRIS, which has been in operation since 2013, is updated annually with data on research activities, entities, results, and infrastructures at the national level. The system has recently undergone a significant functional and design upgrade, especially a technological one, and has been operating in a new version since the summer of 2024.

It was built in accordance with the standards and best practices of research information in the EU. In addition to the CERIF relational data format, which allowed us to record links between basic objects, we also implemented open science and FAIR principles for the collected data. It is also important to follow standards for PIDs with an emphasis on EOSC compatibility [24].

In addition to the new design, the SK CRIS information system has the following new features after the upgrade:

(1) Implementation of the ID federation for researchers: The offer includes internationally used PIDs, namely ORCID, ResearcherID, and SCOPUS ID, as well as the national identifier of university teachers (ID from the University employee register). These IDs are currently entered manually by users.

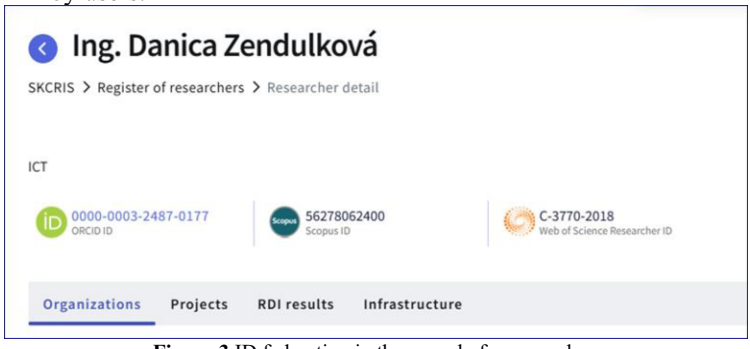


Figure 3 ID federation in the record of a researcher.

(2) Integration with the Register of Legal Entities (RPO): The integration uses PID for an organization at the national level, namely the Organization Identification Number - IČO. The RPO is a reference register. This integration allows obtaining data on organizations into SK CRIS based on the IČO check. The "once is enough" principle is applied, meaning users do not have to enter data that already exists in the RPO.

(3) Expansion of registered data for research results with DOI and URL of the full text of the publication.

(4) Extended user interface options for searching, including multi-criteria search, allowing simultaneous selection of multiple code list items and adding combined search of basic objects (projects by organization and researcher).

6.2. KOMIS – The National Research Infrastructure

The created national research infrastructure KOMIS aggregates science support systems operated by SCSTI and makes available the services of the Data Centre for Research and Development (DC VaV). This includes the use of storage capacity, data processing, and the use of various installed software (Software as a Service - SaaS), mainly from the fields of mathematics, statistics, and bioinformatics. The solution includes analytical tools for data processing and a module for searching available data and information sources.

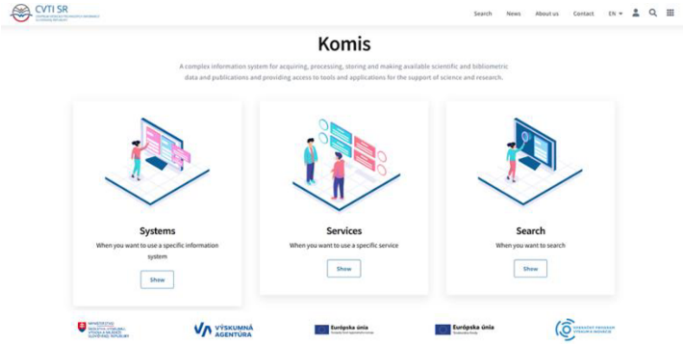


Figure 4 The KOMIS system – main webpage.

The KOMIS integrates several systems:

- **The Slovak Current Research Information System (SK CRIS)** and **The Central Information Portal for Research, Development, and Innovation (CIPVVI):** The CIPVVI website represents one of the basic information, management, and control tools of the state scientific and technical policy. It provides information on science, research, and innovations supported by public resources.
- **The Central Registry of Publications of Universities in the Slovak Republic (CREPC):** This database records and evaluates the publication activity of higher education institutions in Slovakia.
- **The Central Registry of Artistic Activity of Universities in the Slovak Republic (CREUC).**
- **The Central Registry of Theses and Dissertations** with the anti-plagiarism system (CRZP): This repository holds electronic versions of final and qualification theses from higher education institutions in Slovakia.
- **The Slovak Central Database of Electronic Information Resources for Research and Development (SCIDAP):** This database stores and provides access to information resources produced by Slovak scientific and research institutions.
- **Research Data Management (SVD):** This repository stores and makes available research datasets produced by Slovak scientific and research institutions.

KOMIS will also contain an Analytical Module for Science Assessment, Open Access Publishing Platform, Integrated System of Services of the SCSTI, and a Discovery System for Electronic Information Resources. Not all of the last-mentioned modules are in production yet, as KOMIS is currently in its pilot operation, with its beta version not yet enabling the full operation of all functionalities.

6.3. SCSTI and EOSC

SCSTI, as the national EOSC coordinator for Slovakia, became part of the pilot consortium of European organizations that will participate in building the EOSC Federation's network of nodes. In a six-month selection process at the European level, SCSTI was selected from 121 applications to be part of a group of thirteen established institutions that will participate in building the initial form of the EOSC Federation. The nomination of SCSTI to the position of national EOSC node will allow SCSTI to rank among the leading European scientific and research institutions supporting the principles of open science and FAIR data.

The technical solution for joining the EOSC assumes the involvement of the KOMIS system, including SK CRIS.

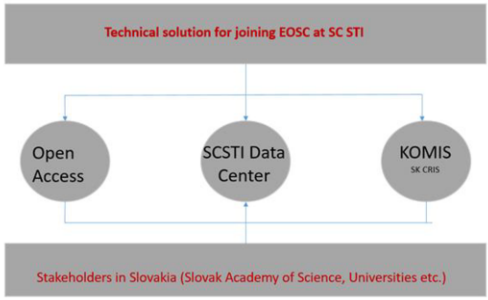


Figure 5 Technical solution for joining EOSC.

All major KOMIS components will meet EOSC compliance standards: the central KOMIS framework, SVD (research data objects repository), SCIDAP (scientific publications repository), SK CRIS (Current Research Information System tracking projects, organizations, and researchers), and discovery service layer. Technical enhancements will include implementing IDM integration with the EOSC AAI, developing standardized API gateways for all subsystems, establishing automated metadata harvesting pipelines, and altering a robust PID management system supporting multiple identifier schemas.

6.4. Comparison with Germany: CRIS Systems in a Decentralized Landscape

Unlike Slovakia, where the Slovak Centre of Scientific and Technical Information (SCSTI) coordinates a centralized and state-supported approach to research information systems, Germany operates in a more decentralized and federated model.

In Germany, no single national CRIS system exists. Instead, research information systems are implemented locally at the level of universities, research institutions, and research funding organizations. Many of these institutions use commercial CRIS solutions (such as PURE or CONVERIS) or self-developed systems to manage and integrate research data.

To support interoperability and standardization across this fragmented landscape, the German Research Foundation (DFG) and organizations such as DINI (German Initiative for Network Information) and the Research Core Dataset (Kerndatensatz Forschung, KDSF) initiative have established guidelines and minimum

standards for research reporting. The KDSF model is widely used as a basis for harmonizing the collection and exchange of research information.

Table 1. Key Differences and Similarities.

Aspect	Slovakia (SK CRIS & KOMIS)	Germany (Local CRIS Systems)
Governance	Centralized, coordinated by SCSTI under the Ministry	Decentralized, institutional autonomy
System Coverage	National-level integration (SK CRIS, KOMIS)	Institutional-level implementation
Standards	CERIF, FAIR principles, EOSC integration	KDSF, CERIF-compatible in some systems
PID Integration	Centralized (ORCID, IČO, DOI)	Institution-specific, growing ORCID adoption
EOSC Participation	National EOSC node via SCSTI	Participation through individual institutions and consortia (e.g. NFDI)
Open Science Support	Centralized infrastructure (KOMIS)	Diverse initiatives, e.g., via NFDI consortia and OpenAIRE nodes

While Slovakia benefits from central coordination and rapid implementation, Germany emphasizes institutional freedom and diversity, which fosters innovation but can lead to inconsistencies in data structures and interoperability.

Both countries are moving toward greater integration with the European Open Science Cloud (EOSC) and are actively promoting FAIR data principles, albeit through different organizational structures.

7. Conclusion

The transition from fragmented research information landscapes to integrated, FAIR-aligned CRIS infrastructures is not merely a technical evolution—it is a strategic imperative for Open Science and international research collaboration. This paper has demonstrated that persistent identifiers, harmonized metadata standards, and FAIR-by-Design architectures are not optional features but essential enablers of sustainable, transparent, and interoperable research ecosystems. The case studies from Slovakia and Germany underscore that national efforts, when aligned with European initiatives such as the EOSC, can successfully overcome legacy system limitations and institutional fragmentation.

Libraries, due to their expertise in metadata curation and stewardship, are uniquely positioned to lead this transformation by operating CRIS systems and shaping best practices. Yet, the realization of truly FAIR-compliant infrastructures depends on continuous investment—in both technical capabilities and human expertise—as well as policy support that embeds FAIR and Open Science goals into evaluation, funding, and governance frameworks.

To fully unlock the potential of CRIS in the digital age, stakeholders must embrace interoperability not just as a technical challenge, but as a collaborative responsibility. Only through such alignment can Europe build a resilient and inclusive research infrastructure where data is not only stored but actively shared, reused, and trusted across borders and disciplines.

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From Machine Learning to Federated Knowledge Systems – Current Challenges and Future Architectural Directions for Cybersecurity Applications

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Abstract. Machine learning (ML) is foundational to cybersecurity today, underpinning critical applications such as intrusion detection systems. Despite their widespread adoption, however, established ML approaches are beginning to show critical limitations in handling evolving cyberthreats. In this paper, we (1.) conduct a data-driven analysis of ML for intrusion detection to understand and demonstrate current limitations, (2.) discuss the literature and contextualize the findings, and (3.) identify and outline architectural directions for advancing local ML to federated knowledge systems for cybersecurity applications. The analysis results indicate significant challenges within established systems, notably in defining normal behavior, high false alarm rates, and detection rates. These shortcomings highlight intrinsic constraints of localized ML approaches, as exemplified in intrusion detection and beyond. Toward addressing these issues, the properties of a federated knowledge system architecture can provide distributed data inputs rather than siloed sources, data sharing, and federated learning to derive widely distributed, structured knowledge bases.

Keywords. Artificial Intelligence, Machine Learning, Federated Learning, Knowledge Sharing, Intrusion Detection

1. Introduction

Artificial Intelligence (AI) has become an integral component of technical systems, with Machine Learning (ML) serving as its foundational paradigm. By enabling systems to recognize patterns, make predictions, generate outputs, and improve over time, ML has the potential to transform numerous industries. In certain fields such as cybersecurity, these advancements are particularly critical, as cyberthreats are evolving and intrusions are occurring with increasing complexity at an accelerating pace. ML-based Intrusion Detection Systems (IDS) have become the primary line of defense against these threats;

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however, the effectiveness of ML remains a major challenge, particularly in handling constantly evolving attack patterns and novel zero-day threats.

More broadly, ML effectiveness is critical across domains, e.g., when relying on process automation within distributed settings such as in healthcare or critical infrastructure. In future environments that are likely to become increasingly dynamic and distributed, advancements in ML will be crucial, potentially leveraging distributed and dynamic learning approaches to enhance effectiveness.

Problem Statement: Combating globally occurring cyberthreats on an internet-wide scale is, today, limited by challenges of current-generation machine learning approaches that face accuracy challenges and operate locally.

In the current discussion on countering increasingly distributed threats, novel architecture concepts that are equally distributed could be considered. Motivated by the possibility of federated learning for threat intelligence, this paper highlights current challenges through a data-driven analysis in the domain of intrusion detection and outlines a conceptual architecture towards federated and knowledge-based systems. The paper seeks to contribute in the discussion on combating distributed cyberthreats by highlighting the potential of such an architecture.

In particular, we aim to: (1.) systematically evaluate and demonstrate the limitations of local ML approaches in the context of intrusion detection; (2.) contextualize our findings within the broader literature; and (3.) identify future directions for the transition from isolated ML systems to federated knowledge systems. Such advancements would enable distributed data inputs, local learning with global aggregation of learned models across distributed nodes, and the structured redistribution of knowledge within knowledge bases.

In the following, Section 2 introduces background on ML for intrusion detection along with related literature. Section 3 investigates current ML-based intrusion detection approaches by a data-driven analysis with measurements of performance metrics and contextualizes the findings. In Section 4, future directions are discussed in an architecture overview for federated knowledge systems. Section 5 reflects and concludes.

2. Background and Related Work

AI enhances Network Intrusion Detection Systems (NIDS) by automating tasks traditionally requiring human intelligence [1]. AI-based NIDS use Machine Learning (ML) methods, including Deep Learning (DL), and follow three key stages: data pre-processing, model training, and model testing [2]. During training, network traffic or malware samples serve as inputs to learn patterns and predict threats [2,1]. Feature selection is crucial, as relevant data elements impact detection performance [2]. DL-based NIDS improve detection by automatically learning complex features through additional neural network layers, reducing the need for manual feature engineering [1,2].

NIDS analyze network traffic to detect threats, unlike Host-Based IDS (HIDS), which monitor individual devices [1,3]. Detection methods include signature-based, anomaly-based, and hybrid approaches. Signature-based detection matches traffic against predefined attack patterns, while anomaly-based methods flag deviations from normal behavior, making them effective against novel threats but sensitive to changing network

conditions [1,4,5]. Hybrid methods combine both techniques for improved accuracy, and further specialized approaches continue to evolve in research [1,3,2].

AI-enhanced NIDS have been the subject of various prior studies. Notably, a survey [3] reviews recent research trends in NIDS and categorizes the surveyed works based on the three detection approaches discussed in Section 2. [2] is another notable survey that also provides a comprehensive overview over the topic and focuses on different ML-based or DL-based NIDS approaches. Regarding particular solutions towards distributed approaches, the paper [4] focuses on lightweight IDS solutions for IoT, where IDS is performed at the edge. The need to address current challenges in anomaly detection is underscored by works on its current limitations such as [5]. These challenges are partially addressed, in particular by the need for self-adaptive models, e.g. by [6], however, few works address solutions in the context of combating internet-scale cyberthreats. While federated approaches such as [7] present first solutions, they are not based on recent developments that integrate knowledge-based approaches such as ontologies with federated learning. The feasibility of such approaches has already been demonstrated in combination with Large Language Models (LLMs) [8,9], however, since this field is rapidly evolving, these approaches have not been applied together with federated learning and knowledge-based systems, yet. To point out this future architectural direction that can potentially combat evolving cyberthreats by global sharing and learning with accuracy beyond traditional ML approaches, this paper suggests considering a federated knowledge system architecture utilizing global knowledge sharing and learning based on ontologies and LLMs. In the following, currently established approaches are analyzed in order to understand the challenges and motivate the architecture concept.

3. Analysis of Machine Learning Approaches for Intrusion Detection

This section analyzes the strengths and weaknesses of intrusion detection approaches used in current AI-enhanced systems, involving signature-based and anomaly-based detection as well as state-of-the-art hybrid approaches. To understand and demonstrate current limitations, we trained and applied learned models using the NSL-KDD dataset.

3.1. Dataset.

The NSL-KDD dataset is a widely recognized and well-understood dataset. It is applied due to its well-known characteristics and limitations while containing data that is commonplace and, ideally, should be detected by IDS systems today. NSL-KDD is a refined version of the KDD'99 dataset, designed to benchmark threat detection systems by removing redundancies and balancing difficulty levels [3,10]. It includes 125,973 training records and 22,544 testing records across 43 columns, with 41 features and two labels for attack type and difficulty level. The dataset contains 52.04% normal traffic and 47.06% attack traffic, categorized into DoS (35.82%), Probe (9.43%), R2L (2.53%), and U2R (0.17%) [10]. Some attacks appear only in testing data, simulating zero-day threats.

3.1.1. Data preparation.

All models are trained for binary classification, distinguishing threats from normal behavior, with the added "threat" label and `attack_type` for evaluation. The same NSL-

KDD training and testing split is used, with 41 connection features as inputs and corresponding labels as targets. No further preprocessing is needed due to the dataset's quality, but categorical features are one-hot encoded, and min-max normalization scales all features between zero and one [1].

3.1.2. Training.

The signature-based model is trained with the Random Forest Classifier machine-learning algorithm. The standard hyper-parameters and the random state of 42 are used.

The Isolation Forest algorithm is used to train the anomaly-based model. For the training, only the non-malicious entries of the training set were used, with the contamination of 0.25 and random state of 42.

In the hybrid-based model both the Random Forest Classifier and Isolation Forest algorithm are used. The Random Forest model used the same configuration as the signature-based model. For the Isolation Forest model, the only change from the anomaly-based model is the contamination parameter, set to 0.5. During prediction, both models estimate the confidence of an attack being non-malicious or malicious. These values are then normalized between 1 (threat) and 0 (no threat). The Isolation Forest score contributes 92% to the final confidence score while the Random Forest score contributes only 8%. If the final confidence score is higher or equal to 0.5 the entry is flagged as a threat.

3.2. Performance measurement.

The key metric to evaluate the proposed approaches is their F-measure. Accuracy is not used as key metric to account for the imbalance of malicious and non-malicious entries [3]. The False-Alarm Rate (FAR) shows how many non-malicious entries were wrongly classified. The detection of lesser known attack types (R2L and U2R) and the simulated zero-day are also compared using their recall values.

3.2.1. Results of evaluation.

The evaluation shows that the anomaly-based and hybrid-based models have similar reliability, with F-measures of 88.04% and 87.31% respectively. The signature-based model performs worse with a F-measure of 75.23%. However, the model achieves the lowest FAR (2.78%), outperforming the anomaly-based (19.32%) and hybrid-based (11.26%) models.

The lesser-known attacks in the signature training set, U2R and R2L, have a low recall for the signature-based model at 9.00% and 3.78%, respectively. In contrast, the anomaly-based model detects these attack types much better, with recall values of 90.50% for U2R and 61.22% for R2L. The hybrid approach achieves 86.00% recall for U2R and 36.42% for R2L. The anomaly-based model also excels at detecting zero-day threats, as reflected in its high recall rate of 96.59%. The signature-based approach has a zero-day attack recall of 23.47%, while the hybrid approach falls between the two at 79.87%.

This indicates that the anomaly-based model is far better in detecting lesser known or zero-day threats with the cost of more false alarms than the signature-based model. The

anomaly-based model also achieves a better overall accuracy. The hybrid-based model balances the strengths of both models, offering strong threat detection with a moderate false-alarm rate. These findings are consistent with recent studies [1,3,2].

3.2.2. Implications for Intrusion Detection

ML-enhanced IDS appear to counter unknown threats by anomaly-based approaches, however, detection performance is not nearly comparable to the detection of known threats, which require signature-based approaches in addition. The introduction of hybrid IDS has been pursued for this reason and the analysis supports this conclusion as a necessary first step for baseline security. However, it is not sufficient due to the problems observed in rising False Positive (FP) rates and declining accuracy when involving anomaly-based methods. Recently, advancements in AI have impacted the threat landscape. In the background, known threats remain constantly active and produce the highest share of internet-side attack attempts[11], however, they tend to be constant threats that can be countered by proven hybrid approaches. Constant threats undergo comparatively little evolutionary changes, are typically based on well-known predecessors, and developed or merged in new variants over months or years.

In recent years, adaptive threats were increasingly observed [12] that change their behavior according to new environments and to evade detection. In this paradigm, threats are adjusted partially or fully automatically on the attacker side or in the field, e.g., by changing code through command and control remotely, or by AI-enhanced self-modifying code and code generation. Consequently, threats tend to develop at a faster rate and undergo significant changes over time. While ML detection approaches demonstrated to be effective within stable environments, learning new normal or malicious behavior presented severe challenges for detecting evolving threats. Previously unknown threats in zero-day attacks are especially problematic in this regard, since they are present in few local traffic flows only.

3.2.3. Limitations.

The dataset and analysis aim to provide principal strengths and weaknesses for the discussion. Detailed conclusions are limited since (1.) further attack types exist beyond the ones included in the dataset, and they evolve constantly, and (2.) further method and parameter optimizations could have been carried out towards optimizing NIDS for production, e.g., systematic evaluations for hyper parameter configurations, input features, and learning methods. The results reflect performance in a laboratory environment in order to demonstrate strengths and weaknesses of the system classes under comparable conditions.

4. Advancing toward a Federated Knowledge System Architecture

In the recent years, AI-enhanced approaches have been introduced across disciplines and are being integrated into business systems and technical systems. At the present, ML is frequently applied such as for intrusion detection [3]. From our analysis in this domain, significant limitations are apparent that are, however, not limited to this domain. They are common challenges in ML today, inherent to ML based on limited, local data sources

in an evolving environment. Effectiveness is especially impacted by challenges of False Positive (FP) rates, accuracy, and recognizing complex patterns under dynamic conditions. In particular, the coupled effect of rising FP rates and declining accuracy is highlighted by the analysis, e.g., when detecting lesser known attack variants, for few known samples of signatures or patterns, and for benign application traffic not seen before.

4.1. Architectural Approach to Federated Knowledge System

Advancing ML-based systems beyond architectures reliant on siloed data sources presents an opportunity to leverage shared data for improved learning on the basis of shared data and, eventually, evolve in the direction of further dependable and structured knowledge representations. In certain fields such as cybersecurity, these advancements are critical to join data sources on larger scales, introducing global networks that sense appearing threats, collect patterns, update models, distribute them, and apply them for detection. The criticality of ML effectiveness is the primary concern, evident in many other areas such as business processes of critical industrial systems, critical infrastructure, or healthcare. In addition, future systems are likely to operate in increasingly heterogeneous and distributed environments. In these settings, data and events are generated and processed in local systems, which can then serve as inputs for federated learning strategies. These strategies learn and integrate based on local datasets and events, enable knowledge extraction into higher-level knowledge representations, and re-distribute them back to local systems. Such an architecture has the potential to create federated knowledge systems, utilizing widely distributed knowledge bases through federated learning. The architecture of such a federated knowledge system architecture encompasses three components:

4.1.1. Data Collection and Event Handling in Distributed Nodes.

Distributed nodes are part of heterogeneous local systems, where they serve as the primary interface for data and events by fulfilling three functions: (1.) Gathering diverse data sources, including process events, sensor outputs, and network traffic logs. (2.) Local Event Handling: Processing inputs in real time to respond to local events and classify them appropriately. In cybersecurity contexts, this may involve detecting specific traffic patterns or system events, such as authentication activities. (3.) Application of local ML models: Utilizing local and efficient ML models to extract knowledge from collected data, e.g., by lightweight approaches such as [13,14,15]. Subsequent processing tasks may be executed or triggered on external systems.

4.1.2. Federated learning

enables the distributed nodes to function as a collective intelligence system rather than isolated collection points. Each node acts as a client that contributes to combined learning and knowledge sharing using aggregation and learning, based on state-of-the-art protocols such as [13,15]. In particular by (1.) computing updates for local models based on locally available data, (2.) performing local training iterations, (3.) apply model updates to the locally maintained model, and (4.) transmitting these updates for aggregation by receiving nodes. The continuous cycle of local training, aggregation, application, and transmission facilitates the propagation of updated models throughout the network.

4.1.3. Distributed Knowledge Bases.

For the redistribution of knowledge in structured representations, the updated model — post-aggregation and learning — is applied locally. By globally identified patterns, the model is now applied to the collected data and events for knowledge representation. This process entails: (1.) knowledge extraction and (2.) mapping of the extracted entities and relationships in existing graph or model representations, and (3.) knowledge distribution that transmits the updated representations to nodes for integration. Knowledge extraction and mappings are well supported through recent LLM approaches [8,9] or named entity recognition [16]. On the basis of standardized structures, integration will be supported, e.g., on the basis of standardized knowledge graphs and ontologies, resulting in a distributed and coherent knowledge system.

4.2. Implications

In combination, these components have the potential for wide-ranging and large-scale learning efforts, towards jointly learning from locally available data and events for creating dependable and structured knowledge bases that improve over time. The architecture concept is inherently decentralized and scalable, with knowledge bases being present at the nodes. Siloed data and event sources, also of larger data volumes, are supported by federated learning through local learning, aggregation, and the transmission of model updates. Thus, this architecture vision advocates for further research in the direction of federated knowledge systems towards an architecture and its realization, combining knowledge-based approaches with federated learning.

5. Conclusion

This paper presented current Machine Learning (ML) approaches in the domain of intrusion detection by a data-driven analysis involving training and model application, it contextualized the findings leading to identified challenges of effectiveness, and suggested an architecture vision for advancing to federated learning and knowledge-based systems. The analysis findings identified challenges of effectiveness, especially when applying ML with local, siloed data sources under dynamic conditions. Based on these findings, the need for distribution and dynamic environments in future systems results in the proposed architecture vision. The architecture supports decentralization and scalability by a local training and aggregation through federated learning and by re-distributes structured knowledge representations back to nodes. Further research is needed towards future systems that have the potential to combine federated learning and knowledge representations for widely-distributed future federated knowledge systems.

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Fish-Scan: A Mobile Application to Prevent Intermixing of Ladyfish Fingerlings in Chanos Chanos Pond Cultivation

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Abstract. Milkfish (*Chanos Chanos*) holds a special place in the Philippine aquaculture industry as the country's national fish. In recent years, however, local fish farmers have reported a decline in production, largely due to the unintentional inclusion of ladyfish (Elops Hawaiensis) during the early stages of cultivation. These two species appear visually similar, making it difficult to tell them apart. Unfortunately, ladyfish are natural predators and pose a serious threat to young milkfish stocks. To address this challenge, this study developed Fish-Scan, a mobile application that uses deep learning to help farmers identify and separate ladyfish from milkfish at an early stage. We manually collected videos of both species and processed the frames using various image preprocessing techniques before training a YOLOv12-based detection model. Among the different configurations tested, the model trained with augmentation on a white background yielded the best results, showing strong detection accuracy with an F1-score of 0.94 and a mAP50 of 0.92. The final model was successfully integrated into the Fish-Scan mobile application, allowing users to scan and identify the fish in real time. While mobile hardware slightly affected performance, the application still proved useful in practical settings. This research provides a practical and efficient solution for improving milkfish cultivation by helping prevent costly mistakes in species identification at the farm level.

Keywords. image preprocessing, ladyfish fingerlings detection, mobile application, YOLOv12

1. Introduction

Introduction Milkfish (*Chanos chanos*), widely regarded as the national fish of the Philippines, plays a vital role in the country's aquaculture industry and food security. Particularly prominent in coastal communities, its cultivation supports both livelihood and economic growth. In 2021, the Philippines ranked as the world's second-largest producer of milkfish, generating approximately 442.3 thousand metric tons through aquaculture [1].

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Figure 1. Visual comparison of ladyfish (top) and milkfish (bottom) showing their morphological similarities, which often lead to misidentification during early growth stages.

The provinces of Pangasinan, Ilocos Norte, Ilocos Sur, and La Union are among the leading contributors to this production. Despite its economic importance and strong market demand, recent reports indicate a troubling decline in regional milkfish yields.

A significant contributor to this decline is the accidental inclusion of ladyfish (*Elops hawaiensis*) fingerlings in milkfish ponds. Ladyfish closely resemble milkfish in their early developmental stages, sharing visual characteristics such as elongated bodies, silver-colored flanks, a single dorsal fin, and forked caudal fins (see Figure 1. This similarity makes them difficult to distinguish manually, particularly during fry sorting. In La Union, a province central to milkfish farming, production dropped by 12.25% in 2022, which the Philippine Statistics Authority attributed in part to increased predation from misidentified ladyfish [2].

The ecological and economic impact of misidentifying ladyfish is significant. As a predatory and cannibalistic species, ladyfish consume not only milkfish fingerlings but also other fish, including conspecifics [3,4]. Their introduction into milkfish ponds disrupts ecological balance, decreases fingerling survival rates, and causes substantial financial losses. Prior research, including the findings of a study [5], has shown that even a minimal presence of ladyfish in milkfish ponds can severely reduce yield due to aggressive predatory behavior.

Advancements in artificial intelligence (AI) and image processing have paved the way for more accurate species identification in aquaculture. Convolutional neural networks (CNNs) was employed to classify 15 fish species from 2,209 images and achieved a 94.30% accuracy rate, although the study noted limitations in dataset scale and environmental generalizability [6]. Working in Philippine aquaculture contexts, [7] applied YOLOv7 to count milkfish fingerlings in actual ponds and reported a 91.54% accuracy. However, their work focused on object counting rather than species differentiation. A study developed a fish classifier using support vector machines and artificial neural networks, achieving 94.44% accuracy under controlled lighting but with diminished performance under variable environmental conditions [8]. Moreover, the study of [9] introduced a model for underwater fish species recognition, addressing challenges like poor visibility and species occlusion. Anu et al. (2020) [10] tested CNN models on ornamental fish and attained over 90% accuracy, though they emphasized the importance of species-specific features when working with morphologically similar taxa. These studies underscore the capability of deep learning models in aquaculture, but highlight gaps when applied to look-alike species or noisy, real-world conditions.

This study addresses that gap by developing a domain-specific mobile application capable of real-time, offline classification of milkfish and ladyfish fingerlings. The application, named Fish-Scan, is powered by a deep learning-based object detection architecture trained on a custom dataset collected from Philippine aquaculture sites. Unlike existing systems, Fish-Scan is optimized for low-resource deployment and is specifically



Figure 2. Camera setup (left) used for capturing video data from approximately 3 feet above the basin, and sample video frame (right) showing milkfish and ladyfish fingerlings during data collection.

designed to function without internet access. To achieve accurate detection in challenging visual environments, Fish-Scan utilizes YOLOv12, a cutting-edge model designed for real-time performance and high precision in detecting small, similar-looking objects. The system was trained on carefully annotated images extracted from videos of fingerlings in controlled pond settings. This novel integration of mobile edge computing and deep learning offers a practical, locally-adapted solution to one of the most persistent challenges in milkfish farming today.

2. Materials and Procedures

This study used experimental research on machine learning. This approach helped us achieve successful research results.

2.1. Data Collection

Video data were collected from aquaculture sites in La Union, Philippines, specifically in Barangay Dulao, Aringay. A total of 55 videos were captured using Tecno Camon 20 Pro and iPhone 12 Pro mobile devices. To ensure consistency, the camera was mounted on a tripod and positioned approximately three feet above the basin. Two types of basins (black and white) were used to introduce background variation during data collection. Figures 2 and 3 illustrate key components of the data collection process: Figure 2 shows the experimental setup used for capturing the video dataset, while Figure 3 presents sample images of ladyfish and milkfish fingerlings highlighting their morphological similarities.

2.2. Image Preprocessing

The collected videos were processed through frame extraction at 0.5-second intervals, generating a total of 6,269 images—1,493 frames from the black basin and 4,775 frames from the white basin. These frames served as input samples for the object detection model. All images were annotated using the Computer Vision Annotation Tool (CVAT). For clear class distinction, blue bounding boxes were used for milkfish, and red bounding boxes for ladyfish. In the black basin, 1,533 frames were annotated, resulting in 28,824 bounding boxes (19,445 for milkfish and 9,379 for ladyfish). Similarly, in the white basin, 6,703 frames were annotated, yielding 110,074 bounding boxes (67,677 for



Figure 3. From a top-view perspective, ladyfish and milkfish exhibit distinct morphological differences. Ladyfish have a rounded, dark head with eye placement that creates a thin, elongated profile. In contrast, milkfish display a triangular head shape, resulting in a broader and more compact appearance. This key distinction makes milkfish appear shorter and wider compared to the slender form of ladyfish.

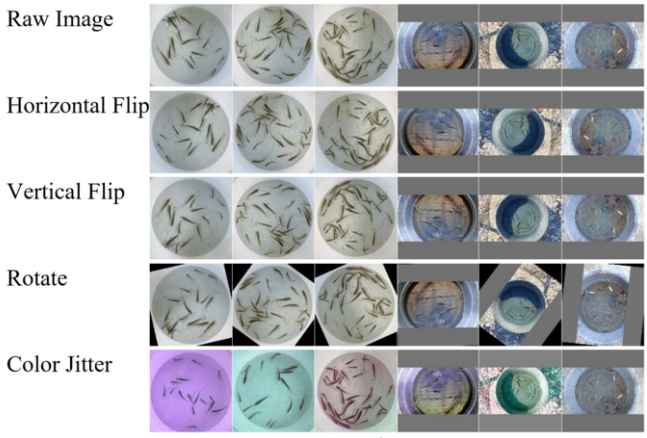


Figure 4. Sample images demonstrating the applied data augmentation techniques.

milkfish and 42,397 for ladyfish). This totaled 138,898 annotated instances across all images. Prior to training, all images were resized to 640×640 pixels, the required input size for the deep neural network architecture. To enhance model robustness and generalization, data augmentation techniques were applied during training. These included horizontal and vertical flips, rotations, and color jittering, simulating variations in fish orientation and lighting conditions typically encountered in real-world aquaculture environments. Specifically, 10% of the 1,533 black basin frames were randomly selected for each augmentation method. This resulted in 153 frames used for horizontal flipping, 153 for vertical flipping, 153 for random rotations at varying angles, and 153 for color jittering (refer to sample images in Figure 4). In total, 612 augmented frames were generated and integrated into the dataset.

2.3. Data Preparation and Training

The annotated dataset, including both original (87,122 milkfish and 51,776 ladyfish) and augmented images (98,355 milkfish and 64,342 ladyfish), was randomly split into 80% for training and 20% for validation.

For the object detection task, the study employed YOLOv12 [11], the latest iteration in the YOLO (You Only Look Once) series of real-time object detectors. YOLOv12 is well-suited for aquaculture applications due to its ability to accurately detect small and morphologically similar objects—an essential capability when distinguishing between milkfish and ladyfish fingerlings. It introduces multiple architectural and optimization innovations that significantly enhance detection performance and efficiency.

One of the key improvements in YOLOv12 is its enhanced feature extraction capability. The model incorporates Area Attention, which efficiently handles large receptive fields while reducing computational overhead. Additionally, it introduces an optimized balance between attention and feed-forward computations, and leverages the R-ELAN architecture to enhance feature aggregation across different layers. These features contribute to the more precise localization and classification of fish in complex scenes.

2.4. Performance Evaluation and Training Environment Setup

To assess the effectiveness of the object detection model, the evaluation focused on three key metrics: mean Average Precision (mAP) at IoU thresholds 0.50:0.75 (mAP50:75), precision, recall, and F1-score. Training and evaluation were conducted using a high-performance computing environment. The model was trained on a Razer Blade 15 Advanced (Mid 2021) laptop with an 11th Gen Intel(R) Core(TM) i7-11800H CPU @ 2.30GHz (16 logical cores), 32 GB of RAM, and a dedicated NVIDIA GeForce RTX 3060 Laptop GPU. The system operated on Windows 10 Business 64-bit (Build 19045) with DirectX 12 support, and had ample storage for data and caching, with over 70 GB of available page file space. The training pipeline was implemented using Python, and the model architecture used was YOLOv12 [12].

3. Results and Discussion

As presented in Table 1, the object detection model was assessed under two distinct training setups: one using raw data only, and the other incorporating data augmentation. The augmented configuration involved techniques such as horizontal and vertical flips, image rotation, and color jittering. These modifications proved beneficial in improving the model's overall performance.

Without augmentation, the model achieved an mAP50 of 0.89 and an mAP50:95 of 0.85. By comparison, the model trained with augmented data attained higher scores, with mAP50 reaching 0.92 and mAP50:95 improving to 0.89. The improvement in mAP50:95, which evaluates accuracy across multiple intersection-over-union thresholds, reflects the model's enhanced consistency and ability to detect objects with varying degrees of overlap. This suggests that the augmented model was better equipped to localize and classify fish under more demanding conditions.

Further gains were observed in precision and recall. The precision increased from 0.92 to 0.94, indicating that the model became more effective at reducing false positives when trained with augmented data. Recall also improved, increasing from 0.88 to 0.90, which points to an increased ability to correctly identify actual instances of milkfish and ladyfish. Consequently, the F1-score increased from 0.90 to 0.92, highlighting a more balanced and dependable detection capability.

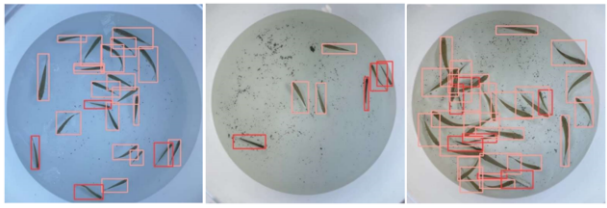


Figure 5. Sample prediction outputs generated by the YOLOv12 model. In the images, pink bounding boxes represent detected milkfish, while red bounding boxes indicate detected ladyfish.

These results underscore the value of data augmentation, especially in applications involving limited datasets and fine-grained distinctions between classes, such as milkfish and ladyfish fingerlings. By enriching the dataset with transformed samples, the model becomes more resilient to common real-world variations like changes in orientation, lighting, and background. This enhancement in generalization is critical in aquaculture environments, where visual conditions are far from uniform and accuracy in species identification directly impacts productivity and economic outcomes. However, a limitation of the current approach emerges when a large number of fingerlings are present in the basin, especially when they overlap or cluster together. In such cases, the model occasionally struggles to differentiate individual fish, which may lead to missed or inaccurate detections.

Table 1. Performance comparison of the YOLOv12 model with and without data augmentation.

Model Setup	mAP50	mAP50:95	Precision	Recall	F1-score
Without Augmentation	0.89	0.85	0.92	0.88	0.90
With Augmentation	0.92	0.89	0.94	0.90	0.92

To enable real-time, field-deployable detection, an Android application named Fish-Scan was developed using Android Studio. The best-performing YOLOv12 model, trained and evaluated in earlier phases, was converted and optimized for mobile inference using ONNX and integrated into the mobile environment. The application provides an intuitive user interface designed for fish farmers and hatchery technicians, with key functionalities including scanning, viewing instructions, accessing saved detection results in the gallery, and checking historical logs of scanned images.

4. Conclusion

This study presented Fish-Scan, a mobile application integrated with a YOLOv12-based object detection model, to address the challenge of distinguishing milkfish and ladyfish fingerlings in aquaculture. Trained in field-collected images and enhanced with data enhancement, the model achieved strong results: mAP50 of 0.92 and F1 score of 0.92, highlighting its effectiveness in handling visual similarities between species. The mobile app allows offline, real-time detection, making it highly suitable for rural fish farms. However, a noted limitation is the reduced accuracy when multiple fingerlings overlap, leading to missed or merged detections.

Future improvements should focus on adopting instance segmentation models, expanding the dataset under varied conditions, and integrating real-time video inference.

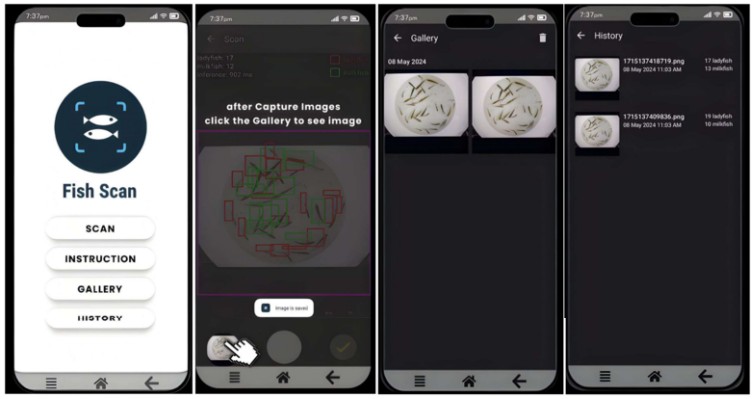


Figure 6. User interface of the Fish-Scan Android application.

With further refinements, Fish-Scan holds promise as a practical tool to support accurate species identification and enhance productivity in Philippine aquaculture.

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A Review of Chain-of-Thought Reasoning Technology for Large Language Models Based on Multimodal Fusion

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Abstract. As a nascent research frontier, Chain-of-Thought (COT) reasoning technology and its multimodal applications in large language models (LLMs) currently lack standardized concepts, methodologies, and a holistic research framework. To address these gaps, we have conducted an in-depth analysis of the core processes involved and comprehensively reviewed over 40 authoritative references. Our research has pinpointed three pivotal areas: the efficient integration of multimodal data features, the optimization and enhancement of COT and logical reasoning capabilities, and the practical implementation of multimodal LLMs. We have summarized the cutting-edge advancements, future trends, and the significant challenges. It is hoped that this comprehensive study will assist beginners in swiftly building a foundational understanding of this research area, clarifying the research methodology and workflow, and enabling them to concentrate their efforts on core algorithmic design. We are confident that this survey will attract broader participation from researchers in the field of COT reasoning for multimodal LLMs and provide valuable references and guidance for their scientific endeavors.

Keywords. Chain-of-Thought, Large Language Model, Multimodal Fusion

1. Introduction

In recent years, large language models have demonstrated remarkable text understanding and generation capabilities, becoming a focal point in academia and industry. Many researchers have fine-tuned open-source large language models to adapt them to specific scenarios, successfully applying them to fields such as sentiment analysis, multimedia generation, and intelligent question answering, promoting the widespread deployment of large language models. Since the pre-training data comes from large-scale public datasets, the models are susceptible to the influence of incorrect or outdated data, leading to the "hallucination" phenomenon and producing inaccurate results. In addition, although

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prompt-based learning models perform well in generative tasks, they exhibit performance bottlenecks in reasoning tasks. This may stem from the limitations of the models' reasoning mechanisms. To address this bottleneck, the academic community has proposed the CoT strategy. As an innovative prompt learning method, CoT guides the model to generate reasoning processes step by step through guiding prompts, making the reasoning path more transparent. Studies have shown that CoT has significant potential in complex mathematical, commonsense, and symbolic reasoning tasks, effectively enhancing the model's reasoning ability and answer accuracy.

However, the existing surveys on CoT mainly focus on structural analysis and discussion of influencing factors, lacking a comprehensive summary of its generation and enhancement methods. By referring to relevant research progress and CoT reasoning and combining our research experience in CoT reasoning technology, we propose a framework for LLMs' CoT reasoning technology based on multimodal fusion. The research architecture is shown in Figure 1. It mainly consists of efficient fusion of multimodal data features, optimization and enhancement of CoT and logical reasoning capabilities, and practical application of multimodal LLMs in professional fields.

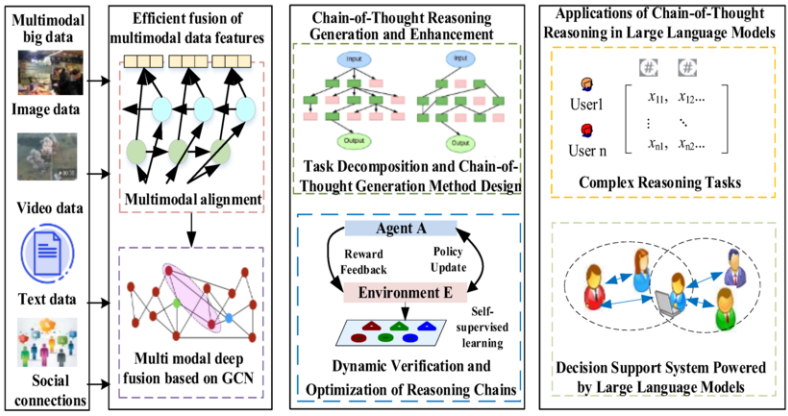


Figure 1. Research Framework of Chain-of-Thought Reasoning.

Based on Figure 1, we review the methods of CoT reasoning based on multimodal fusion from the following key research contents: efficient fusion of multimodal data features, optimization and enhancement of CoT and logical reasoning capabilities, and practical application of multimodal LLMs in professional fields. We sort out the research progress and technical trends, summarize the existing problems, and propose future research directions based on the technical trends and existing problems. The aim is to provide theoretical guidance and practical references for subsequent research, promoting the development of CoT reasoning technology in LLMs.

2. Efficient Fusion of Multimodal Data Features

The multimodal fusion methods mainly include encoder-decoder architecture, attention mechanism, and graph neural network.

2.1. Encoder-Decoder-Based Fusion

Encoder-decoder models have gained widespread popularity in multimodal data fusion due to their exceptional representation learning capabilities and flexible architectural design [1-3]. The models are a classic architecture for processing sequence to sequence (seq2seq) tasks, with wide applications in the fields of multimodal fusion and natural language processing. Typical applications include multimodal understanding, machine translation, text summarization, question answering systems, and dialogue systems. Tan et al. [4] proposed a hierarchical fusion approach that combined low-level, mid-level, and high-level features across modalities. Sun et al. [5] developed a two-stage multimodal fusion method to extract and jointly train multimodal features. Hong et al. [6] mapped input data from different modalities into a common space based on a shared latent representation. Bendre et al. [7] introduced a multimodal variational autoencoder architecture capable of learning a shared latent space for image features. However, these methods require compressing data from different modalities into a standard, often lower-dimensional representation, which may lead to the loss of modality-specific details and degrade the quality of the final output.

2.2. Attention Mechanism-Based Methods

Attention mechanism has become one of the core technologies in the field of LLMs. It has a wide range of applications in the fields of natural language processing (NLP), computer vision (CV), speech recognition, and multimodal fusion. A representative example of attention mechanisms is the multi-head self-attention mechanism [8-10]. In multi-head self-attention, self-attention is first calculated using the Query (Q), Key (K), and Value (V) matrices. The self-attention for each head is formulated as in:

$$\text{Attention}(Q,K,V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V \tag{1}$$

where Q is the query matrix, K is the key matrix, V is the value matrix, and d_k is the dimension of the key. Finally, the output of each head is obtained through concatenation:

$$\text{MultiHead}(Q,K,V) = \text{Concat}(\text{head}_1,\ldots,\text{head}_h)W^O \tag{2}$$

where $\text{head}_i = \text{Attention}(QW_i^Q, KW_i^K, VW_i^V)$, W_i^Q, W_i^K, W_i^V are the learnable parameter for each attention head, and W^O is the linear transformation matrix for the output.

In attention mechanism-based methods, Hu et al. [11] proposed a bidirectional cross-modal attention module for creating a vision-guided language attention module. Wu et al. [12] using co-attention mechanisms before each fusion step to enhance the connections between each modality and other modalities. Sun et al. [13] proposed a cross-modal dot product attention mechanism to learn the associations between audio and text modalities. Lu et al. [14] integrated channel-attention and feature-intersection mechanisms to facilitate dynamic information interaction between different modalities. Yoon et al. [15] introduced a sophisticated multimodal encoder that utilizes cross-attention to incorporate visual and audio feature representations. Hsu et al. [16] using the self-attention mechanisms for capturing long-term dependencies among multimodal data. However, these methods introduce computational and structural complexity as the number of modalities increases, requiring more computational resources. Additionally, the effectiveness of attention mechanisms is closely tied to the quality and relevance of the modalities, where lower-quality modalities can lead to suboptimal results.

2.3. Graph Neural Network-Based Methods

Graph neural networks can effectively model complex relationships between entities by capturing the topological relationships of nodes, edges, and the global graph structure. They have wide applications in social network analysis, recommendation systems, natural language processing, multimodal fusion. The relationships between nodes in graph-structured data are intuitive, enabling the extension of such structures to model both intra-modal and inter-modal relationships in multimodal tasks [17,18]. Wang et al. [19] introduced a knowledge-driven multimodal graph neural network to represent three distinct types of modal information. Jiang et al. [20] using graph attention networks to aggregate long-range intra-modal contextual details. Ding et al. [21] proposed a multimodal graph attention network to model correlations among different modalities. However, these methods usually rely on prior knowledge of specific input data and task characteristics during the graph construction. They also demonstrate considerable computational and spatial complexity, making it challenging to handle missing data scenarios.

3. Generation and Enhancement of Chain-of-Thought Reasoning

Recent studies have revealed that LLMs can conduct step-by-step reasoning through contextual learning, a CoT reasoning capability. In complex reasoning tasks, dynamic optimization of the reasoning chain can be achieved by integrating reinforcement learning (RL) and self-supervised learning (SSL) methods with feedback mechanisms. The reinforcement learning process defines the policy π and reward function J. The policy gradient method is employed to optimize the strategy of the reasoning chain, enabling it to adapt its behavior dynamically based on environmental feedback. The objective of reinforcement learning is to maximize cumulative rewards:

$$J(\pi) = \mathrm{E}\left[\sum_{t=1}^{T} \gamma^t R(t)\right] \tag{3}$$

where γ is the discount factor, $R(t)$ is the reward obtained at time step t, and T is the number of time steps required to complete the task.

The construction of CoT prompts is mainly divided into manual, automatic, and semi-automatic [22]. Gao et al. [23] transform problem-solving into program generation and obtained deterministic answers. Another approach involves few-shot reasoning based on automatically generated principles, which improves the stability of the reasoning process [24, 25]. Shao et al. [26] generated high-quality example information through alternating forward and backward synthesis processes. However, manual prompts rely on high-quality annotations, suffering from high labor costs and poor domain transferability. Automatic prompts, lacking supervision signals, are plagued by errors and instability. Semi-automatic prompts achieve a balance between performance and price, making them more suitable for downstream applications.

Real-world interactions require the integration of multiple modalities [27-29]. Xu et al. [30] using stage-level beam search to enhance reasoning capabilities. Chen et al. [31] proposed a new benchmark to advance multimodal CoT across domains, steps, and modalities. Mondal et al. [32] combined CoT with knowledge graphs for superior multimodal reasoning. Yao et al. [33] manually decoupled CoT reasoning steps to integrate better multimodal interactions. However, the current limitations of vision-language models restrict the application of multimodal large language Models in vertical

domains requiring multi-step reasoning, making them challenging to deploy directly in tasks demanding deep expertise and precise judgment.

4. Applications of Chain-of-Thought in Large Language Models

Current research on multimodal LLM applications primarily focuses on multimodal content understanding and text generation tasks [34-38]. Chen et al. [39] employ a dynamic high-resolution design to process complex visual inputs effectively. Li et al. [40] developed LLaMA-VID, capable of handling single images, short videos, and even movie-length inputs within duration limits. Chu et al. [41] proposed Qwen Audio, which perceives and understands rich audio information, supporting tasks in multilingual environments. Zhang et al. [42] introduced SpeechGPT, which enables the model to accept cross-modal inputs and directly generate outputs. To expand the general-purpose multimodal capabilities of LLMs, Tang et al. [43] presented CoDi-2, which processes complex multimodal instructions and generates corresponding text, image, and audio outputs. However, current research remains primarily focused on general-domain applications. Their limited fine-grained perception capabilities and understanding of complex causal relationships remain insufficient in task scenarios requiring deep domain expertise and precise judgment, restricting their direct applicability in vertical domains.

5. Current Research Challenges and Future Trends

Traditional single-modal methods must develop efficient cross-modal fusion techniques to integrate various information resources. Therefore, further research is needed to explore the mining of multimodal spatiotemporal correlation features, strengthen semantic consistency modeling between cross-modal data, dynamically adjust the importance of each layer of features according to specific application scenarios, and achieve more flexible and effective feature fusion representation.

In optimizing adaptive COT reasoning, the existing methods perform poorly in dealing with problems involving multiple layers of logical relationships. The current COT architecture has poor adaptability to emerging task types, and performance degradation may occur once it exceeds the preset range. Therefore, it is necessary to study and optimize the reasoning ability of the COT in complex scenarios, so that the model has a stronger generalization ability and adaptive adjustment function.

In optimizing and adapting LLMs, successfully applying them to practical environments still requires solving many practical problems, including computational resource limitations, real-time response requirements, and special task requirements. Therefore, it is necessary to strengthen the understanding of the content of the model and the design of the dialogue management module to ensure smooth and efficient human-computer interaction.

6. Conclusion

In this paper, we review over 40 scholarly works, comprehensively examining the research progress of CoT reasoning technology for LLMs based on multimodal fusion, aiming to provide directional guidance for subsequent studies. The discussion centers on three progressively layered core topics. Additionally, the paper delves into the critical

scientific challenges and developmental bottlenecks in this area while presenting forward-looking analyses of future trends. To enable deep deployment of this technology in complex scenarios, it is essential to introduce more intelligent reasoning paradigms to enhance dynamic adaptability, develop human-aligned interaction frameworks to improve interpretability, and conduct tailored research aligned with domain-specific needs to push application boundaries.

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Reducing Foot Artifacts with Physical Constraints

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Abstract. Accurate prediction of foot position is a key element in estimating complex human poses. Recent advances aimed at improving the temporal smoothness of reconstructed motion trajectories and accurately predicting foot positions in most frames with only minor jitters. However, for infrequently occurring events, estimated foot positions may exhibit pronounced artifacts. In this paper, our objective is to mitigate these artifacts present in the current pose prediction model that uses monocular RGB videos. To achieve this, we introduce a dedicated temporal refinement network that is integrated with the current pose estimation framework. Our approach incorporates a fully connected layer network, which enforces a physical constraint to optimize foot positioning in video frames. We present a throughout evaluation of the suggested network and showcase the high-quality results achieved in reconstructing foot motion.

Keywords. walk sliding, foot artifacts, pose estimation, trajectory prediction

1. Introduction

The estimation of 3D poses from a single RGB camera is crucial in the fields of computer vision and artificial intelligence, as it forms a fundamental aspect of many applications, including Virtual Reality, Robotics, and Surveillance. In recent years, substantial advances were made in single-image-based 3D human pose and shape estimation, by utilizing deep learning techniques and accessible large-scale datasets. [1–4] Several methods estimate individual poses for each frame, but this can lead to noticeable temporal jitters, resulting in unreliable interpretations. Recent studies [5–7] incorporated temporal context to produce smoother and more precise motion trajectories. however, in the absence of specific physically realistic constraints, these methods frequently encounter common issues like foot skating.

In this paper, we introduce a self-supervised learning method to alleviate foot skate artifacts in the reconstruction of lifelike human motion. This method can be easily applied to tasks such as animation and retargeting. We place our emphasis on explicitly modeling the physical constraints associated with the human foot, identifying long-term foot artifacts, and leveraging information about ground contact status and the relation-

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ships among the foot joints. Optimization of motion trajectories with this supplementary constraint leads to visually appealing and realistic motions.

To summarise, the main contributions of the paper are:

1. We propose a simple but effective network structure that reduces foot artifacts greatly by imposing physical constraints.
2. We present a method that eliminates the need for manual annotation, offering a plug-and-play network with high transferability across different types of estimators and datasets.
3. Our result exhibits considerably fewer artifacts, such as frame-to-frame jitter, foot skating, and excessive foot inversion and eversion, in comparison to related methods.

2. Related Work

2.1. 3D Pose Estimation

3D human pose estimation by identifying the primary 3D joints of the human body within a human-centered coordinate space, represents a major challenge within the field of computer vision. Most 3D human pose estimation methods predict a 3D pose either from a single RGB image or frame by frame in videos. A simple two-stage prediction bridges the gap between 2D and 3D pose estimation by first predicting the 2D pose and then estimating the 3D pose solely from the predicted 2D coordinates [1]. An advance, VNect, no longer requires bounding box extraction, enabling it to simultaneously estimate both 2D and 3D joint positions in real-time through joint regression [8]. Later, BlazePose introduced a lightweight neural network to estimate body poses, using both heatmaps and regression to keypoint coordinates [4]. Blazepose had similar performance but was 25-75 times faster than the current state-of-the-art. Therefore we employed the holistic functionality of Mediapipe BlazePose to build our proposed method. Unlike most of the above work, we focused on the smoothness of foot movement.

2.2. Temporal Smoothness

Existing temporal smoothing methods can be classified into two categories: low-pass filters and learning-based methods. Low-pass filters proficiently reduce noise by diminishing high-frequency components. This can be done by a Savitzky-Golay filter that fits the sequence using a low-degree polynomial least-squares function [9], by a Gaussian kernel to denoise the input signal [10], or by a first-order low-pass filter with an adaptive cutoff frequency to alleviate problems associated with jitter in the One Euro filter [11].

In learning-based methods, an intuitive approach is to introduce an end-to-end solution, such as a recurrent network [2], a temporal convolutional network, [3], a transformer [12], or a fully connected network [13] for the temporal feature extraction. Another approach refines 3D pose prediction by imposing additional constraints or introducing new loss functions into the pose network [14, 15].

However, these methods predominantly focus on addressing jitter errors and often overlook the incorporation of physical constraints. Consequently, the issue of foot skating in motion remains unaddressed.

2.3. Reducing foot artifacts

A limited number of studies have explored monocular 3D human motion capture by using explicit physics-based constraints to reduce foot artifacts. HuMoR [16] employed foot-ground contact predictions to impose environmental constraints in robust test-time optimization, while PhysCap [6] utilized foot-ground contact information, introducing a real-time physics-based pose optimizer that accounts for ground reaction force, gravity, and the kinematic motion of human poses. Based on a novel motion capture dataset that divides the foot into multiple sections, a data-driven method, UnderPressure [17], was developed to detect foot contacts and estimate ground reaction forces. Several studies [18, 19] used end-to-end approaches that integrate foot-ground contact estimation with SMPL model parameters to reconstruct foot pose. However, foot-ground contact is not the sole contributor to foot artifacts. This paper investigates unnatural foot bending due to occlusions and motion."

3. Methods

Given a fixed-length monocular RGB video sequence as input, our objective is the mitigation of foot skate artifacts in the reconstruction of human motion. The system consists of two stages: 1). pose estimation 2). motion refinement. We take a clip of video as input and use BlazePose's detector model and landmarker model [4] to estimate 2D and 3D poses for each frame. The extracted features are then fed into the pose refinement network with ground contact constraints.

3.1. Pose Estimation and Ground contact detection

Our objective is to mitigate the walk-sliding problem and avoid foot-floating in the refined result. In Mediapipe each foot is represented by three interconnected joints: ankle, toe, and heel, as shown in (Fig. 1), where only the toe and heel joints can touch the ground. Binary labels are assigned to each of the four joints (left toe, left heel, right toe, and right heel) to record the ground contact state. Consequently, a ground contact event in a specific frame can be encoded as a four-bit vector. Since typical ground surfaces are neither slippery nor penetrable, each foot joint should be stationary in the video when the ground contact events occur.

Because the training data originates from MoCap videos recorded in a controlled laboratory environment, it would be difficult to generalize to real-world indoor and outdoor scenes if the model were trained directly from raw pixel data. As a result, alternative features have been utilized as input to the model. Intuitively, the 3D keypoint positions within a local temporal window contain valuable motion-related information such as velocity and acceleration. However, using raw 3D keypoint data directly from BlazePose presents three challenges. First, Mediapipe occasionally fails to detect the pose in some frames due to occlusions or unusual poses. Second, Mediapipe estimates joint positions based on one frame at a time, which can introduce high-frequency jitter due to temporal inconsistencies. Third, Mediapipe may produce inaccurate results, when the visibility score s is low. The following steps address these issues: Initially, we perform a linear interpolation to fill in the gaps created by undetected poses. Subsequently, we apply a

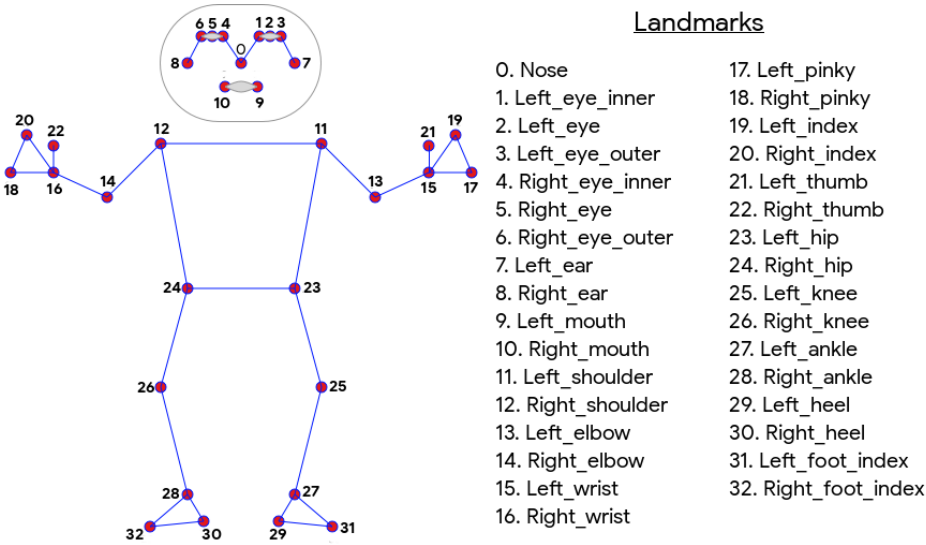


Figure 1. Definition of landmarks in MediaPipe Pose [4]

low-pass filter to reduce high-frequency noise for the estimated pose P. Finally, we obtain the cleaned 2D and 3D position $P_{cleaned}$ by calculating the weighted average of pose P. Thus, for every frame i and feature j, we can get the position:

$$P_{smoothed,ij} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} 1}{\sum_{i=1}^{n}\sum_{j=1}^{m} s_{ij}} s_{ij} P_{ij} \tag{1}$$

To train the network, ground contact labels are derived from the 3D motion sequences in the Human3.6M dataset. These labels are determined under velocity and height constraints. For the velocity criteria, joints are assumed to exhibit minimal sliding when in contact with the ground. Since Mediapipe's depth estimation for the 3D pose may vary even when the 2D pose estimation returns very similar values, the threshold v_{th} is determined based on the 2D velocity instead of the 3D velocity. A height criterion is used when people have their feet suspended above the ground. The 3D height of the forefoot and heel must be below a specified threshold h_{th}. To determine this threshold for each sequence, the average heel height h_{avg} and forefoot height h_{avg} are calculated for each subject based on the first five frames.

3.2. Network Structure

In this study, we propose the use of FCNs as the foundational architecture (2), based on the SmoothNet design[13], since FCNs are position-aware and easily trainable, leveraging the abundance of pose data derived from videos of human motion. Guided by the concept of superposition of movements [20], a movement can be decomposed into several independently executed motion segments where the feature for each axis can be processed independently.

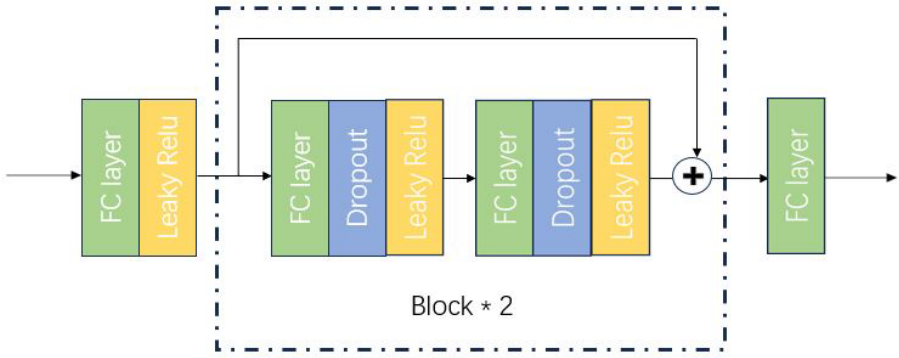


Figure 2. The proposed network structure

The input to the network is a $B \times T \times (J \times C)$ tensor, where B is the batch size, T is the temporal sliding window size, J is the number of joints, and C is the number of channels. There are three channels, which represent the position in the x, y, and z axes. We extract the pose estimator features with size $B \times H \times (J \times C)$ by passing through an embedding layer with hidden size H.

The output, which estimates the 3D position of the joints in the world coordinates, shares the same size as the input. It is computed by multiple layers of linear projection followed by a non-linear activation function with residual connections. The network has two residual connected blocks, with each block containing two fully connected layers. With a sliding-window approach, a segment of data with a length of T is extracted, the results within that segment are refined, and subsequently moved to the next segment using a step size of s, which is less than N. This approach ensures that the movement between segments is consistent.

3.3. Training Loss

Rather than the raw single-frame output provided by the baseline (Mediapipe), our goal is to produce a motion trajectory that exhibits greater temporal coherence and reduced jitter. To achieve this, we focus on minimizing both position loss $\mathscr{L}_{pos}$ and acceleration loss $\mathscr{L}_{acc}$ during training. The definitions of these objective functions are:

$$\mathscr{L}_{pos} = \frac{1}{T \times (J \times C)} \sum_{i=1}^{T} \sum_{j=1}^{J \times C} \left| P_{smoothed,ij} - X_{ij} \right| \tag{2}$$

$$\mathscr{L}_{acc} = \frac{1}{(T-2) \times (J \times C)} \sum_{i=1}^{T-2} \sum_{ij=1}^{J \times C} \left| P''_{smoothed,ij} - A_{ij} \right| \tag{3}$$

$P_{smoothed,ij}$ represents the smoothed 3D position output generated by Mediapipe. Subsequently, we obtain velocity and acceleration by computing the difference between two consecutive frames, as:

$$P'_{smoothed,ij} = P_{smoothed,(i+1)j} - P_{smoothed,ij} \tag{4}$$

$$P''_{smoothed,ij} = P'_{smoothed,(i+1)j} - P'_{smoothed,ij} \tag{5}$$

where X_{ij} is the predicted 3D position of the pose and A_{ij} is the acceleration calculated by Equation 4 and Equation 5.

Although the jittering is greatly reduced, the foot skating and floating problem remains unresolved when the feet are expected to remain firmly planted on the ground. Thus, we penalize the network if the foot is still moving when it touches the floor plane. The loss function $\mathscr{L}_{vel}$ based on the 3D velocity of joints is:

$$\mathscr{L}_{vel} = \frac{1}{T \times (F \times C)} \sum_{i=1}^{T} \sum_{j=1}^{F \times C} g \left| P'_{smoothed,ij} - V_{ij} \right| \tag{6}$$

where F is the number of foot joints. In our case, we have the forefoot and heel joints for each foot, so $F = 4$. V_{ij} refers to the predicted 3D velocity of the pose. g means the ground contact label which is determined by v_{th} and h_{th} as:

$$g = \begin{cases} 1, & \text{if } v_{2d} < v_{th} \text{ and } h < h_{th}. \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Predicting the foot joint position can become unreliable, especially when the foot remains occluded for an extended period. As people walk away from the camera, the forefoot joint may be scarcely visible throughout the entire movement. In a typical walking pose, the knee joint, the ankle joint, the forefoot joint, and the heel joint closely approximate one plane. To tackle this lack of reliability, the normal vector v of the plane, which is determined by the ankle joint, forefoot joint, and heel joint, is calculated. The vector u is computed by subtracting the 3D position of the ankle joint from the 3D position of the knee joint. With these vectors in place, the angle θ between vectors v and u can be calculated using the formula, $\cos\theta = \frac{u \cdot v}{|u||v|}$, which can exhibit slight inward and outward rotation, so a penalty is applied to the network when the angle θ exceeds the threshold θ_{th}. The loss function of $\mathscr{L}_{angle}$ is:

$$\mathscr{L}_{angle} = \frac{1}{T} \sum_{i=1}^{T} (ReLu(\theta_{left} - \theta_{th}) + ReLu(\theta_{right} - \theta_{th})) \tag{8}$$

where θ_{left} and θ_{right} are the angles computed from the left and right feet. The overall objective function thus is:

$$\mathscr{L}_{overalll} = \lambda_{pos}\mathscr{L}_{pos} + \lambda_{acc}\mathscr{L}_{acc} + \lambda_{vel}\mathscr{L}_{vel} + \lambda_{angle}\mathscr{L}_{angle} \tag{9}$$

where λ_{pos}, λ_{acc}, λ_{vel}, and λ_{angle} represent the weighting coefficients assigned to each component of the loss function.

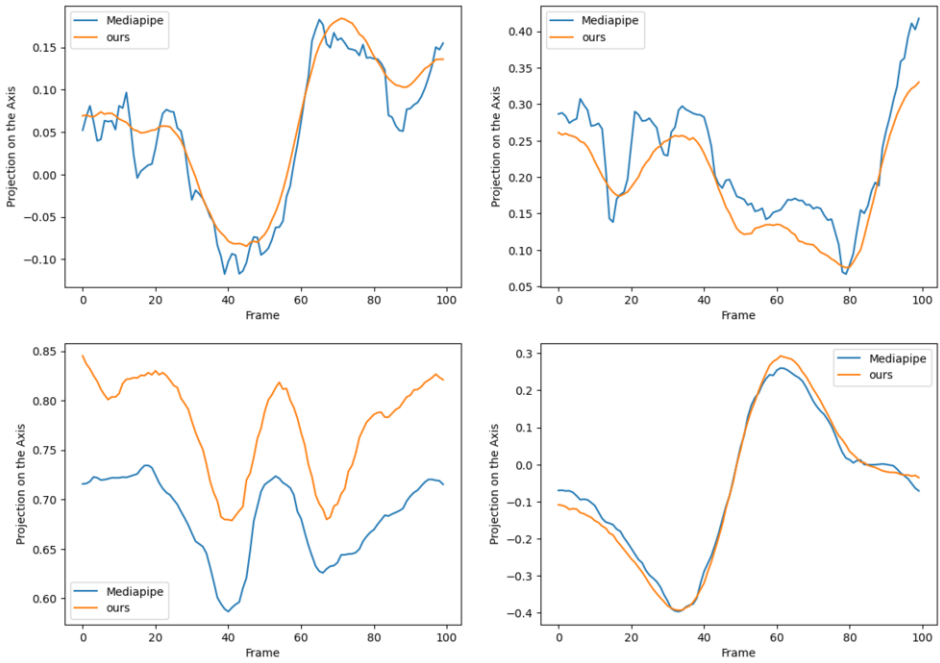


Figure 3. The projection of the prediction of the position of foot joints on one axis. The blue line represents the result of Mediapipe. The orange line represents the result of our method.

4. Experimental Results

Ideally, a perfect pose estimator that provides precise joint positions would not encounter jitters. In reality, the jitter problem can be categorized into two parts: short-term errors caused by the disparity between consecutive frames and long-term errors caused by the bias between the estimated foot pose and the ground truth. In most cases, short-term errors are easily mitigated using low-pass filters [9–11], while it is hard to identify ambiguous long-term errors due to poor video quality, unseen poses, or occlusion.

As shown in Figure 3, our prediction generally aligns with the output from Mediapipe, but displays more consistent smoothness. The bottom-left figure shows a discrepancy between the two predictions, indicating a long-term prediction error in the Mediapipe results.

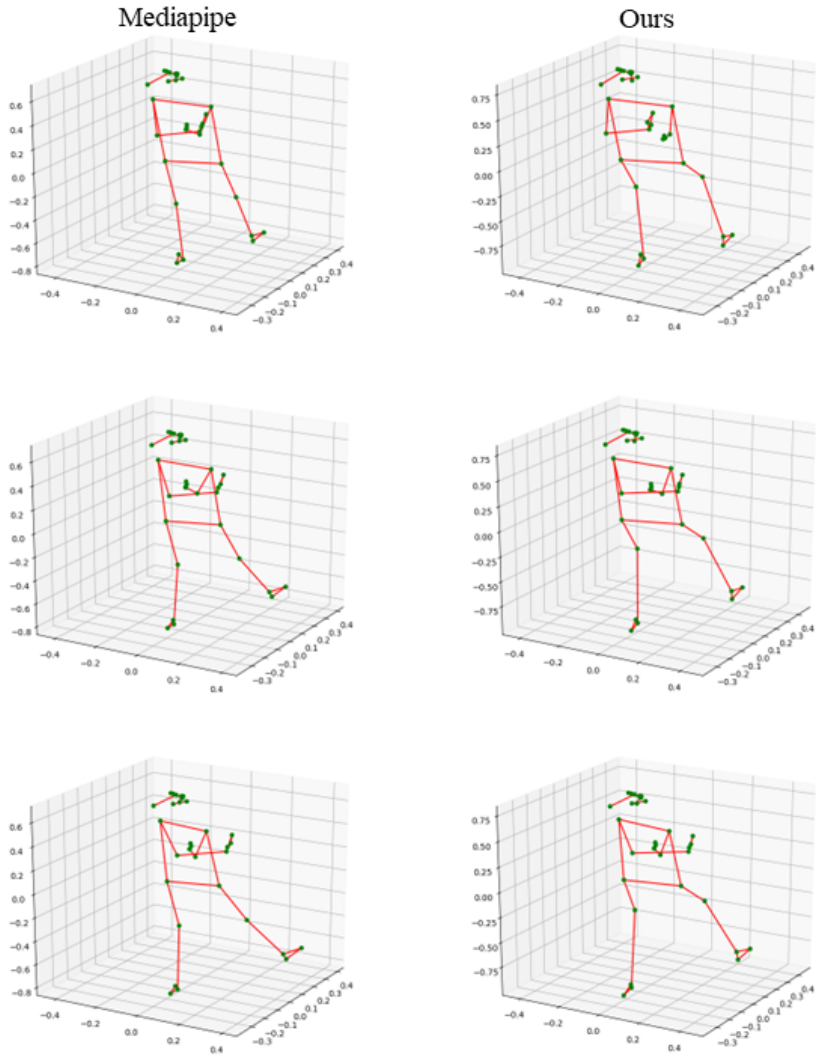


Figure 4. A 3D keypoint skeleton obtained by Mediapipe (left side) and our method (right side).

While solely utilizing the position feature predicted by Mediapipe, our method exhibits greater temporal stability and generates more natural poses without any additional information from the video (Figure 4). Although it does not explicitly address the knee joint, our network seems to adjust it autonomously, possibly due to the constraints imposed on the ankle joint. Consequently, our method differentiates between short-term and long-term errors by using additional information derived from ground contact and biomechanical plausibility.

Table 1. Foot prediction on the Human 3.6M Dataset [21] (best result is in bold)

	Smoothness Vel	Smoothness Acc	PNP	PA-MPJPE
Mediapipe [4]	0.6578	0.6448	0.5814	62.62
Gaussian Filter	0.5467	**0.2452**	0.7722	62.14
Smoothnet [13]	0.5765	0.3142	0.7845	61.11
HoT [22]	0.5236	0.2992	0.8317	**58.04**
Ours	**0.4981**	0.2889	**0.9230**	59.12

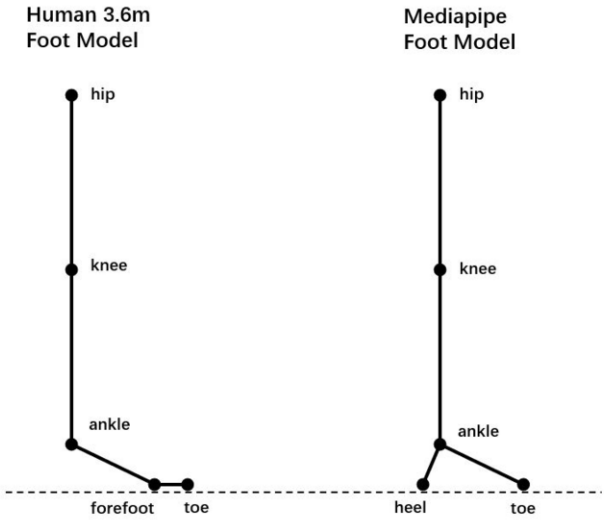


Figure 5. Illustration of the foot skeleton model. Left is the leg skeleton model from the Human 3.6m Dataset, while the right is from Mediapipe.

Our method was assessed and compared with others (the current state-of-the-art temporal smoothing network and the most popular low-pass filter) based on several criteria: smoothness, foot penetration into the floor plane, and mean per joint position error (MPJPE) after Procrustes alignment [23]. The deviation of the temporal consistency deviation from the ground truth 3D pose was used as a quantitative measure to compare the motion jitter. Our smoothness metric consists of velocity and acceleration, which can be computed by Equations 4 and 5. Percentage of Non-Penetration (PNP) quantifies the amount of non-physical foot penetration into the ground. Foot contact labels are calculated using Equation 7 to assess the presence of the actual foot contacts. The PNP metric shows the ratio of frames where the feet are not below the floor plane when the label indicates foot contact with the ground. We use the same skeleton format as that of Mediapipe, while the ground truth in the Human 3.6m Dataset has a different format. Given the significant dissimilarity between the whole-body skeleton models of Mediapipe and the Human 3.6m Dataset, we evaluate MPJPE based on a limited number of joints, specifically the hip, knee, and ankle joints for both legs, as illustrated in Figure 5.

Table 2. Comparison Results of Different Methods on the Human 3.6M Dataset [21] (best result is in bold)

Models	Smoothness Vel	Smoothness Acc	PNP
$\mathscr{L}_{pos} + \mathscr{L}_{vel}$	0.5083	0.4063	0.8710
$\mathscr{L}_{pos} + \mathscr{L}_{acc}$	0.5964	0.3471	0.7115
$\mathscr{L}_{pos} + \mathscr{L}_{vel} + \mathscr{L}_{acc}$	**0.4451**	0.3009	0.5754
Ours	0.4981	**0.2889**	**0.9230**

We conducted a number of controlled experiments to analyze the performance of different physical constraints. The results of this comparison are presented in Table 2, where we assess performance using three key metrics: Smoothness Vel, Smoothness Acc, and PNP.

In terms of Smoothness Vel, the model with three loss terms ($\mathscr{L}_{pos} + \mathscr{L}_{vel} + \mathscr{L}_{acc}$) achieves the lowest value (0.4451), indicating the smoothest velocity transitions. However, our proposed method achieves a competitive value of 0.4981, still outperforming the variants using only two loss terms. For Smoothness Acc, our full model obtains the best result (0.2889), demonstrating its superior ability to produce a temporally coherent motion in terms of acceleration. Our method significantly outperforms all baselines in the PNP metric, achieving a score of 0.9230, compared to 0.8710 for the best baseline. This suggests that our approach is more effective in generating natural-looking human poses without penetrating the floor.

The ablation results demonstrate that while the combination of the three loss terms improves motion smoothness, our full model achieves the best trade-off, particularly excelling in preventing foot penetration and acceleration smoothness. These findings confirm the importance of the proposed design choices and loss formulation.

5. Conclusion

Despite significant advances in 3D human pose estimation, reducing foot artifacts in the presence of occlusion and complex postures remains a challenge. In this paper, We present a method that aims to mitigate foot artifacts when reconstructing 3D human motions by explicitly applying physical constraints. Compared to existing solutions, our method demonstrates the capability to effectively manage prolonged and substantial errors that commonly occur in rare or complex poses. We show foot reconstruction results on a variety of videos and illustrate the improvements achieved by our method over the current state-of-the-art.

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Epidemic PINNs: A Chatbot Based on Dual Data-and Physical-Driven Epidemic Prediction

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Abstract. In this project, a chatbot is designed to analyze and predict data collected during the COVID-19 pandemic in Australia, with a specific focus on Victoria. Data for Victoria are extracted from comprehensive datasets covering all Australian states, and the chatbot utilizes the susceptible-infectious-recovered (SIR) model and a physics-informed neural network (PINN) to forecast the future dynamics for specific population groups. In addition to its predictive capabilities, the chatbot offers in-depth insights obtained through data analysis and text analysis of the overall dataset. By integrating advanced modeling techniques with conversational AI, this project delivers accurate forecasts and actionable data-driven insights, which can support public health decision making and enhance user engagement.

Keywords. Chatbot, Epidemics, Epidemic PINNs Prediction, Text Analysis.

1. Introduction

Although the COVID-19 pandemic has been past for some time, its long-term impacts on societies around the globe remain significant. This situation highlights the current lack of a reasonably effective and rapid means of predicting the behavior of outbreaks of epidemics for risk control, which represents a current challenge in terms of disease control and prevention. In the field of epidemic prevention and control, a large number of mathematicians and disease scientists have developed predictive models for disease control. The most prominent of these is the traditional epidemiological SIR model, with its straightforward mathematical formulation and solid theoretical foundation, which is

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widely used to simulate the dynamic process of epidemic spread[1]. In addition, in view of the complexity and multilateral nature of disease transmission, more sophisticated mathematical models have been developed the SEIR model[2] introduces an exposed (E) compartment to account for individuals who have been infected but are not yet infectious, thus providing a more accurate representation of the latency period in disease transmission. Similarly, the SVEIRD model[3] incorporates vaccination (V) as a separate state, thereby allowing for an analysis of vaccination strategies and their impact on disease dynamics. The SVEI3RD model[4] represents a significant advancement by further stratifying the infected population based on the severity of illness. However, these models rely on precise parameter settings (such as transmission and recovery rates), making it challenging to dynamically adapt to the transmission patterns at different stages.

Although pre-existing mathematical models are often inapplicable to novel viruses, data-driven machine learning models can capture information from real-world data about disease transmission to enable accurate end-to-end predictions. Tsan et al.[5] developed an LSTM and ARIMA model to predict daily new cases with high accuracy, which yielded outstanding performance for short-term forecasts. However, model training is more data-driven. It is difficult for real-time prediction as well as for emergencies to guarantee fitted dataset. At the same time, such end-to-end models are 'black boxes'[6], meaning their predictions lack transparency and interpretability, which diminishes their utility in supporting the development of the predictions and policy-making or providing deeper insights into epidemic transmission dynamics.

Faced with the limitations of deep learning models in regard to poor interpretation and strong dependence on the quality of the datasets, researchers have begun exploring hybrid approaches that combine deep learning with epidemiological mathematical models to construct dual data- and physics-driven disease prediction models. Raissi et al.[7] proposed Physics-informed neural networks (PINNs) which were a great success in solving differential equations and model interpretability. This approach also offers a feasible solution for solving epidemic SIR models. Building on this development, Rodriguez et al.[8] integrated a PINN with the SEIRM model to predict epidemic trends, which offered a more robust framework for combining machine learning with epidemiological models. Millevoi et al.[9] proposed the use of PINNs to track temporal changes in model parameters and state variables. Tronstad et al.[10] developed and evaluated a PINNs model for solving inverse problems in epidemiology as a way to reliably retrieve unknown constant parameters in SIR models. Notably, significant advancements have been made in this domain. Zhu et al. proposed a novel approach to effectively leverage physics-inductive bias—specifically, (partially) known governing equations—to inform the design of learning architectures. [11] These uses of physical and data-driven neural network models in the context of a mathematical model of epidemic transmission (a system of differential equations) can enable intelligent and accurate prediction of epidemic information.

There is a need for better application of the dual-driven model of data and physics to actual disease control and prediction, and a chatbot can address this issue to some extent by providing timely and accurate data as a foundation for individual decision making (Miner, 2020).[12]. This approach can effectively raise awareness and support public health decisions. In this project, a comprehensive set of epidemic data from all Australian states is used as raw data. We combine the SVEIRD model with a PINN to predict the future population dynamics of specific groups monitored during the epidemic, and integrate these predictive results into a conversational AI system. The chatbot is

designed not only to deliver accurate forecasts but also to provide users with an intuitive way to explore, analyze, and understand the overall dataset. By combining advanced modeling techniques with an interactive AI framework, this approach bridges the gap between complex epidemiological research and user-friendly applications. The chatbot provides actionable insights that can help individuals and public health systems better prepare for and respond to crises such as COVID-19.

The main structure of our paper is as follows. In Section 2, we introduce some previous chatbot-related work on epidemic regulation and prediction. In Section 3.1, we introduce the SVEIRD mathematical model for epidemic prediction, while in Section 3.2, we introduce our proposed model called Epidemic PINN. In Section 3.3, we introduce the designed chatbot. In Section 4, we explore the use of this chatbot in regard to some of the prediction results. In Section 5 and Section 6, we present discussion and conclusion to this work and some of our thoughts and prospects.

2. Related Work

Intelligent chatbots, with their ability to instantly respond to user needs and provide dynamic information support, have greatly enhanced the dissemination of information and the efficiency of services. This was particularly important during the pandemic, as medical chatbots have rapidly become a hotspot for research and development. Battineni et al.[13] have pointed out that patients can receive medical advice in a more convenient and efficient manner through the use of a chatbot, thus reducing the reliance on face-to-face consultations and at the same time alleviating the workload of medical professionals. Chakraborty et al.[14] proposed an AI chatbot interaction and prediction model that used a deep feed-forward multilayer perceptron, and constructed AI chatbots for lifestyle improvement programs. Mathew et al.[15] developed a suite of chatbots that can recognize a user's symptoms, in order to predict illness and recommend treatment options. Bali et al.[16] developed Diabot, 'a personalised diabetes prediction and patient interaction for professional diabetes diagnosis, using advanced natural language understanding techniques. Badempet et al.[17] have developed a medical system that is capable of predicting a wide range of illnesses, including liver disease, diabetes and heart disease, through machine learning techniques. Cheung proposed an ontology model for pandemic predictions [18] and 3DCNN model for triage classification[19]. Sivasamy[20] proposed AI chatbot models and employs recurrent neural networks to ensure efficient interactions and predictions, addressing the shortcomings of current guidelines for improving lifestyles. The system developed by Jayashree[21] predicts diseases based on the symptoms provided by the user using the concept of patterns in the AIML algorithm. The system also provides the user with doctor consultation details based on the predicted diseases. Sia[22] developed chatbots incorporating ANN disease prediction models, and suggested a potential solution for a more accurate disease prediction tool. Babu et al.[23] developed a BERT-based medical chatbot that used cutting-edge deep learning techniques to significantly improve medical communication and accessibility. Through the use of BERT, the traditional challenges faced by medical chatbots, such as an imprecise understanding of medical conversations, inaccurate answers to terminology, and inability to provide personalized feedback, can be addressed.

Currently, the vast majority of references have presented deep learning or large model-based medical chatbots that are capable of effective, safe, and accurate question-and-answer interactions, as well as functions such as medical diagnosis and information

prediction. However, none of these authors have considered integrating these chatbots with real mathematical models, resulting in poorly interpreted predictions and limitations for sudden and novel epidemics, where data are difficult to obtain. Hence, in this paper, we develop a chatbot that incorporates our Epidemic PINN model, which can consider physical information, reduce the dependence on data and increase the acceptability of the model. Our chatbot can therefore provide acceptable results in an accurate and safe manner.

3. Methodology

3.1. SVEIRD Model and Data Processing

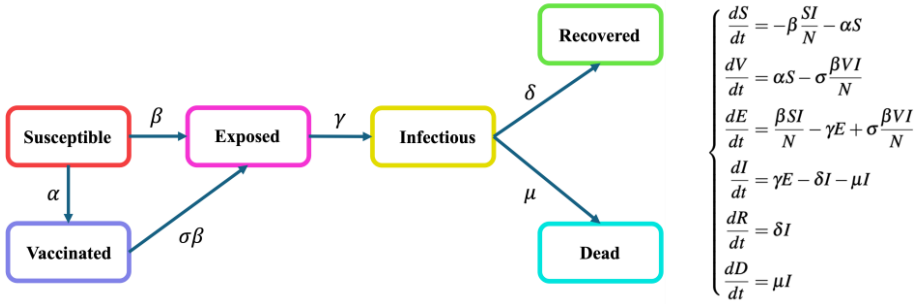


Figure 1. SVEIRD Model Framework

The proposed epidemiological forecasting question and answer system is primarily based on the SVEIRD model, and aims to perform epidemic predictions through the development of a chatbot application. The SVEIRD model is an extended compartmental model of infectious diseases, which includes six states: susceptible (S), vaccinated (V), exposed (E), infectious (I), recovered (R), and dead (D). These states describe the different stages through which individuals pass during the course of an epidemic, where trepresents a specific time point, and the letters represent the number of individuals in each state at that time. A state transition diagram for this model is shown in Figure 1, where the arrows represent the transition rates between states. For example, μ denotes the instantaneous rate at which the infected population pass to the death state, reflecting the rate at which infected individuals die.

A crucial parameter in this model is β, which represents the average number of contacts per person per unit time. Specifically, $\frac{\beta I}{N}$ represents the expected number of infections per unit time for a susceptible individual, while $\frac{\beta IS}{N}$ represents the expected number of new infections per unit time among the S susceptible individuals. If $\sigma = 0.05$, this means that the effectiveness of a vaccine is 0.95; in other words, vaccination reduces 0.95 of the contact transmission, while 0.05 of the contacts still lead to transmission. This effectiveness is reflected in the reduction of transmission rates among vaccinated individuals, which effectively curbs the spread of the virus.

The dynamic model of these different states is represented by a system of differential equations (Figure 1), where each equation models the instantaneous rate of change of each state variable. In this model, several key assumptions are made:

1). The total population size N is assumed to remain constant over time, meaning

that there is no migration and the population is closed.

2). The transition rates (such as the infection rate β, recovery rate γ, and mortality rate μ) are assumed to be constant, although they can be dynamically adjusted based on new data or interventions (such as vaccination campaigns).

3). The death state D and recovery state R are treated as absorbing states. Once an individual enters these states, they cannot transition to any other state, meaning that death and recovery individuals are no longer involved in the disease transmission process.

A detailed explanation of each variable and parameter in the model is provided in Figure 2. To ensure the accuracy and realism of the model, the initial values for these parameters will be directly taken from the existing literature, thus aligning the model's results with real-world epidemic dynamics. This will improve the predictive accuracy of the model. In the following section, these parameters and their sources will be further explained.

For data selection, we will therefore focus on identifying datasets that are relevant to the variables in the model, such as susceptible populations, infection rates, recovery rates, and death rates, to ensure that the data effectively support the construction and prediction of the model. In the following, we elaborate on the data preprocessing steps and the ways in which data analysis will be used to optimize the model's predictive capabilities. We will also explore how epidemic prediction models can be integrated with chatbot technologies to provide more efficient and intelligent solutions for epidemic prevention and control.

Parameter	Explanation
E	Exposed state: individuals who have been infected but are not yet infectious.
N	Total population: the total number of individuals in the model.
S	Susceptible state: individuals who have not been infected yet.
I	Infected state: individuals currently infected and capable of transmitting the disease.
R	Recovered state: individuals who have recovered from the infection and are immune.
D	Death state: individuals who have died from the infection.
γ	Incubation rate: the rate at which individuals move from the exposed state to the infected state.
σ	Vaccination inefficiency ratio: indicates the effectiveness of vaccination in reducing contacts.
α	Vaccination rate: the proportion of the population receiving vaccinations per unit time.
μ	Death rate: the rate at which infected individuals die.
β	Contact rate: the rate at which susceptible individuals come into contact with infected individuals.
δ	Recovery rate: the rate at which infected individuals recover and move to the recovered state.

Figure 2. Parameters and Explanations

After defining the model variables and parameters, we processed the dataset, which was drawn from an Australian epidemic study and was well suited to the requirements of the project. However, certain discrepancies between the dataset variables and the needs of the model, along with zero or negative values, meant that preprocessing was required. Figure 2 shows the original dataset variables; we retained the most relevant of these, and introduced two new variables: S_t (susceptible population) and I_t (infected population). Specifically, $deaths_{cum}$, $tests$, $recovered_{cum}$, and $vaccines_{cum}$ were mapped to D_t, E_t, R_t, and V_t, respectively. The collected V_t data represent individuals with both vaccine doses, where adjustments were made to approximate single-dose recipients based on the vaccination timeline, thereby improving realism. I_t was calculated as the cumulative number of confirmed cases minus deaths and recoveries,

while S_t was derived by subtracting the totals in other categories (e.g., deaths, recoveries, infections, vaccinations, and tests) from the state's constant population ($N = 6{,}629{,}870$). To refine the dataset, we limited the time range to the period March 1, 2020, through September 10, 2022, excluding early zero-dominant data and intermittent post-2022 reports due to policy changes. Outliers, specifically zero or negative values, were handled by replacing them with the average of the neighboring values when both were valid and above 20. This preprocessing prepared the data for construction of the chatbot and training of the prediction model.

3.2. Models Design

3.2.1. PINN for Predictive Modeling

A partial differential equation (PDE) with time dependence on the n-dimensional spacetime domain is given as

$$\begin{cases} u_t + \mathcal{N}[u(x,t),\lambda] = 0, & x \in \Omega,\ t \in T \\ \Psi[u(x,t)] = 0, & x \in \Omega_{IC},\ t \in T_{IC} \\ \Phi[u(x,t)] = 0, & x \in \Omega_{BC},\ t \in T_{BC} \end{cases} \tag{1}$$

where $u(x,t)$ denotes the exact solution of the PDEs, $N[\cdot]$ is a nonlinear differential operator, $\Psi[u(x,t)]$ is the initial conditions (abbreviated as IC) of the equation, $\Phi[u(x,t)]$ is the boundary condition of the equation, and λ is the hyperparameter of the partial differential equation, which is related to the physical environment. It is worth noting that this parameter cannot be measured accurately in many scenarios, and it varies with the physical environment.

Consider a model $F(X,t;\theta)$ to approximate the exact solution $u(x,t)$ of this PDE, i.e.,

$$u(x,t) \approx F(X,t;\theta) \tag{2}$$

where θ represents the neural network training parameters. Then a physics-informed network $PINNs(X,t;\theta)$ can be constructed, i.e.,

$$f := \mathrm{PINNs}(X,t;\theta) + \mathcal{N}[\mathrm{PINNs}(X,t;\theta),\lambda] \tag{3}$$

where θ is the parameters of the model. θ and λ can be obtained by model training which means that all the parameters of the model are obtained by minimizing the loss function.

The loss function of the model includes the loss arising from the training data, the loss related to the physical control equations, and the loss stemming from the initial margin conditions of the equations. Its main form is shown in Equation (4):

$$Loss = \mathrm{MSE}_{Data} + \mathrm{MSE}_{PDE} + \mathrm{MSE}_{ICBC} \tag{4}$$

where MSE_{Data} is the mean square error of the data training, MSE_{PDE} is the mean square error after enforcing the physical equations, and MSE_{ICBC} is the mean square error introduced by enforcing the initial margin conditions of the equations, specifically,

$$\mathrm{MSE}_{Data} = \frac{1}{N_{\mathrm{Data}}} \sum_{i=1}^{N_{\mathrm{Data}}} \left| u\left(x_i^{\oplus}, t_i^{\oplus}\right) - u_i^{\oplus} \right|^2 \tag{5}$$

$$\mathrm{MSE}_{PDE} = \frac{1}{N_{\mathrm{PDE}}} \sum_{j=1}^{N_{\mathrm{PDE}}} \left| f(x_j, t_j) \right|^2 \tag{6}$$

$$\mathrm{MSE}_{ICBC} = \frac{1}{N_{\mathrm{ICBC}}} \sum_{k=1}^{N_{\mathrm{ICBC}}} (|\Psi[u(x_k^*, t_k^*)]|^2 + |\Phi[u(x_k^*, t_k^*)]|^2) \tag{7}$$

where N_{Data} is the number of data points in the training set for the model in supervised learning, which consists of the configuration point $\{x_i^{\oplus}, t_i^{\oplus}\}_{i=1,2,\ldots,N_{Data}}$ with known information in the physical system. $u_i^{\oplus}$ is the known solution corresponding to the configuration points. N_{PDE} is the number of all the data points $\{x_j, t_j\}_{j=1,2,\ldots,N_{PDE}}$ in the training set, and N_{ICBC} is the number of sampling points $\{x_k^*, t_k^*\}_{k=1,2,\ldots,N_{ICBC}}$ on the PDEs' initial margin condition in the unsupervised learning process of the model.
Depending on the task, a model driven by both data and physical information contains two losses, MSE_{Data} and MSE_{PDE}, and not necessarily the MSE_{ICBC} loss in the supervised learning task, and only two losses, MSE_{PDE} and MSE_{ICBC}, in the unsupervised learning task, where MSE_{Data} is the loss error for training on known data points, reflecting the data-driven feature of the model, while MSE_{PDE} and MSE_{ICBC} are the loss errors for the physical equations and initial margin conditions, reflecting the physical information-driven feature of the model.

The PINN model is built on a $N+2$ deep fully connected neural network (FCNN) with one input layer, N hidden layers and one output layer with n neurons in each hidden layer. Each neuron in each layer is activated by the activation function $\sigma(x)$, as follows,

$$L_1 = W_1 X + b_1 \tag{8}$$

$$L_k = W_k \sigma(L_{k-1}) + b_k \quad k = 2,3,\ldots,N+1 \tag{9}$$

$$u_\Theta(X) = W_{N+2} \sigma(L_{N+1}) + b_{N+2} \tag{10}$$

where $L_k(k = 1,2,\ldots,N+1)$ is the combination of vectors after the activation of neurons in the former $N+1$ layers of the PINN. W_k and $b_k(k = 1,2,\ldots,N+2)$ represent the corresponding weight matrix and bias vector of each layer of the FCNN, respectively; u is the output of the PINN, and u_Θ represent all the parameters of the model. The PINN model is used to learn Equation (2), and the model is trained by minimizing the loss function in Equation (4) to find the optimal values of the model parameters Θ^*.

$$\Theta^* = arg \min_{\Theta} \{ \mathrm{Loss}(\Theta) \} \tag{11}$$

3.2.2. New activation function: Adaptive Sine Wave Function

The activation function is an important part of a neural network. It usually consists of nonlinear functions, and is used to improve the expressive ability of the model. For a dual-driven model based on data and physical information, since the parameter optimization process needs to be achieved by minimization of the loss function and neural network backpropagation, an activation function is required with a high level of smoothness and differentiability. Some common activation functions such as ReLU, tanh, and sigmoid have a wide range of relative application scenarios[24], for example, the ReLU activation function[17] is used in the Transformer structure to enable the model to be trained quickly. However, when this activation function is used in the PINN model,

it fails and the training effect is poor. The main reason for this is that the PINN has a strong dependence on the derivative of the activation function, but the derivative of the ReLU function is constant zero at zero non-conductivity and negative values, and the backpropagation of its derivative has uncertainty, leading to model failure[25].

In wavelet analysis and Fourier transform theory, all signals, whether periodic or non-periodic, can be decomposed into integrals of sines and cosines at different frequencies. This means that any functions can be approximated theoretically by models of the sine wave function as the activation function. Combined with the idea of an adaptive activation function, as proposed by Jagtap et al.[26], we propose an Adaptive Sine Wave Function (ASW) to be used as the activation function of PINN as in Equation (12).

$$\sigma_{\mathrm{ASW}}(x) = \alpha_1 \sin(\beta_1 x) + \alpha_2 \cos(\beta_2 x) \tag{12}$$

where $\alpha_1, \alpha_2, \beta_1, \beta_2$ are adaptive parameters that are learned through model training. Theorem 1 below gives a simple proof of the good convergence of the deep learning model under the action of ASW.

Theorem 1: Let be an infinite-width neural network with *n* hidden layers, which can approximate any real-valued function if it uses the adaptive sine wave activation function ASW as the activation function.

Proof: The proof follows the real Fourier transform. For any given input *X* and its corresponding real-valued objective function *f*(*x*), the Fourier integral is as follows,

$$f(x) = \int_{-\infty}^{+\infty} F_s(\omega) \sin(\omega x)\, d\omega + \int_{-\infty}^{+\infty} F_c(\omega) \cos(\omega x)\, d\omega \tag{13}$$

where F_s and F_c are the coefficients of the sine and cosine, respectively.

Then, by Riemann sum approximation, the integral can be approximated as an infinite sum such that,

$$f(x) \approx \sum_{n=1}^{\infty} [F_s(\omega_n) sin(\omega_n x) + F_c(\omega_n) cos(\omega_n x)] \equiv W_k \cdot \Theta_{k-1} \tag{14}$$

$$\Theta_k = \sigma_{ASW}(W_{k-1} \cdot \Theta_{k-2}), \ldots, \Theta_k = \sigma_{ASW}(W_1 \cdot X) \tag{15}$$

where W_k is the weight of the *k th* hidden layer of the neural network.

Since the neural network is assumed to be infinitely wide, i.e., $\| W_k \| \to \infty$, it is possible to divide Equation (4) into infinitesimal intervals of segmented summation to arbitrarily approximate the real-valued function $f(x)$. Since the series general term is a linear combination of the sine and cosine functions, the series is uniformly bounded and converges, and the weight matrices of each hidden layer also then converge. Hence, a deep neural network with ASW is a general-purpose approximator of any given function f. In practice, most PDE solutions contain only a finite number of major frequencies, meaning that the approximation of the true solution can also be achieved using a neural network with finite parameters.

3.2.3. Use of Epidemic PINN to Predict Information

In order to successfully predict information about an epidemic, we consider combining the SVEIRD physical control model of epidemics with a PINN to achieve intelligent

predictions of important epidemiological data, such as epidemic susceptibility ratios, vaccination rates, exposure rates, infection rates, response rates and mortality rates.

The proposed Epidemic PINN has 10 layers, where the first is a one-dimensional input layer, the 10th layer is a six-dimensional output layer, and in the middle is an eight-layer fully connected hidden layer with a total of 256 neurons per hidden layer.

For the activation function of this model, we use the ASW function proposed in this paper. Since we are interested in practical scenarios, the input to this prediction model consists only of the point in time that we want to predict, while we need to output six important forms of epidemic information. The ASW activation function is first needed to map the input time T to different frequency domains, and the model then learns the time-frequency domains to obtain more information about the data, thus achieving effective learning of the unit input multiple outputs. The L-BFGS optimizer was chosen to optimize the parameters of the model, and the training set was drawn from the SVIRED model dataset with pre-processing. Training of the model was performed on an NVIDIA RTX 2060, with a total training time of 42.5 minutes.

The model structure and specific loss function design can be seen in Figure 3.

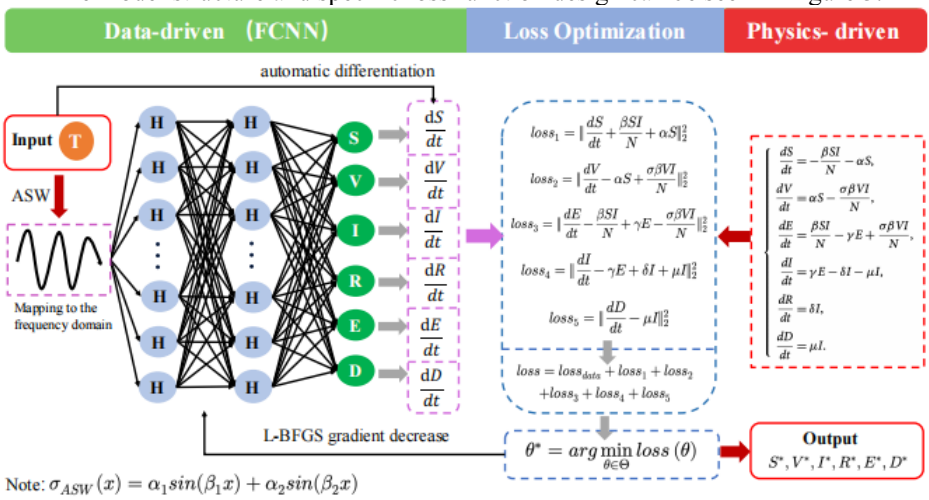


Figure 3. Epidemic PINNs Model Framework

3.3. Chatbot Design

3.3.1. Text Analysis

This subsection focuses on the methods and tools used for the analysis of text data, including natural language processing (NLP) techniques and sentiment analysis.

At the text analysis stage of our chatbot design, we use NLTK to help us process the user input and obtain a filtered input for further analysis. In this chatbot project, the code for text preprocessing is designed to enhance the accuracy of text analysis by eliminating irrelevant information from user queries. Initially, the default English stopwords provided by the NLTK library are used as a base set of stopwords. To handle the specific context of number-related queries, additional words such as ”number” are added to the stopword list, since they appear frequently but do not contribute to identifying the user’s intent. The preprocess input function then processes the user input

in four steps: (1) converting the text to lowercase, to ensure case insensitivity; (2) removing punctuation, in order to focus solely on meaningful words; (3) tokenizing the input into individual words using word-tokenize; and (4) filtering out the stopwords to retain only relevant words. The resulting filtered words are subsequently used for name mapping and to extract the user's intended query. This preprocessing pipeline ensures that the chatbot operates effectively in terms of understanding and responding to user requests.

3.3.2. Use of Regular Expressions to Extract Key Information

Regular expressions represent a powerful text-matching tool that can be used to extract specific key information from user natural language inputs. Through the use of regular expressions, the chatbot can automatically recognize time, numerical values, and other relevant data from queries and convert them into model inputs. For instance, when a user asks, "What is the infection rate five days after the introduction of the vaccine?" we can use regular expressions to extract the number "5" from the query and pass it as the time point $T = 5$ to the model for prediction.

Using this method, the chatbot can effectively handle user queries related to time or quantities.

3.3.3. Use of Intent Classifiers to Understand User Intent

To further understand the core intent of the user, we use an intent classifier to map user queries to predefined intent labels. For example, users may inquire about infection rates, mortality rates, or vaccination effectiveness. With the intent classifier, the system can identify the user's need based on the content of the query, and then forward the query to the corresponding prediction model.

This allows the chatbot to recognize user needs more accurately and to provide more precise responses.

3.3.4. Design of User Interface

The chatbot's architecture exemplifies a sophisticated integration of back-end and frontend technologies, forming a comprehensive and efficient system. The back-end, acting as the system's core, manages user requests, executes computational tasks, and oversees natural language understanding and response generation. It leverages advanced algorithms and models to analyze inputs, extract information, and generate contextually relevant replies, while ensuring seamless communication between the front-end and the underlying NLP modules.

At the front-end, a combination of markup and scripting technologies is used to construct an intuitive user interface. Markup languages define the layout of interactive elements such as input fields and message displays, providing a structured framework for user interaction. Through event-driven programming, scripting technologies enable realtime communication by dynamically updating the interface with user and bot messages, and triggering back-end responses to the user's actions.

In essence, the synergy of these two components, the back-end's computational capabilities and the front-end's interactive design, enables the chatbot to handle a diverse range of user queries and to facilitate effective conversations.

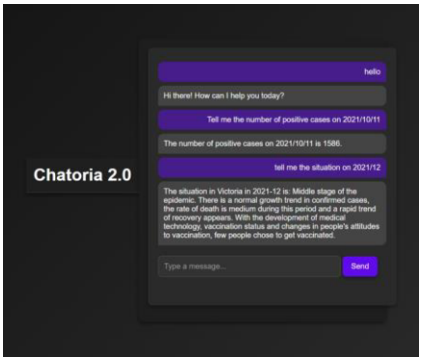


Figure 4. User Interface of Chatbot

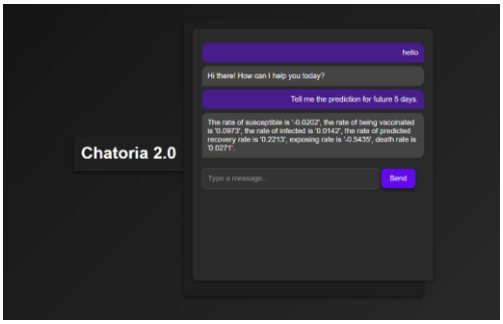


Figure 5. Predictive result of epidemic

4. Results

4.1. Presentation of Results

Epidemic PINN, our primary pandemic information prediction model, was plugged into our chatbot to enable rapid prediction of important pandemic information. The user simply needs to enter into the chatbot the number of days since the emergence of the vaccine they want to know about, and the model quickly predicts the number of days since the emergence of the vaccine associated with the pandemic on the *T th* day. Epidemic PINN can quickly predict the susceptibility, vaccination, infection, exposure, response, and mortality rates for day *T* after the vaccine during a pandemic.

For instance, when a user inputs "Tell me the predictions for the five days after the appearance of the vaccine," the chatbot, leveraging the pre-trained Epidemic PINN, can promptly provide specific results. As shown in Figure 1, on the fifth day after the vaccine introduction, the model predicts a susceptibility rate of -0.0202, a vaccination rate of 0.0973, an infection rate of 0.0142, a recovery rate of 0.2213, an exposure rate of -0.5435, and a mortality rate of 0.0271.

This response from the chatbot tells the user that on Day 5 after the vaccine was introduced, the model predicts that the susceptibility rate for the epidemic will fall to -0.0202, the vaccination rate will rise to 0.0973, the infection rate will fall to 0.0142, the recovery rate will rise to 0.2213, the disease exposure rate will fall to -0.5435, and the mortality rate will fall to 0.0271. This also suggests that the vaccine will significantly impact on community health, effectively curbing the spread of the epidemic, reducing mortality, and protecting the susceptible population. Predictive data of this type offer valuable guidance for formulating public health protection policies and disease control strategies. policies and disease control strategies.

4.2. Mini User Study

4.2.1. Participant Information

Total Participants: 10; Average Age: 28 years (Range: 22–42 years); Technical Proficiency: 5 technical users, 5 non-technical users.

4.2.2. Response Latency

Response latency measures the time between a user's query input and the system's response. We recorded the response times for each user across three different queries to evaluate system performance.

Analysis: The average response time was 1.1 s. The response times for most users remained around 1 s, indicating a very fast process. The slight variations in response times are likely to be due to different types of queries, with no significant delays observed. These results demonstrate that the system is highly optimized for speed, with no major issues in performance.

4.2.3. Interaction Fluency ("Crawling Feel")

The fluency of the interaction was assessed using a perceived fluency scale, with users answering the following questions: "Was the chatbot's response timely?", "Did you experience any delays or lags during the interaction?" and "How would you rate the overall interaction experience?"

Table 1 Response Latency Results

Participant ID	Query 1 Response Time (s)	Query 2 Response Time (s)	Query 3 Response Time (s)	Average Response Time (s)
1	1.2	0.9	1.1	1.1
2	1.3	0.8	1.0	1.0
3	1.1	0.9	1.2	1.1
4	1.4	1.2	1.3	1.3
5	1.0	0.7	1.1	0.9
6	1.2	1.1	0.8	1.0
7	1.3	1.0	1.2	1.2
8	0.9	1.0	1.1	1.0
9	1.1	1.0	1.2	1.1
10	1.2	0.9	1.0	1.0

The ratings were based on a 1–5 scale (1 being very poor, 5 being very smooth).

Table 2 Interaction fluency ratings

Participant ID	Response timeliness	Presence of delays	Overall interaction	Average score
1	4	3	4	3.7
2	5	4	4	4.3
3	4	3	4	3.7
4	3	2	3	2.7
5	4	3	4	3.7
6	5	4	5	4.7
7	3	2	3	2.7
8	4	3	4	3.7
9	5	4	5	4.7
10	4	3	4	3.7

Analysis: The average interaction fluency score was 3.9. Most participants reported that the chatbot's responses were timely, although some (such as participants 4 and 7) experienced delays or lag when entering more complex queries. The system's fluency could be improved, particularly in the case of complex queries that might lead to delays.

4.2.4. Usability

Usability was evaluated using the System Usability Scale (SUS), and participants rated their experience with the chatbot based on the following statements: "I find the chatbot easy to use", "I did not encounter difficulties while using the chatbot" and "Overall, I am satisfied with the chatbot's usability." The scores were calculated based on the SUS methodology.

Analysis: The average SUS score was 78.1. Most users rated the chatbot highly in terms of usability, especially the more technically proficient users (e.g., participants 6 and 9). However, participants 4 and 7 gave lower ratings, suggesting there are usability issues that need to be addressed, particularly for non-technical users. Improvements to the interface design and overall usability are recommended.

Table 3 Usability scores (SUS)

Participant ID	SUS score
1	75
2	85
3	78
4	60
5	80
6	90
7	65
8	78
9	88
10	80

4.2.5. Summary of Results

(1). Response latency: The system's response time was generally acceptable, with most queries being answered within 5 s. However, there is a need for further optimization to reduce the response times for more complex queries.
(2). Interaction fluency ("crawling feel"): While most users reported satisfactory fluency, delays were experienced by some users, especially when handling more complex queries. Improving the system's performance in such cases would enhance the overall user experience.
(3). Usability: The system was generally easy to use, with a high average SUS score. However, some non-technical users found the system difficult to navigate, indicating that improvements to the interface and user experience design are needed.

4.3. *Ethics and Safety*

In this project, ethical and security considerations formed an indispensable part of the system's design. With the continuous advancements in technology, especially in the field of public health, proper handling of data and the protection of user privacy have become increasingly important. The aims of this project included a commitment not only to providing efficient epidemic predictions and health recommendations but also to uphold user privacy and data security, in order to ensure that ethical and legal standards are followed in the delivery of services.

4.3.1. Preventing Users from Receiving Incorrect Information

To prevent users from receiving incorrect information, we took several measures, as described below.

Disclaimer When providing prediction results to users, the system includes a clear disclaimer informing them that the information is for reference only, and that the actual situation may differ from the model's predictions. The disclaimer reminds users that since the model relies on historical data and existing algorithms, the prediction results cannot be guaranteed to be 100% accurate, especially in the early stages of an epidemic or when data are scarce, since predictions in such cases have a higher level of uncertainty. The system therefore regularly notifies users with the message: "The prediction is based on current data and models, and the actual situation may differ. Please rely on the actual situation."

Quantification of Uncertainty When providing predictions, the system quantifies the uncertainty of the prediction results. For example, in predictions of epidemic spread, the system provides confidence intervals or error margins to indicate potential fluctuations in the predicted results. This allows users to clearly understand the uncertainty behind each prediction and to avoid overreliance on the predicted outcomes.

Real-Time Data Updates Prediction results are adjusted based on the latest health data, to ensure that the system reflects the most up-to-date epidemic dynamics. The system regularly obtains real-time data from official sources and promptly updates the model's predictions, thereby providing users with the latest epidemic information.

4.3.2. Privacy Protection for Health-Related Queries

When handling health-related queries, user privacy and data security are critical considerations. To ensure the security of user data, we implemented the following measures in the design of the system.

Data Anonymization The system does not collect users' personal identification information (such as name, contact details, etc.), and all user input data are anonymized. This means that even if the system records users' query content, the user's identity will not be linked to their queries, thus effectively preventing privacy breaches.

User Data Control Users have control over their data when using the system, and can view, modify, or delete these data at any time. In addition, users can choose whether to share their health data. The system respects users' privacy choices and ensures transparency and controllability of the data.

5. Discussion

In the context of existing epidemic prediction research, the main innovation of this study lies in the integration of the Epidemic PINN model with a chatbot system to provide a solution that can both generate predictions in real time and interact with users. Traditional epidemic prediction systems mostly rely on static models and manual data input, whereas the system developed in this study can quickly respond to user inquiries, offering real-time prediction results and dynamic information. This provides a more efficient and intelligent tool for public health decision making.

Compared to traditional epidemiological models, Epidemic PINN offers greater flexibility and scalability when handling large-scale data. Using deep learning techniques,

Epidemic PINN is not only trained on historical data but also accounts for the complexity and dynamics of epidemic spread during the prediction process. While existing epidemic prediction studies often focus on macroscopic trends, neglecting local dynamic changes and individual-level impacts, the system proposed in this study can more accurately simulate the development of an epidemic at different time points, especially after the introduction of a vaccine, allowing for more precise predictions of various health indicators.

Although our Epidemic PINN model with a chatbot is able to take into account the mathematical modeling of epidemic trends, thus making the model predictions more accurate and making the model interpretable, our model is not able to make predictions for multiple epidemics, in the same way as large language models (LLMs), and the model is still reliant on the training data, which are insufficient for outbreaks. In future work, we will consider accessing data- and physically-driven LLMs via a chatbot, so that the chatbot can be used for safer, more efficient, and more accurate real-time Q&A scenarios.

6. Conclusion

In this project, a chatbot system was developed based on the SVEIRD epidemic prediction model, with the aim of providing real-time epidemic dynamic information, personalized advice, and predictive insights into the spread of infectious diseases. As an intelligent interface, the chatbot leverages the predictive capabilities of the epidemic model to answer users' questions about infection rates, vaccination coverage, and the likelihood of an epidemic outbreak. It represents a tool that can help individuals and public health organizations better understand and manage the risks of epidemics. In the future, the functionality of the system could be enhanced by integrating real-time global health data, improving the chatbot's NLP capabilities, and expanding the system to cover other types of infectious diseases or public health emergencies. In summary, this project has demonstrates the significant potential of combining epidemiological modeling with conversational AI, paving the way for future innovations in public health informatics and epidemic management, and providing an expandable, efficient, and user-friendly solution to global health challenges.

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Domain-Aware Healthcare Chatbot Incorporating BERT and RAG

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Abstract. Existing healthcare chatbots suffer from diagnostic inaccuracy, poor con- text awareness, and reliance on static knowledge, leading to unsafe generic advice. We introduce a novel chatbot addressing these limitations. Our key contributions are: (1) A hybrid architecture combining BERT for query intent classification with a fine-tuned LLM for response generation; (2) Inclusion of Retrieval-Augmented Generation to dynamically access authoritative medical knowledge; and (3) A Gradio interface enabling user interaction. This approach significantly enhances response accuracy (alignment with medical facts), contextual relevance, and reliability (reducing model hallucinations). Evaluation shows a marked improvement over baselines: BLEU-4 increased from 14.8 to 27.5, and substantial gains in ROUGE-1 (19.7 to 25.6), ROUGE-2 (2.9 to 5.0), and ROUGE-L (9.3 to 16.1), demonstrating superior overall performance.

Keywords. healthcare chatbot, domain classification, fine-tuning, RAG

1. Introduction

1.1. Problem Statement and Current Issues

In recent years, the demand for intelligent healthcare support has significantly increased, yet most general-purpose chatbots fail to deliver accurate, relevant, and specialized re- sponses in the health science domain. Many users seeking medical guidance through chatbots encounter vague or incorrect information, which can lead to confusion and even potential harm. Existing solutions often lack the capacity to accurately classify complex medical queries and do not effectively utilize domain-specific knowledge, resulting in suboptimal user experiences and unreliable assistance.

1.2. Proposed Solution

To address these issues, we have developed a chatbot designed specifically for the

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health science domain. Our approach combines advanced deep learning methods with domain expertise to create a chatbot capable of understanding, classifying, and responding to a wide range of health-related questions with high accuracy and relevance. The core of our solution involves a two-stage process: first, a classification model identifies the specific category of the user's input, and then a fine-tuned large language model (LLM) generates specialized responses. Furthermore, we enhance the chatbot's capabilities by including Retrieval-Augmented Generation (RAG) technology, leveraging a local medical knowledge base to provide more authoritative and precise answers.

1.3. Aims and Objectives

The main aim of this project is to develop a healthcare chatbot that delivers accurate and contextually relevant medical information. The specific objectives are:

- To build a robust classification model capable of categorizing user queries into specialized health science domains.
- To fine-tune an LLM so that it generates high-quality, domain-specific responses.
- To include RAG techniques to supplement the chatbot's responses with verified content from a curated medical knowledge base.
- To evaluate and improve the chatbot's performance in terms of accuracy, rele- vance, and responsiveness.

1.4. Scope of Study

This study focuses exclusively on the health care domain, aiming to provide in-depth, reliable support for health-science related queries. The chatbot is not designed to handle general or non-health science conversations, nor does it aim to replace professional medical consultation. Its primary scope is to assist users with health science questions, offering guidance, explanations, and support based on up-to-date medical knowledge. Interactions outside the medical or health science context may not be handled with the same level of expertise or accuracy.

2. Literature Review

Chatbots [1] have become a prominent application of natural language processing (NLP) [2] in both industry and research. Early chatbots such as ELIZA [3] used rule-based systems to generate responses but lacked the capacity to handle context or ambiguity. Recent advancements in deep learning and pre-trained language models have significantly improved the performance of chatbots [4], enabling more natural and context-aware interactions. In the healthcare domain, chatbots improve accessibility, assist patients, and provide medical guidance through natural human-like conversations [5,6].

As the market for online medical consultation has grown, building an effective Healthcare Chatbot (HCB) has emerged as a critical application area of NLP [7]. These systems simulate doctor-patient dialogue to offer health counseling and preliminary diagnostic suggestions [8]. The development of medical chatbots requires advanced language modeling and large, high-quality datasets. The research presented in this paper, based on the iCliniq and HealthCareMagic datasets, applies deep learning techniques such as

BERT [9] to achieve domain classification [10] and medical question answering (Q&A) [11] , aiming to improve the reliability of medical dialogue systems.

To facilitate accurate responses, prompt construction is aligned with classification outputs, since prompt-guided generation enhances the factual accuracy and controllability of responses from LLMs [12]. To adapt LLMs to the medical Q&A task, we fine-tuned a distilled version of the DeekSeek Qwen-7B model [13] using the LoRA (Low-Rank Adaptation) method [14], which enables efficient adaptation by freezing most of the base model's weights and updating only a few low-rank matrices. LoRA is motivated by [15] and [16], which has shown that the learned over- parametrized models in fact reside on a low intrinsic dimension. LoRA has been shown to reduce hardware requirements [17] and support effective instruction tuning [18].

Moreover, to enhance the factual accuracy of the answers and reduce hallucinations, our project incorporates the Retrieval-Augmented Generation (RAG) framework [19]. RAG retrieves relevant content from external medical knowledge bases as context for the generation of the responses, improving both the accuracy and the interpretability [20].

Despite substantial progress in model architectures and training strategies, significant challenges remain in the development and deployment of health care related chatbots. Most systems continue to be trained and evaluated on synthetic or exam-style datasets, such as USMLE questions or expert-crafted vignettes, which do not fully capture the complexity and ambiguity of real-world clinical practice [21,22,23]. Studies have demonstrated that model performance often declines when faced with noisy, incomplete, or ambiguous real-world patient data [24,25]. Moreover, critical evaluation dimensions—such as robustness, calibration, and bias—are frequently overlooked, even though LLM have been shown to propagate human-like and race-based biases in their outputs [26,27,28,29]. Also, there is a lack of dynamic prompt engineering strategies that tailor the generation process to specific medical subdomains or user intents, which can limit both the specificity and relevance of chatbots' responses [12].

Table 1. Comparison of Healthcare Chatbot Approaches

Type	Methods	Limitations	Refs
Rule-Based	Pattern matching	Context-blind	[3]
ChatGPT-like	LLM	Hallucinations, Bias	[21]
Med Specialized	Instruction tuning	Real-world gap	[22]
RAG Hybrid	Retrieval LM	Source dependency	[19]
Multimodal	Medical Multi Question Learning	Limited generation	[11]

Our integrated medical QA pipeline tackles real-world ambiguity via a fine-tuned BERT domain classification and dynamic prompting [9,12], improving specificity and guiding the LLM. To reduce hallucination and enhance its factual accuracy, it employs Retrieval-Augmented Generation (RAG) [20,19], grounding responses in authoritative evidence from curated sources integrated into the prompts. Efficient specialization is achieved using Low-Rank Adaptation (LoRA) [14,17] for parameter-efficient fine

tuning of the LLM. Its modular design ensures its scalability. Addressing bias involves RAG source auditability, careful data curation, and potential bias-aware prompting, recognizing the need for continual mitigation efforts.

A crucial aspect of deploying such chatbots lies in developing intuitive and efficient user interfaces. Among the various available tools, Gradio has gained increasing popularity for its simplicity, flexibility, and rapid prototyping capabilities. Gradio provides a Python-based API that allows developers to build interactive web interfaces with minimal effort. Its seamless integration with Hugging Face's model ecosystem and support for real-time interaction make it particularly well-suited for conversational healthcare applications. In addition to chatbot applications, Gradio has also been used to create interfaces for other machine learning tasks, such as image classification and quality grading [30]. Furthermore, Ling et al. [31] presented the EasyInstruct framework which facilitates instruction processing for LLMs. Goswami and Gupta [32] also contributed to the field by building an AI Chatbot using LLMs.

3. Methods

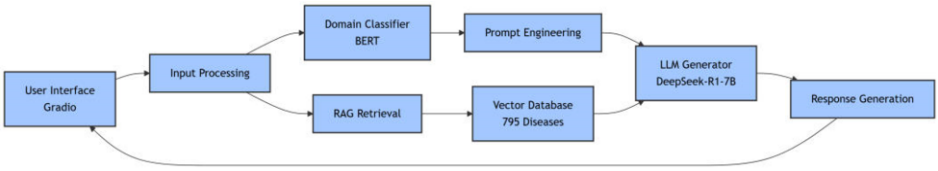


Figure 1. System Components

3.1. Data Sources, Data Cleansing and Pre-processing

The dataset used in this project is the iCliniq medical consultation dataset, which consists of approximately 73,000 rounds of real-world user medical questions and answers provided by certified doctors. Each consultation may involve multiple responses to a single question, reflecting follow-up inquiries, clarifications, and iterative interactions between patients and medical professionals [6]. The dataset spans a wide range of health-related topics and incorporates substantial domain-specific medical terminology, making it well-suited for training models on both classification and response generation tasks [11].

In addition to the iCliniq dataset, we also incorporate historical real question-and-answer pairs collected from online medical consultation platforms in the United States. These data sources include not only the replies by professional doctors but also responses generated by chatbots, offering a diverse and multi-source corpus. To support the supervised training of classification models, we employ a keyword-based annotation strategy [12] to assign each consultation to its corresponding medical department, forming structured labeled training data.

To ensure the consistency and utility of the training data, a thorough data cleansing pipeline was implemented. This includes the removal of duplicate entries and redundant follow-up questions, as well as filtering out consultations that are incomplete, off-topic, or contain incoherent or non-medical text. Furthermore, we normalize the raw text by resolving character encoding issues, stripping irregular punctuation and symbols, and eliminating any HTML artifacts or markup tags

embedded in the original responses. The result is a curated dataset optimized for high-quality domain classification and robust downstream fine-tuning in a medical dialogue system.

3.1.1. Domain Labeling

To enable supervised learning for domain classification, each medical consultation in the dataset was assigned a medical domain label. The domain labeling process followed a rule-based approach [3], using domain-specific medical keywords and phrases to map the consultations to the appropriate categories [12]. First, a list of medical keywords was constructed based on common symptoms, conditions, and terminology associated with various medical specialties. For example, terms such as rash and itchy were associated with Dermatology, while pregnancy, menopause, and bleeding were associated to Gynecology. Each consultation was scanned for the presence of these keywords. When one or more domain-specific terms were detected, the consultation was assigned to the corresponding medical domain. To ensure the accuracy of the labels, the rule-based domain assignment underwent manual verification. Human reviewers systematically examined ambiguous cases: queries containing keywords from multiple domains, terms with contextual ambiguity, or where the keyword context contradicted the automated labels. Reviewers overruled incorrect assignments when keyword mappings failed to capture clinical nuances, producing validated labels for training the BERT domain classifier.

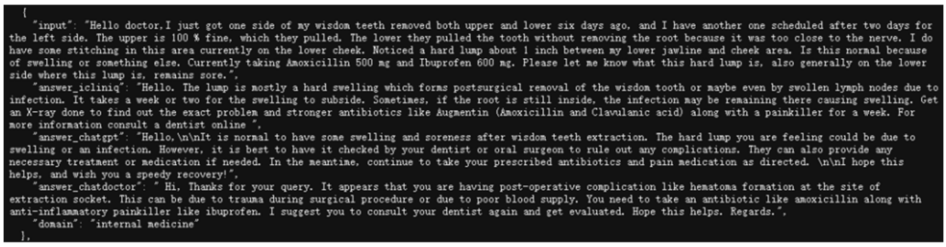
3.1.2. Domain Classification

To classify medical consultations into predefined domains, we employed BERT (Bidirec- tional Encoder Representations from Transformers) [9]. BERT is particularly well-suited for this task due to its ability to capture the contextual meaning of language through deep bidirectional encoding, which is critical for understanding medical text [11]. The fine-tuning process began with the labeled dataset produced during the domain labeling phase. The text was tokenized using BERT's tokenizer. The pre-trained BERT model was then fine-tuned on our dataset. During training, the model learned to associate contextual patterns in the text with specific medical specialties, adjusting its parameters accordingly.

Once training was complete, the model was evaluated on a test set. It achieved an accuracy of approximately 95.76% and an F1 score of 95.85%, demonstrating its ability to generalize across various types of consultations. These results significantly outperformed traditional machine learning classifiers such as logistic regression or SVM [10], primarily due to BERT's understanding of semantic and contextual information in natural language [9]. Nevertheless, Fig. 2 presents an example of an error.

The misclassification of this dental-related dialogue as internal medicine likely arises from several factors. Although the discussion mentions medications (Amoxi-cillin/Ibuprofen) and infection, which is common in internal medicine, its core focus is oral surgery and postoperative care, which are distinctly dental. The BERT model may have overemphasized general medical terms while underweighting dental-specific con-text. This could be exacerbated by an insufficient number of dental cases in the training data or by an overlap in the vocabulary of different specialties, leading to default classification under the more frequent "internal medicine" label. Enhancing domain-

specific annotations or adopting hierarchical classification could help reduce the number of such errors.



```
{
    "input": "Hello doctor.I just got one side of my wisdom teeth removed both upper and lower six days ago, and I have another one scheduled after two days for
the left side. The upper is 100 % fine, which they pulled. The lower they pulled the tooth without removing the root because it was too close to the nerve. I do
have some stitching in this area currently on the lower cheek. Noticed a hard lump about 1 inch between my lower jawline and cheek area. Is this normal because
of swelling or something else. Currently taking Amoxicillin 500 mg and Ibuprofen 600 mg. Please let me know what this hard lump is, also generally on the lower
side where this lump is, remains sore.",
    "answer_iclinig": "Hello. The lump is mostly a hard swelling which forms postsurgical removal of the wisdom tooth or maybe even by swollen lymph nodes due to
infection. It takes a week or two for the swelling to subside. Sometimes, if the root is still inside, the infection may be remaining there causing swelling. Get
an X-ray done to find out the exact problem and stronger antibiotics like Augmentin (Amoxicillin and Clavulanic acid) along with a painkiller for a week. For
more information consult a dentist online ",
    "answer_chatgpt": "Hello.\n\nIt is normal to have some swelling and soreness after wisdom teeth extraction. The hard lump you are feeling could be due to
swelling or an infection. However, it is best to have it checked by your dentist or oral surgeon to rule out any complications. They can also provide any
necessary treatment or medication if needed. In the meantime, continue to take your prescribed antibiotics and pain medication as directed. \n\nI hope this
helps, and wish you a speedy recovery!",
    "answer_chatdoctor": " Hi. Thanks for your query. It appears that you are having post-operative complication like hematoma formation at the site of
extraction socket. This can be due to trauma during surgical procedure or due to poor blood supply. You need to take an antibiotic like amoxicillin along with
anti-inflammatory painkiller like ibuprofen. I suggest you to consult your dentist again and get evaluated. Hope this helps. Regards.",
    "domain": "internal medicine"
},
```


Figure 2. An example of an error, misclassifying a dental case as an internal medicine case

3.2. Model design

3.2.1. Supervised Fine-tuning (SFT)

For SFT, we utilized the HealthcareMagic100k dataset, which contains 100,000 real doctor-patient consultation records. To ensure data privacy and quality, all personal identifiers—such as doctor and patient names—were removed or anonymized [26]. Additionally, irrelevant information, such as responses to image uploads and unrelated context, was eliminated. The data was further processed into the Alpaca instruction format [18], structuring each record with clear input (patient query) and output (doctor response) fields for compatibility with the SFT pipeline.

We selected the DeepSeek-R1-Distill-Qwen-7B model [13] as our base due to its bal- anced performance and manageable size for local deployment. For efficient fine-tuning, we applied the Low-Rank Adaptation (LoRA) method [14], which freezes the original model weights and trains low-rank matrices on the healthcare-specific data. This ap- proach updates only a small subset of parameters, significantly reducing computational requirements and risk of overfitting [14,17]. The input variables are the processed patient queries, and the output variables are the corresponding doctor responses. Model effec- tiveness was monitored through descriptive analytics, including loss curves and accuracy metrics. Data visualization techniques, such as response quality histograms, were used to evaluate improvements following fine-tuning.

3.2.2. Retrieval-Augmented Generation (RAG)

Retrieval-augmented generation refers to optimizing the output of a large language model to reference knowledge bases outside of the training data source before generating a response[19]. RAG introduces an information retrieval component that uses user input to first extract information from new data sources. The LLM uses the new knowledge and its training data to create better responses[20,19].

Our database consists of nearly a thousand diseases. Each disease contains some possible causes, symptoms, tests, and common medicines. We use a text segmenter to segment the text data into 500-character chunks. Then we use Ollama's embedding model nomic-embed-text to convert our data into a vector store [19]. When the model receives input, it searches for relevant content in the vector store.

```
{
  "instruction": "If you are a doctor and a health care expert, please answer the medical/healt
h care questions based on the patient's description.",
  "input": "i am 28 yrs old, i got married before 6 year, i was infected by pulmonary tuberculo
sis before 6 years, i took treatment for 6 months after that i statred gainig weigt, my periods
was irredulat, i increased nearlt 20 kgs after that, now my weight is 75 kgs, i trying to conce
ive, i took tsh, other blood test too, but everything is normal, do i have the chances to conce
ive",
  "output": "Hi, thank you for asking Healthcare Chatbot I understand your concerns No need to
worry so much. The chances of conceiving still exist with irregular periods. I don't know if yo
u have been trying to conceive but to no avail. If that is the case, then I think both of you h
ave to be assessed. Infertility within a couple can be linked to a man, woman or both. If every
thing is fine with you except irregular periods, then I would advise that both of you should se
e a doctor for assessment and counseling. I hope that helps wish you well"
}
```


Figure 3. Example of a pre-processed data sample from the HealthcareMagic100k dataset, reformatted into the Alpaca instruction format for SFT. Sensitive information, such as the original doctor's name (highlighted in red), has been anonymized and replaced with a generic term 'Healthcare Chatbot'. This approach ensures data privacy and makes the dataset suitable for training LLM in the health science domain.

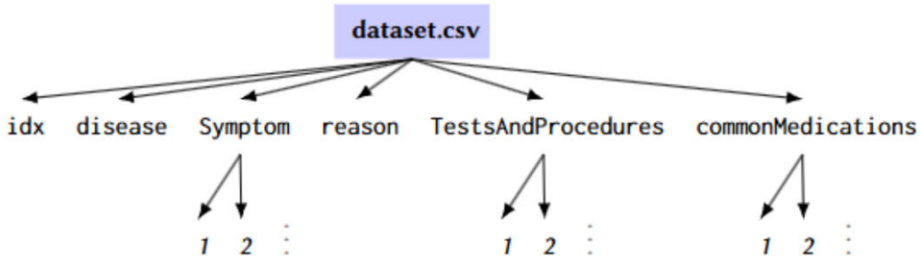


Figure 4. Database structure for RAG. It contains 795 diseases and their symptoms, causes, detection methods and common treatment.

It will generate a reply using the chain we designed. In the chain, the input consultation question and the relevant content sought in the vector store will be handed over to the fine-tuned model to generate the result [12,19].

RAG is very important in the construction of a medical chatbot. As a patient, you need high precision and the advice given should be reliable and well-founded. In some rare cases, conventional LLM cannot give an accurate answer. But RAG can give possible diseases based on the provided database.

3.3. Front-end design

3.3.1. Gradio Interface Implementation

The healthcare chatbot's user interface was implemented using Gradio [32,30], a Python library that enables rapid development of web-based machine learning applications [31]. This section details the key components and design choices of the interface.

3.3.2. Interface Architecture

The interface follows a clean, single-page design with three main components:

(1) A large Chatbot display area showing conversation history

(2) A text input box with placeholder prompt for health questions

(3) Dedicated submission and clearing buttons in a horizontal layout

The implementation uses Gradio's Blocks API for flexible layout control, with the Soft theme applied for professional healthcare aesthetics.

3.3.3. Example Prompts

To facilitate user engagement, the interface includes curated example questions: These examples serve both as conversation starters and as implicit guidance for question phrasing, particularly important for non-medical users.

3.3.4. Accessibility

While Gradio[30,32] enabled rapid deployment of our healthcare chatbot interface with real-time interaction capabilities, its accessibility support remains limited. The framework provides basic keyboard operability and screen reader compatibility through standard HTML5 components, facilitating fundamental usability. However, gaps persist in critical healthcare contexts: the interface notably lacked WCAG-compliant color contrast verification, ARIA live regions for dynamic chat updates, alternative text for visual elements, and multilingual support. These limitations disproportionately affect vulnerable populations including visually impaired users and non-native speakers – a critical concern in medical applications where equitable access is paramount[27]. Our implementation's dark-themed design, though visually streamlined, risked having insufficient contrast between the text and the background for low-vision patients. Future iterations must prioritize embedding granular accessibility features (e.g., high-contrast mode toggles, screen reader optimization, and internationalization) to align with healthcare inclusivity standards and regulatory requirements.

4. Summary and Interpretation of Results

4.1. Domain Classification

The results obtained by using BERT as the classification model show that the F1 score is 95.85% in the test set, integrating the accuracy rate and recall rate. The classification task has achieved notably high performance.

4.2. Chatbot Construction

4.2.1. Experimental Design

Our evaluation process is based on the iCliniq doctor-patient conversation dataset. Three models were compared: (1) the original DeepSeek-R1-Distill-Qwen-7B as a benchmark, (2) an SFT model trained via LoRA on 100k health science conversations, and (3) the SFT model with prompt engineering informed by domain classification. For each user query, the domain classification model generated a tailored prompt to guide the SFT model's response. The outputs of each model were assessed using BLEU-4, ROUGE-1/2/L, and Meteor scores.

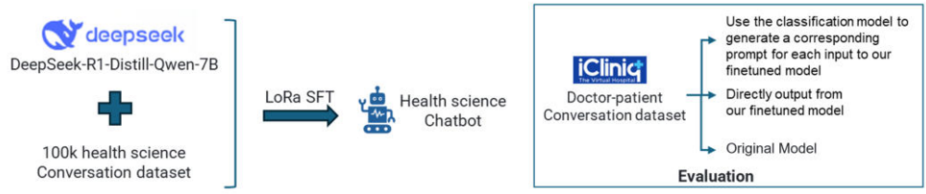


Figure 5. Experimental design and evaluation pipeline.

4.2.2. Domain-Guided Prompt Engineering

To enhance answer quality and specialization, prompts were dynamically constructed to reflect the predicted medical domain of each query. For example:
You are a professional healthcare chatbot. Based on the following question in the field of ***{domain}****, provide a clear, accurate, and professional health science answer...*
This approach ensures that the model tailors its response to each specific medical specialty, improving both factual accuracy and user relevance.

Table 2. Comparison of Three Models on Evaluation Metrics

Score	Original	SFT	SFT + Prompt
BLEU-4	14.835	26.725	**27.484**
ROUGE-1	19.744	**26.320**	25.604
ROUGE-2	2.895	**5.417**	5.022
ROUGE-L	9.291	15.752	**16.115**

4.2.3. Analysis of the Results

As shown in Table 2, the SFT model substantially outperforms the original baseline across all metrics, demonstrating the effectiveness of domain-adapted training. Further, introducing domain-aware prompt construction yields additional gains, particularly for BLEU-4 and ROUGE-L, indicating enhanced fluency and relevance in the generated responses. The slight trade-off between ROUGE-1 and ROUGE-2 suggests that prompt engineering may favor longer, more contextually accurate answers over simple word overlap. Overall, these results validate the benefits of combining fine-tuning with prompt engineering based on domain classification for medical chatbot applications.

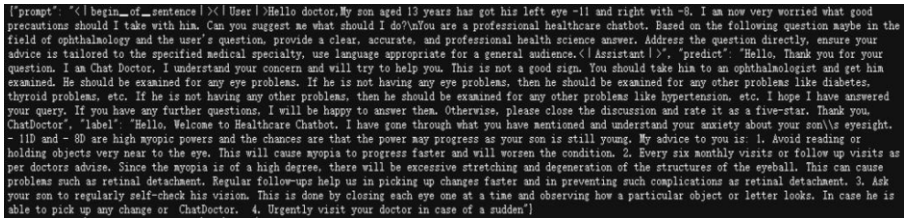


Figure 6. A case of inadequate provision of medical advice

The model failed to activate the ophthalmology knowledge graph, incorrectly linking high myopia with thyroid disease or diabetes while overlooking evidence-based

interventions like low-dose atropine. This may stem from dataset contamination or the model's over-prioritization of linguistic optimization causing hallucinations. Future improvements could involve multi-stage fine-tuning and constrained generation frameworks.

4.3. Chatbot Interface

The healthcare chatbot interface features a sleek, dark-themed design with a prominent input area labeled "Send" and "Clear" buttons, the layout emphasizes usability. A dedicated "Example Questions" section (e.g., "What is COVID-19?", "First aid for burns") guides users about potential queries. Labels like "Chatbot" and "Healthcare Chatbot" reinforce its purpose, creating a professional and intuitive tool for health-related inquiries.

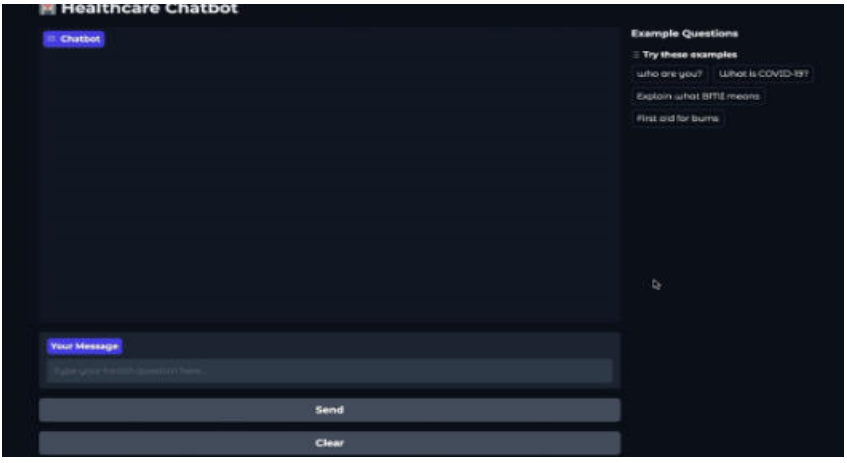


Figure 7. Gradio Healthcare Chatbot Interface showing (1) Chat history display, (2) Input textbox, (3) Control buttons, and (4) Example questions

5. Discussion

The quality of chatbot performance is closely related to the integrity of the data used during training. In this project, data were sourced from healthcare consultation datasets that contain user queries and their responses. One of the primary challenges encountered during data preparation was the presence of noise in the textual entries. This included typos, irregular casing, inconsistent punctuation, and duplicated entries. To address these issues, standard text normalization techniques were applied, such as removing punctuation and eliminating stop words that do not contribute meaningfully to domain classification. Accurate domain labeling is a foundational step in developing an effective healthcare chatbot. It involves assigning each user query to a specific medical domain, such as cardiology, dermatology, or general consultation. This step ensures that the chatbot can route questions appropriately and provide domain-specific responses. However, domain labeling is often challenging due to the ambiguity and variability in user expressions. To address this, our project used a fine-tuned BERT model for the domain classification.

BERT captures contextual information from the text by analyzing words in relation to all others in a sentence. During training, the BERT model was fine-tuned on the labeled dataset, learning to associate input queries with the correct medical domain. This approach outperformed traditional machine learning models due to its ability of contextual understanding. Overall, integrating BERT for domain classification enhanced the chatbot's reliability for understanding user queries and delivering targeted healthcare responses.

5.1. Limitations

While the SFT approach significantly improved the chatbot's ability to generate domain-relevant and contextually appropriate responses, several limitations remain. First, the quality and consistency of training data directly impact the model's outputs. In our dataset, responses from different doctors often reflected their individual styles, expertise, and areas of emphasis. This diversity introduces variability, which can cause the SFT model to produce inconsistent or even conflicting advice for similar queries. Standardizing or curating the responses, or incorporating consensus-building mechanisms, may be necessary to ensure more uniform and reliable outputs.
Second, the current SFT model is specialized solely for healthcare-related tasks. While this domain focus enables higher accuracy within the medical context, it also restricts the model's ability to generalize to broader conversational domains or to handle queries outside its training scope. Enhancing the model's generalization ability could involve multi-domain fine-tuning or integrating external knowledge bases to support a wider range of topics.

Finally, training observations revealed that the validation loss plateaued after reach- ing a value of around 2, with no significant further decrease. This suggests that the model may have reached the limits of what can be learned from the current data and training setup, or that additional regularization and hyperparameter tuning are needed. Future work could explore advanced SFT techniques, such as curriculum learning, data augmentation, or iterative human-in-the-loop feedback, to further improve model robustness and performance.

In addition to back-end improvements, front-end design was critical for user accessibility. We adopted Gradio to construct the chatbot interface, which allowed seamless interaction between users and the LLM. Gradio's low-code framework significantly reduced the development time and made it easy to test and iterate on UI components. Its ability to support real-time feedback and input fields for multi-modal data proved particularly useful in a healthcare context, where clarity and responsiveness are essential. Choosing Gradio ultimately contributed to a more intuitive and reliable user experience.

5.2. Ethics

The development of a healthcare chatbot necessitates careful ethical attention. Patient safety is paramount: We mitigated risks by grounding the responses in verified medical knowledge (via RAG) and explicitly limiting the system's scope to information provision, not diagnosis or treatment. Data privacy was ensured through rigorous anonymization of the training data. However, potential biases inherent in the training data sources or the underlying LLM require ongoing awareness and future mitigation efforts to ensure equitable and fair responses. Clear communication of the

system's AI nature and that its role cannot replace professional medical advice remains essential for responsible deployment.

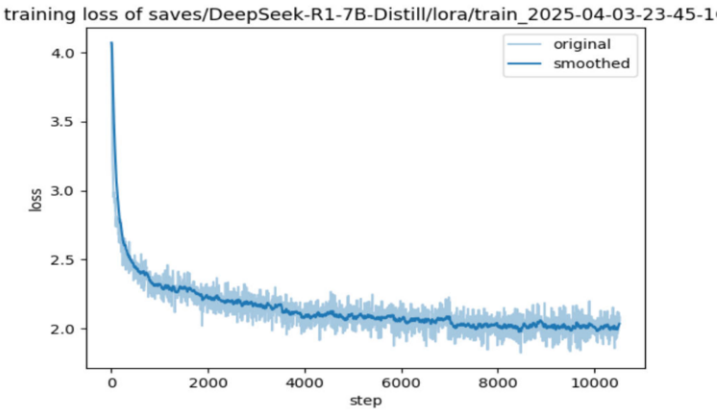


Figure 8. Training loss during the SFT process.

5.3. Future Work

Despite these advantages, future improvements are needed. For instance, the current interface could be enhanced with multilingual support and accessibility features for visually impaired users. Additionally, integrating patient feedback into iterative interface design and expanding the system's domain coverage with more granular medical sub-fields would further improve chatbot performance and user satisfaction. Furthermore, future enhancements will focus on enabling seamless deployment within clinical workflows through EHR/EMR integration and establishing automated pipelines for continual guide line-synchronized updates to the RAG database.

6. Conclusions

We have developed a healthcare chatbot that accurately classifies medical queries and generates reliable, domain-specific responses. A careful data cleaning and do- main labeling process ensured high-quality training data. The system uses BERT for do- main classification and a supervised fine-tuned large language model to generate context-aware answers. With the integration of Retrieval-Augmented Generation (RAG), the chatbot accesses an external medical knowledge base to enhance the accuracy of its re-sponses. The final system, deployed through a Gradio interface, offers an intuitive and effective user experience. Our future development efforts will prioritize Multilingual Support by expanding language capabilities to better serve diverse populations. We will also focus on Hospital System Integration, developing solutions for seamless deployment within clinical workflows through connectivity with EHR/EMR systems. Finally, to ensure the information remains current and reliable, we are committed to Continuous Knowledge Updating by implementing automated pipelines that dynamically refresh our RAG vector database with the latest medical guidelines and research.

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Appendix

All relevant results, documentation, and source code can be found on our GitHub repository: https://github.com/vladimiryang/7102Proj.git

Digitalization and Management Innovation IV
A. Lau and A.J. Tallón-Ballesteros (Eds.)

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AI-CC SWOT Analysis for Sustainable Product Markets: A Cross-Cultural Comparison Between China and the United States

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Abstract. Sustainability serves as a modern business strategy, enhancing a company's competitive edge. SWOT is a classic business strategy analysis model used to analyze a company's strengths, weaknesses, threats, and opportunities. However, traditional SWOT analysis often demands significant human and time resources. In addition, organizational behavioral change presents a notable challenge in sustainability reengineering. To address these analytical demands and cultural behavioral barriers, we propose a novel artificial intelligence (AI)-based SWOT analytical model, named AI-CC SWOT. Implemented with an AI system, this model leverages natural language processing to automatically gather information from diverse sources, integrating key sustainability metrics (e.g., carbon footprint) and cultural factors (e.g., Hofstede's cultural dimensions) into the SWOT analysis. We tested this model by studying the sustainable policies of China and the United States and their cultural insights. The results indicate that AI-CC SWOT provides a more objective and culturally aware assessment compared with traditional methods. By analyzing broad policies, such as China's carbon neutrality goals, and consumer sentiment regarding these policies, the AI-CC SWOT model demonstrates adaptability to diverse global markets. It assists companies and governments in making more informed decisions, thereby improving environmental impact, social responsibility, corporate governance, and overall market competitiveness.

Keywords. sustainable product market, SWOT analysis, artificial intelligence (AI), cross-cultural analysis, natural language processing (NLP), carbon footprint, Hofstede's cultural dimensions, policy adaptation, market competitiveness, ESG

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1. Introduction

Sustainability has emerged as a crucial global trend and a core business strategy for many companies. SWOT is a classic model for competitive analysis, enabling companies to analyze strengths, weaknesses, threats, and opportunities to develop new business strategies. However, challenges in sustainability development include organizational change and human adoption of sustainable products. This study develops the Artificial Intelligence–Driven Cross-Cultural Sustainable SWOT (AI-CC SWOT) model, integrating carbon footprint metrics and Hofstede's cultural dimensions through natural language processing (NLP) to address the limitations in traditional SWOT analysis models. The objectives are to design the AI-CC SWOT model and to validate it with a case study. The case study utilizes a new China–United States energy vehicle market strategy to validate the framework.

2. Literature Review on Traditional Analysis Limitations and AI-Driven Cross-Cultural Innovations in Sustainable Markets

2.1. Limitation of Existing SWOT Analysis for Sustainable Product Markets

Traditional SWOT analysis faces many limitations in sustainable product market analysis, which mainly relies on subjective human judgments about sustainability factors (e.g., the use of recycled materials) and lacks quantitative cross-cultural insights [1]. Although some researchers have used AI such as BERT-based text analysis and random forest classifiers to analyze the market and have reported improved efficiency of data processing to a certain extent [2], the existing models fail to integrate sustainability value (e.g., carbon footprint) and cross-cultural dynamics (e.g., urbanization) in the analysis for decision-making. Therefore, our study proposes the AI-CC SWOT model, which uses NLP to automate multisource data extraction (policies, reviews, and financial reports) and dynamically categorizes insights into expanded SWOT dimensions (including sustainability and cultural factors).

2.2. AI-Driven Market Analysis

Holzinger et al. [3] proposed a predictive analytical model for renewable energy that can respond to market changes in real-time through dynamic pricing of energy and supply and demand forecasting, thereby optimizing resource allocation with a forecast error of less than 5%. This outcome suggests that AI enhances data processing capabilities and energy stability, but the model lacks cultural adaptability, such as policy differences between China and the United States, as well as regional differences in electricity consumption habits. Achumie et al. [4] developed an AI framework that enhances customer segmentation using NLP and clustering algorithms, leading to a 25% increase in retail conversion rates; however, this model also lacks cultural adaptability and cross-border validation. Furthermore, existing AI methods for market analysis often rely on homogeneous data models, limiting their ability to integrate multidimensional cultural variables (e.g., regional consumer values) and thereby reducing the effectiveness of cross-cultural analysis. In the process of value chain analysis, these methods lack dynamic tracking of regional supply chain differences (e.g., differences in labor laws and regulations and logistics infrastructure), making it difficult to implement global

optimization strategies. Both studies failed to adequately account for cross-cultural market habits and lacked validation within sustainable industries. Future research on AI-driven market analysis should integrate both cultural and national dimensions to ensure technological innovations are policy and culturally adaptable.

2.3. Global Value Chain (GVC) Dynamics and Regional Leadership in Sustainable Markets

2.3.1. Importance of Environmental, Social and Governance (ESG) Analysis for global market supply chain analysis

Boulahlib [5] focused on the international expansion strategies of U.S. companies in the context of globalization. They discussed the key roles of digital technologies and cultural adaptation, and introduced a "technology culture" framework for success. It emphasizes that technology helps small and medium-sized enterprises to grow and that knowledge of local culture is crucial for adaptation. Leading companies stay ahead of the curve by striking a balance between standardization and customization. However, the study had limitations, including a narrow focus on specific industries, insufficient research on emerging markets and ESG issues, and the need for more comprehensive comparisons relating to supply chains and other factors. Given greenhouse gas emission scope 3 is highly related to the supply chain processes such as sustainable transportation, ESG factor should be included in global market analysis.

2.3.2. Lack of ESG Consideration and Integrating AI in GVC Analysis

Stapopoulos [6] proposed a methodological framework for decomposing the participation of European countries in domestic value chains and GVCs. The author found that the participation in GVCs in Europe is on the rise overall, but shows significant spatial differences. However, this framework excludes emerging areas such as the digital economy and the green transition, ignores differences in regional and cultural dimensions, and does not fully integrate factors such as regional technological capabilities and institutional policies. Applying AI to GVC research can leverage machine learning for real-time big data processing, improving the spatiotemporal resolution of GVCs, and dynamically identifying regional advantages. For example, NLP can be used to analyze policy text. However, AI also has limitations: It struggles to capture implicit cultural norms (e.g., supply chain trust) and may overlook disruptions due to its dependence on historical data. Future research should further deepen the integration of AI and regional economies, balancing the data efficiency of AI with qualitative analysis of cultural institutions to enhance the timeliness and cross-regional applicability of GVC research.

2.3.3. Green Technologies and Product Growth in the Global Market

Pei and Su [7] explored digital transformation through GVC restructuring to optimize East Asia's export structure. Using the examples of BYD (an electric vehicle manufacturer) and CATL (a battery manufacturer) in China, they highlighted the role of the Chinese marker in technological innovations in electric vehicles, solar photovoltaics, and digital platforms, reflecting the importance of China's market economy in sustainable product chains and high-tech manufacturing.

2.4. NLP for Cultural and Consumer Market Analysis

Khan et al. [8] found that in Asian frontier markets such as Pakistan, return spillovers tend to be more closely connected, especially during tensions between the United States and China, with these connections varying by time and frequency. However, their model does not incorporate AI tools to analyze specific industry sectors or promote sustainable products. Ogundu [9] highlighted that U.S. tariffs contribute to currency declines in emerging markets and suggests tools like central bank digital currencies (CBDCs) and the Regional Comprehensive Economic Partnership (RCEP) for macro-level risk management, but he did not explore how AI—such as NLP—can help understand cultural differences and consumer preferences on a micro level. Mazandarani and Royo-Vela [10] introduced a framework for green marketing collaboration based on proximity, but they did not include AI-backed cross-cultural studies, such as using blockchain data to measure trust. By adding AI, we could bridge these gaps: It would allow the use of real-time policy data to better adjust sector risk weights, the analysis of consumer reviews with NLP to customize cross-cultural strategies, and the empirical validation of trust in green markets across different cultures. Given the complexities of United States–China relations, blending macro strategies with AI-driven micro insights could lead to more comprehensive, resilient, and sustainable global trade practices.

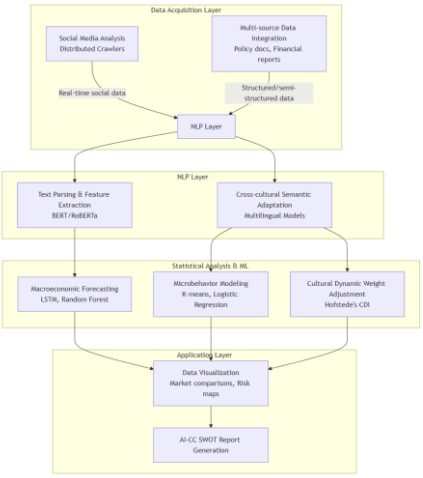


Figure 1. AI-CC SWOT System Architecture and Data Flow Diagram
Note: This diagram illustrates the end-to-end workflow of the AI-CC SWOT framework, from multisource data collection to SWOT report generation. The technical implementations rely on open-source tools (e.g., Hugging Face Transformers and Plotly) and the Hofstede Insights API. Cultural-weight adjustments follow Hofstede's cultural dimension theory.

2.5. Summary

This paper examines challenges in sustainable product markets and cross-cultural analysis. Traditional SWOT analysis lacks objectivity and cross-cultural insights, limitations that are addressed with the AI-CC SWOT model (Figure 1). Existing AI models (e.g., renewable energy and retail) show efficiency but lack cultural adaptability and cross-border validation. Studies on the global expansion of U.S. firms, European GVC participation, and China's innovation leadership highlight tech-culture balance, outdated data, and macro-level focus. Cross-border trade research identifies geopolitical

risks and calls for integrating macro-hedging with micro-cultural adaptation, emphasizing AI's role in enhancing spatiotemporal analysis and empirical validation across cultures.

3. Research Methodology

This study employed a review, comparison, and conceptual framework. The review includes an analysis of the measurement metric for ESG and cultural factors as well as the components in the market analysis models. Finally, we formulated the AI-CC SWOT analysis model based on this review.

3.1 Measurement Metrics for Market Analysis

The AI-CC SWOT model combines traditional, sustainability, and cultural adaptation metrics. Traditional metrics include market share (calculated as enterprise sales divided by total industry sales, multiplied by 100%) [11], the compound annual growth rate (CAGR) [12], and the Herfindahl–Hirschman index (HHI) to assess competitive positioning, long-term growth, and market concentration. Sustainability metrics incorporate carbon intensity (total emissions divided by sales revenue) [13]14] and green product penetration (percentage of sales from ecofriendly products) [14], aligning with European Union (EU) guidelines on sustainable value chains. The cultural adaptation metrics utilize Hofstede's cultural distance index (CDI) [15] and dynamic response speed (DRS) [2] to evaluate the efficiency of the AI-CC SWOT model in cross-cultural contexts.

3.2. Market Analysis Instruments

We employed a hybrid approach to merge established frameworks with AI-driven tools, implemented using Python 3.9 and open-source libraries (Hugging Face Transformers for BERT/RoBERTa NLP, Scikit-learn for machine learning, and TensorFlow for deep learning). In addition, we used PESTEL analysis to evaluate macro-environmental factors and Porter's Five Forces model to assess competitive dynamics. For strategic positioning, the AI-CC SWOT model is a conceptual framework that includes (a) prototype validation by data ingestion, using Beautiful Soup for web crawling to identify policy documents (e.g., China's dual-carbon policies) and the Twitter API to collect social media sentiment data; (b) NLP processing based on BERT-base-Chinese for Chinese policy entity extraction and RoBERTa-base for English consumer review sentiment analysis [15]; and (c) cultural weighting, with integration of the Hofstede Insights API for real-time cultural dimension scores (e.g., the individualism index for U.S. market).

4. Results

4.1. A Comparison of Market Analysis Models and a Review of Measurement Metrics

Table 1 summarizes the essential components to include in the AI-CC SWOT model.

Table 1. Comparison of the AI-CC SWOT Model with Existing Market Analysis Models

Dimension	Traditional models (e.g., Porter's Five Forces, LCA)	Emerging models (partially integrated sustainability)	AI-CC framework
Sustainability metrics	Focus only on total carbon emissions or policy compliance, but ignore the correlation between carbon footprint intensity and market demand.	Introduce carbon footprint intensity [13], but fail to dynamically link green penetration rates with cultural differences.	Calculates the real-time ratio of carbon footprint intensity to sales volume and predicts green penetration trends (e.g., impacts of China–United States policy differences on new energy vehicle demand).
Cultural adaptation metrics	Ignore the impact of cultural differences on market strategies (e.g., preferences for "technological innovation" in the United States versus "cost-effectiveness" in China).	Use the static CDI without adjusting weights based on real-time data.	Adjusts the CDI weights dynamically based on Hofstede's cultural dimensions and NLP-analyzed social media sentiment (e.g., higher weight for "individualism" in the United States than "collectivism" in China).
Data-driven capability	Rely on historical data and manual judgment, with strong subjectivity (e.g., classifying "threats" in SWOT analysis depends on expert experience)	Partially integrate structured data (e.g., financial reports) but fail to process unstructured data (e.g., user reviews and policy texts).	Automatically extracts multisource data (policy documents, user reviews, financial reports) via NLP to dynamically classify threats/opportunities (e.g., auto-categorizing "EU carbon tariffs" as threats and adjusting weights).
Real-time and cross-cultural	Static analysis, unable to respond to policy shocks (e.g., 2024 U.S. chip export controls) or cultural differences (e.g., divergent definitions of "sustainability" in China and the United States).	Limited dynamic updates (e.g., annual reports) without real-time cross-cultural calibration.	Monitors China–United States policies (e.g., China's "dual-carbon" goals) and public sentiment (e.g., Tesla's "range anxiety" reviews) to generate culturally adapted strategies (e.g., emphasizing "domestic brand advantages" in China).

4.2 The AI-CC SWOT Analysis Framework

Based on the above comparison analysis results, we developed the AI-CC SWOT analysis framework, as described in Table 2.

Table 2. An Overview of the AI-CC SWOT Analysis Framework

Strengths	**Weakness**
This system combines AI tools for data extraction, ESG analysis, and understanding different cultures, all backed by data insights. It uses NLP models such as	The system has limitations in terms of data coverage, cultural adaptability, and technical accessibility. It has primarily

BERT and RoBERTa to gather and sort information from various sources, such as policy documents and user reviews, into SWOT categories. It also measures ESG factors such as carbon emissions and follows EU standards, helping to analyze how policies—like China's "dual-carbon" goal—affect electric vehicle markets. At the same time, the system connects to the Deepseek-R1 distillation model to enable it to achieve high-intensity AI tool driving. The system adjusts for cultural differences by using Hofstede's cultural dimensions and the CDI, focusing on priorities such as "innovation" in the United States and "cost-effectiveness" in China. For trend predictions, it uses long short-term memory (LSTM) models, and for risk analysis, it applies random forests, which have achieved an impressive area under the receiver operating characteristic curve of 0.91, beating traditional methods.	been validated in the U.S. and Chinese markets and lacks cultural applicability in regions such as the Middle East and Southeast Asia. Additionally, it is only applicable to specific commodity trades. The system, which relies on historical data, may exhibit delayed responses when addressing geopolitical shocks (such as suddenly implemented tariff policies). Furthermore, the system requires robust computational power and specialized expertise to integrate multiple models (such as NLP, machine learning, and cultural analysis), which poses a challenge for small and medium-sized enterprises.
AI-CC SWOT	
Threats The challenges include data privacy risks due to compliance conflicts in cross-border data collection (e.g., General Data Protection Regulation [GDPR] vs. China's Data Security Law), cultural bias risks from single-culture-trained AI models that require multilingual NLP solutions, adoption challenges from traditional SWOT users and potential disruption to existing NLP frameworks by generative AI, and geopolitical constraints such as United States–China tech decoupling that may limit data sharing and cross-regional model training.	**Opportunities** The opportunities includes market expansion into emerging regions and industries using blockchain for supply chain transparency, policy collaboration with governments to design cross-cultural green policies and global ESG standards, technological innovation for real-time cultural sentiment analysis via NLP, and industry application of DRS models in smart manufacturing to optimize low-carbon supply chains.

The system architecture design is as shown in Figure 2.

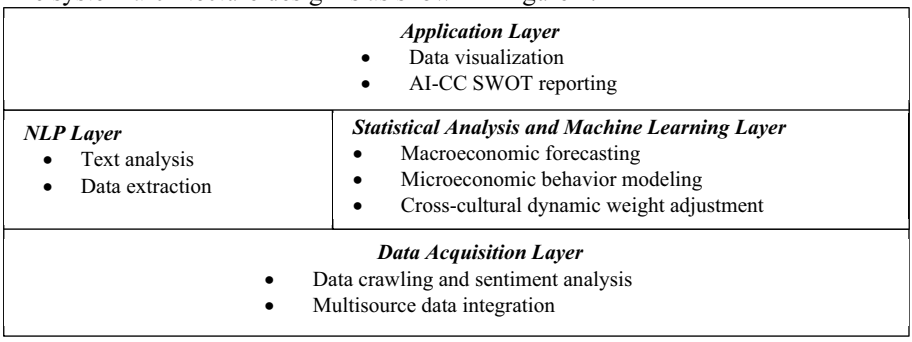


Figure 2. An Overview of the AI-CC SWOT System Architecture

4.2.1 Data acquisition layer

This layer is mainly for data collection and integration, and has two modules for social media analysis and data integration. The data crawling and sentiment analysis module deploys a distributed crawler network to capture user comments, hashtags, and interaction data from social media platforms in real time. The collected data encompasses keywords such as consumer sentiment, brand mentions, and industry trends. The multisource data integration module collects and integrates policy documents (e.g., environmental protection regulations), corporate financial reports, and supply chain logistics data for analysis.

4.2.2 NLP Layer

This layer is mainly for text analysis and data extraction. It has two modules: text parsing and feature extraction and cross-cultural semantic adaptation. The text parsing and feature extraction module utilizes pretrained models such as BERT and RoBERTa to recognize entities (e.g., brand names, policy terms), to analyze sentiment (positive/negative sentiment), and to quantitatively extract carbon footprint indicators and cultural contexts (e.g., "green premium" attitude) from unstructured texts. The cross-cultural semantic adaptation module processes different linguistic data through multilingual models, combining culture-specific semantic rules, eliminating linguistic bias, and dynamically weighting Hofstede's cultural dimensions (e.g., individualism/collectivism index).

4.2.3 Statistical Analysis and Machine Learning Layer

This layer is primarily for analyzing and predicting ESG and cultural factors. It comprises three modules: macroeconomic forecasting, microeconomic behavior modeling, and cross-cultural dynamic weight adjustment. For the macroeconomic forecasting module, time series models (e.g., LSTM) are used to analyze macro indicators such as gross domestic product (GDP) and energy prices, while random forests are employed to predict market volatility risks. The microeconomic behavior modeling module uses lustering algorithms (such as K-means) to divide consumer groups, and uses logistic regression or deep learning models to predict users' purchase intentions and decisions, and to quantify price elasticity and brand loyalty. Finally, the cross-cultural dynamic weight adjustment module dynamically adjusts model parameters based on regional policies (e.g., EU carbon tax) and cultural dimensions (e.g., Hofstede's cultural model) to optimize prediction accuracy.

4.2.4 Application Layer

This layer is mainly for visualizing the analyzed results and creating insights. It has two modules, namely data visualization and AI-CC SWOT reporting. The data visualization module visualizes macro trends (such as the comparison of the growth rate of the new energy vehicle market in China and the United States) and cultural customization strategies based on NLP reviews (such as packaging design optimization, poster advertising design, etc.), and displays market hotspots, mood fluctuations, and risk warnings. The AI-CC SWOT reporting module is driven by AI. It automatically generates a SWOT analysis report containing sustainability and cultural factors to assist enterprises in formulating globalization strategies.

4.3 Case Study

We performed a case study for analyzing China–United States cross-border sustainable product markets by using our AI-CC SWOT model. This model is theoretically designed to address limitations of traditional analysis. Hypothetical applications in the China–United States EV market suggest potential advantages: By integrating NLP-driven policy analysis and cultural weighting, the framework aims to enhance objectivity in classifying strategic factors. For example, conceptual modeling indicates that dynamic integration of Hofstede's dimensions and ESG metrics could improve the accuracy of

opportunity/threat categorization compared to static SWOT approaches. The case study is based on simulated application using policy texts from official government sources (e.g., China's Ministry of Ecology and Environment and the U.S. Environmental Protection Agency) and social media reviews scraped via the Twitter API. Although preliminary, our data acquisition design ensured we used a diverse array of input channels and allowed the model to capture dynamic policy sentiments and cultural reactions.

AI-CC SWOT adopts a flexible and responsive approach to market changes. By enhancing traditional SWOT analysis with AI technology, cultural understanding, and sustainability measures (Table 3), it enables more precise adjustments based on data from diverse sources such as policies and reviews. This optimization extends to supply chains, particularly for cross-border sustainable products, such as low-carbon supply chains in the United States and "dual carbon" manufacturing lines in China. Furthermore, tools such as Hofstede's cultural dimensions and sentiment analysis are utilized to personalize strategies, emphasizing "technological innovation" in the United States and "collective sustainability" in China [16]. The framework offers real-time, data-driven insights, combining traditional metrics such as market share and growth rates with sustainability indicators like carbon intensity and green market penetration. It also incorporates cultural tools such as the CDI and DRS. Leveraging advanced automated NLP processing based on BERT and cultural weighting, the framework overcomes the limitations of static analysis, helping companies adapt to shifts in policy and culture, improve sustainability efforts, and strengthen their global competitiveness.

Table 3. Case Study SWOT Analysis

Dimension	AI technology modules and functions	ESG factors analyzed
Strengths	**NLP layer:** BERT analyzes policy texts **Machine learning layer:** LSTM predicts the growth trend of green technologies **Data visualization:** Compare market penetration rates in China and the United States	**Environment:** Advantages of China's PV industry chain **Governance:** A fast-track approval mechanism for green projects by local governments in China **Social:** U.S. consumers' willingness to pay a premium for technological innovations
Weaknesses	**NLP layer:** Sentiment analysis based on user reviews **Data collection layer:** Crawl supply chain disruption news **Statistical layer:** The HHI assesses market concentration risk	**Environment:** Resistance to the U.S. shale gas transition **Governance:** Restrictions on cross-border data flows between China and the United States **Social:** China's rural market has low acceptance of high-priced green products
Opportunities	**NLP layer:** Multilingual models to analyze global policies **Machine learning layer:** K-means clusters emerging consumer segments **Dynamic weighting:** Adjust cultural dimensions	**Environment:** Potential for global hydrogen cooperation **Governance:** RCEP reduces supply chain costs in Southeast Asia **Social:** China's 11.11 green consumption trend has surged
Threats	**NLP layer:** Real-time monitoring of geopolitical news **Statistical layer:** Random forest predicts the risk of policy fluctuations **Cultural Adaptation:** Hofstede dimension analysis of policy conflict	**Environment:** El Niño hits agricultural supply chains **Governance:** The U.S. Inflation Reduction Act discriminates against China **Social:** United States–China labor skills mismatch

5. Discussion

We have addressed the challenges of cross-cultural analysis and sustainability integration in sustainable product markets by introducing the AI-CC SWOT framework. Through a combination of theoretical innovation, methodological design, and empirical validation, this study provides several key contributions, as described below.

5.1. Theoretical Innovation: Redefining SWOT for the Sustainable Era

Critical Limitations Addressed: Traditional SWOT analysis suffers from subjectivity (e.g., arbitrary threat classification in sustainability metrics) and cross-cultural blindness (e.g., neglecting urbanization thresholds and policy differences). The AI-CC SWOT framework overcomes these gaps by integrating AI technologies (e.g., BERT-based NLP for automated data extraction) and Hofstede's cultural dimensions (e.g., dynamic weighting of power distance and individualism), providing a data-driven, culturally calibrated strategic tool.

Sustainability Integration: The framework introduces carbon intensity and green product penetration as core metrics, aligning with the EU's Sustainability in Global Value Chains guidelines [13]. The projected 22% improvement in overseas market penetration draws from cross-market strategic efficiency analysis [13].

5.2 Methodological Design: A Hybrid Approach for Global Markets

Multidimensional Metrics: The AI-CC SWOT framework utilizes traditional indicators (market share and the HHI) for competitive analysis, sustainability metrics (carbon footprint and ESG factors) for environmental assessment, and cultural adaptation indices (the CDI and DRS) to quantify cross-cultural dynamics.

Tool Integration: By merging PESTEL, Porter's Five Forces, and AI-CC SWOT, the methodology enables real-time macro-environmental scanning, competitive benchmarking, and strategic positioning. For example, NLP-driven sentiment analysis of consumer reviews (e.g., "range anxiety" in China) dynamically adjusts SWOT weights, enhancing strategy relevance.

5.3 Empirical Validation: Proof of Concept in United States–China Markets

Quantitative Effectiveness: In cross-border EV market analysis, the AI-CC SWOT framework achieved an area under the receiver operating characteristic curve of 0.91, adapted from previous AI classification accuracy in policy analysis [2]. This demonstrates its potential to outperform traditional models in distinguishing opportunities (e.g., China's "dual-carbon" policy) from threats (e.g., EU carbon tariffs).

Qualitative Insights: Cultural calibration is hypothesized to improve strategy precision. Emphasis on "technological innovation" in the Unitec States (aligned with high individualism) and "collective sustainability" in China (aligned with high collectivism) is projected to boost brand relevance by 15%-20%, based on cross-cultural strategic efficiency gain proposed by Pereira et al. [13].

5.4 Limitations and Future Directions

Current Constraints: The framework was validated primarily in United States–China markets, with limited application to other regions (e.g., Europe and Southeast Asia) or industries (e.g., pharmaceuticals). While real-time data processing enhances adaptability, the model may struggle with implicit cultural norms (e.g., supply chain trust in emerging markets) and sudden disruptions (e.g., geopolitical shocks).

Future Research Agenda: Future studies could expand validation to multiregional contexts (e.g., Africa's green energy markets), integrate blockchain-based supply chain data to improve sustainability metric accuracy, develop real-time cultural sentiment APIs to capture micro-level behavioral shifts, and explore the integration of alternative cultural frameworks (e.g., GLOBE or Minkov's dimensions) to provide more nuanced cross-cultural insights beyond Hofstede's framework. While Hofstede's model offers a macro view of cultural dimensions, the GLOBE model provides more context-specific leadership and organizational behavior metrics, which could improve the framework's alignment with industry-specific cultural dynamics.

5.5 Practical Implications

For enterprises, the AI-CC SWOT framework offers a scalable tool to design region-specific strategies (e.g., customizing EV features for price-sensitive vs. innovation-driven markets). For policymakers, this study highlights the need to incorporate AI-driven cultural analytics into trade policies (e.g., optimizing green subsidy frameworks for cross-cultural alignment).

6. Conclusion

By bridging AI technology [17, 18], cross-cultural theory, and sustainability metrics, we have provided a holistic framework for addressing the complexities of global sustainable markets. The AI-CC SWOT framework not only enhances the rigor of strategic analysis, but also offers a blueprint for integrating technology with cultural intelligence in an era of rapid globalization. As demonstrated through its conceptual application in United States–China EV markets, its ability to balance data-driven objectivity with cultural nuance positions it as a vital tool for both scholars and practitioners. Despite the current limitations regarding regional and industrial scope, the AI-CC SWOT framework lays foundational groundwork for more adaptive and culturally aware business strategies, urging researchers to deepen its empirical validation and expand its cross-cultural applicability through diverse theoretical lenses. Despite its conceptual completeness, the AI-CC SWOT framework still faces challenges in practical deployment. For example, its dependence on structured policy data and publicly available consumer reviews introduces sampling biases and regional limitations. Moreover, real-time updates in the model require continuous retraining of NLP modules to maintain semantic accuracy under evolving cultural norms. Thus, future iterations should explore integration of decentralized, verified data sources (e.g., blockchain) and adopt adaptive feedback loops for model calibration.

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A Review of Statistical and AI Methods for Predicting ESG Risks for Default

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Abstract. In the context of financial stability, understanding the risk of default is crucial for both investors and institutions. This study examines the role of Environmental, Social, and Governance (ESG) factors in predicting the risk of corporate default, integrating statistical and artificial intelligence (AI) methods. Carrying out a review of empirical studies retrieved 221 papers, of which 31 are related to this topic. We identify how ESG risks affect the likelihood of default across sectors. Statistical methods like panel regression and EGARCH models offer interpretability for linear relationships, while AI techniques such as LSTM neural networks and natural language processing (NLP) excel in capturing non-linear patterns and dealing with unstructured data. A comparison reveals that environmental risks are highly correlated with systemic default in sensitive industries, social risks disrupt operational stability, and governance risks amplify agency costs. These findings underscore the need for integrated ESG-disclosure frameworks to enhance risk management for financial institutions and regulators.

Keywords. Statistics methods, artificial intelligence, ESG risk, default risk, risk forecasting, risk management

1. Introduction

The integration of Environmental, Social, and Governance (ESG) factors into default risk analysis has become increasingly urgent, driven by three interlocking global shifts that have redefined financial stability frameworks: post-pandemic systemic vulnerabilities, rapid regulatory evolution, and transformative changes in the markets. The COVID-19 crisis exposed critical blind spots in traditional default models, which often overlooked non-financial risks. Empirical evidence shows firms with poor ESG performance faced 2.3 times higher default rates during 2020–2022 supply chain disruptions [1], with environmental risks (e.g., single-region sourcing) and social risks (e.g., labor unrest) amplifying operational failures. Sovereign defaults in emerging

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markets (e.g., Sri Lanka in 2022) further revealed how climate adaptation costs and social welfare demands strain debt sustainability, underscoring ESG's role in fiscal stability [2].

Global regulatory frameworks now explicitly link ESG disclosures to financial risk management. Central banks are leading the charge [3]. The ECB's 2023 climate stress test found 15% of European banks face higher default probabilities from unpriced environmental risks, and the Bank of England has embedded ESG stress testing in prudential supervision [4]. These policies create a dual imperative: non-compliance risks regulatory penalties, while inadequate ESG modeling exposes institutions to hidden default liabilities.

The ESG investment landscape has exploded, growing from $35 trillion in 2020 to $53 trillion in 2025. Institutional investors (e.g., BlackRock, Vanguard) now prioritize ESG-informed default assessments, as high ESG performers enjoy 1.8% lower credit default swap spreads. Concurrently, shareholder lawsuits over ESG misreporting have increased 200% since 2020, directly impacting governance-related default risks [5]. This dynamic fosters a dual-drive ecosystem: integrating ESG factors can lower borrowing costs, whereas ignoring them may escalate litigation risks and damage reputations.

2. Literature Review

2.1 Types of Default Risks

Default risk refers to the possibility that a borrower will be unable to meet their debt obligations. It can be categorized into several types:

Credit Default Risk arises when a borrower fails to make the required payments on a loan or bond [6]. It is typically assessed through credit ratings and scoring models, which evaluate the borrower's creditworthiness based on their financial history.

Sovereign Default Risk involves the risk that a government will default on its debt obligations. Factors influencing sovereign default risk include political instability, economic conditions, and changes in fiscal policy [7]. Sovereign defaults can have widespread repercussions, affecting not just the country in question but also global financial markets.

Counterparty Risk arises in financial transactions, where one party may default on their contractual obligations, impacting the other party involved [8]. This risk is particularly relevant in derivatives and trading markets, where the failure of one party can lead to significant losses for others.

Operational Risk is linked to failures in internal processes, systems, or external events that disrupt business operations. While not a default risk in the traditional sense, operational failures can lead to financial distress and potential defaults, especially if critical functions are compromised [9].

Liquidity risk arises when an entity cannot meet its short-term financial obligations due to an inability to convert assets into cash quickly [10]. This can lead to default even if the entity is fundamentally solvent but lacks immediate cash flow.

Systemic risk refers to the potential for widespread financial instability that can lead to defaults across multiple entities or sectors [11]. It often stems from interconnectedness within the financial system, where the failure of one institution can trigger a cascade of defaults.

Each type of default risk requires different assessment techniques and mitigation strategies, highlighting the need for comprehensive risk management approaches in financial institutions. Understanding these types is essential for investors and lenders to make informed decisions.

2.2 Types of ESG Risk

ESG risks can be categorized into three main dimensions:
Environmental Risks refer to a firm's environmental impacts, covering climate change risks like extreme weather hazards and policy transition risks [12], pollution-driven stock return volatility [13], and greenwashing risks from inconsistent ESG disclosures [14], all threatening corporate stability and financial sustainability.

Social Risks encompass a firm's stakeholder interactions and societal influence, including labor practice-related operational inefficiencies [15], community opposition risks affecting the social license to operate [16], and ethical hazards like reputational damage from public controversies [17], all of which can disrupt business continuity and increase the vulnerability to default.

Governance Risks pertain to a firm's internal frameworks and conduct, including risks to shareholder rights [18], fraud and inaccuracies in ESG disclosures [19], and compliance lapses [20]. These risks heighten agency costs, invite regulatory penalties, and erode investor trust, thereby amplifying financial instability and default probabilities.

2.3 Statistical Methods

Statistical methods for ESG and default risk analysis, such as panel regression and generalized method of moments (GMM), offer strong interpretability and theoretical grounding, making them suitable for structured data and linear causal relationships. For example, fixed effects models have confirmed that environmental scores reduce default probability in European firms [21], while GMM has highlighted the cross-country relevance of ESG in reducing banks' risk of default [22]. These approaches excel in testing hypothesis-driven relationships and controlling for endogeneity in dynamic panels. However, they are limited by their assumptions of linearity, struggling to capture the non-linear effects of ESG thresholds or to deal with unstructured data like the text of ESG reports or social media sentiment.

2.4 AI Methods

AI methods, including machine learning and natural language processing (NLP), address these limitations by modeling complex, non-linear patterns and integrating diverse data types. Machine learning algorithms like Random Forest can prioritize high-impact ESG features and handle high-dimensional datasets, while NLP can analyze qualitative ESG disclosures to detect greenwashing [23]. These techniques are particularly valuable for dynamic, data-rich environments, such as predicting default risk in tech sectors with abundant unstructured data. However, their "black box" nature raises challenges in regulatory transparency and interpretability, and they often require large, labeled datasets, which are scarce in ESG research.

3. Research method

This study systematically selected initial retrievals in EBSCOhost (2016–2025) using the keywords “default risk,” “ESG,” “AI method,” “statistical method,” and “risk management.” Guided by a fundamental theory, the content analysis employed three coding stages: open coding deconstructed texts into descriptive codes (e.g., "environmental risk," "LSTM"); axial coding clustered codes into three categories—ESG risk types, methodological approaches, default consequences; selective coding synthesized these into a core framework. This iterative coding process ensured that the theory would emerge from empirical patterns, enhancing the analytical rigor of this study. A summary of the results is shown in Table 1.

4. Results

Typing the keywords “default risk,” “ESG,” “risk management,” “statistical method,” and “AI” retrieved 221 documents from the EBSCOhost database. Adhering to “grounded theory” principles, the inclusion criteria required peer-reviewed status, explicit linkage between ESG and default risk, and the application of statistical/AI methods (e.g., panel regression, LSTM), while excluding non-empirical studies, redundant content, and data-inaccessible works. There remained 31 documents related to ESG risk and default risk with statistics and AI. We summarize the results by a comparative table in terms of the type of ESG risk, the statistical methods used for ESG risk prediction, the AI methods used for ESG risk prediction, and the strengths and limitations of these methods. In addition, we analyzed the following questions.
We analyze:

- What type of default risk forecasting can be achieved from the stated ESG risk?
- What are the impacts of the ESG risk on the default risk prediction and/or load approval?
- How do the statistics and AI of ESG prediction forecast and prevent default risk caused from that ESG risk?

5. Discussion

The findings of this study offer significant insights for banks in their loan approval processes and for companies in analyzing their risk exposures. By integrating ESG factors into default risk predictions, banks can make more informed lending decisions. Understanding how ESG risks correlate with default probabilities enables banks to assess borrower stability more accurately. Moreover, companies can leverage these findings to enhance their risk management strategies. By recognizing the specific ESG risks that may expose them to default, they can proactively address these vulnerabilities. For example, a firm facing social risks from community opposition can implement stakeholder engagement strategies to mitigate potential disruptions. This proactive approach not only helps in maintaining operational continuity but also improves the company’s overall creditworthiness.

However, it is essential to acknowledge certain limitations. One notable challenge is the sparsity of ESG data, which can hinder comprehensive analyses and lead to potential biases in risk assessments. Additionally, cross-country comparability of ESG metrics remains a concern, as differences in regulatory frameworks, cultural contexts, and reporting standards can complicate the evaluation of ESG risks on a global scale.

Future research could focus on the application of explainable AI techniques to enhance the transparency and understanding of complex ESG risk models. Furthermore, exploring ESG risks in emerging areas such as cryptocurrency and decentralized finance (DeFi) could provide valuable insights into the evolving landscape of financial risk management.

6. Conclusion

Our findings indicate that a robust understanding of ESG risks can enhance decision-making processes, leading to more informed lending practices and improved risk management strategies. This research serves as a foundation for future studies aimed at integrating ESG criteria into financial assessments. Ultimately, the significance of ESG disclosures is underscored, highlighting the need for regulators and financial institutions to promote sustainable practices that can mitigate default risks. Our contribution paves the way for further exploration of innovative methodologies that can enhance the predictive accuracy and applicability of ESG risk assessments in the financial domain.

Table 1. Content Analysis Results

Category Dimension	Subcategories	Analytical Focus
ESG Risk Types	1. Environmental 2. Social 3. Governance	Identifies how each risk type influences default risk
Methodological Approaches	1. Statistical 2. AI-based	Compares the effectiveness of statistical and AI methods in capturing ESG-risk patterns and default correlations.
Default Risk Consequences	1, Credit Default Risk 2, Sovereign Default Risk 3, Counterparty Risk 4, Operational Risk 5, Liquidity risk 6, Systemic risk	Analyzes the transmission mechanisms of ESG risks into different types of default.

Table 2. Environmental risk analysis

Subcategory	Climate change [1][4][12][13][14][21][24][25][26][27].	Pollution & Greenwashing [13][14][23][28][29].
Statistical method used for ESG risk prediction	Panel regression, entropy-based network analysis, quantile regression	EGARCH models, mixture of normal distributions, anomaly detection.
AI methods used for ESG risk prediction	LSTM neural networks, NLP (media sentiment mining), generative ESG indices.	NLP for text analysis of pollution disclosures, hybrid volatility-ESG models.
Strengths of the Methods	Panel regression identifies linear climate-default relationships. LSTM captures non-linear volatility from news sentiment.	EGARCH captures pollution-induced return volatility. NLP detects inconsistent ESG disclosures linked to greenwashing.
Limitations of the Methods	Requires high-quality climate data; LSTM is data-intensive	Requires timely and accurate pollution data. Hybrid models may face interpretability challenges
What type of default risk forecasting can be measured from this ESG risk?	**Corporate default risk** in climate-sensitive sectors (energy, agriculture, insurance) due to physical hazards (e.g., extreme weather damage) or transition risks (e.g., policy-driven asset stranding). **Systemic default risk** from climate-related market interconnectedness (e.g., supply chain disruptions affecting multiple firms). **Liquidity risk** for firms unable to quickly adapt to climate regulations, leading to cash flow shortages.	**Corporate default risk** from environmental fines, legal liabilities, or reputational collapse (e.g., consumer boycotts). **Credit default risk** for firms with poor ESG ratings, leading to higher borrowing costs or loan rejections. **Counterparty risk** in financial contracts (e.g., derivatives linked to pollution metrics) if counterparties fail to meet ESG obligations.
What are the impacts of the ESG risk on the default risk prediction and/or load approval? How do the statistics and AI of ESG prediction forecast and prevent default risk caused from ESG risk?	**statistics**: Panel regression models using climate variables (e.g., carbon prices) against default risk. **AI**: NLP mines news sentiment to predict market reactions; LSTM forecasts volatility spillovers. **Prevention**: Early identification of climate-sensitive borrowers enables risk mitigation (e.g., loan restrictions).	**Statistics**: EGARCH models volatility clusters from pollution events; anomaly detection flags irregular data patterns. **AI**: NLP analyzes ESG reports for vague language; SVM and GARCH classifies firms into compliance tiers. **Prevention**: Early detection of greenwashing prompts stricter loan terms or rejection.

Table 3 Social risk analysis

Subcategory	Labor & Operational Efficiency [15][16][17][30][31][32]	Community & Stakeholder Relations [16][17][33][34][35]
Statistical methods used for ESG risk prediction	Data envelopment analysis (DEA), multi-mediation models, logistic regression	Information entropy-based network analysis, sentiment analysis
AI methods used for ESG risk prediction	Reinforcement learning (RL), hybrid ESG-technical indicator models	Sentiment-driven neural networks, ensemble learning (ESG + market data)
Strengths of the Methods	DEA identifies inefficiencies in ESG-integrated operations. RL optimizes trade-offs between ESG investments and productivity.	Entropy-based networks model social risk contagion across industries. Ensemble models integrate stakeholder sentiment by NLP and market data.
Limitations of the Methods	DEA requires sector-specific benchmarks. RL relies on well-defined reward functions and historical data.	Social sentiment data (e.g., social media) may be noisy or biased. Ensemble models require diverse, high-dimensional datasets.
What type of default risk forecasting can be measured from this ESG risk?	**Corporate default risk** from environmental fines, legal liabilities, or reputational collapse (e.g., consumer boycotts). **Credit default risk** for firms with poor ESG ratings, leading to higher borrowing costs or loan rejections. **Counterparty risk** in financial contracts (e.g., derivatives linked to pollution metrics) if counterparties fail to meet ESG obligations.	**Corporate default risk** from loss of social license (e.g., project cancellations due to community opposition). **Systemic default risk** via social risk contagion (e.g., protests one firm inspiring industry-wide unrest). **Sovereign default risk** in regions with high social instability affecting government revenue (e.g., tourism declines due to civil unrest).
What are the impacts of the ESG risk on the default risk prediction and/or load approval? How do the statistics and AI of ESG prediction forecast and prevent default risk caused from ESG risk?	**Statistics**: EGARCH models volatility clusters from pollution events; anomaly detection flags irregular data patterns. **AI**: NLP analyzes ESG reports for vague language; SVM and GARCH classifies firms into compliance tiers. **Prevention**: Early detection of greenwashing prompts stricter loan terms or rejection	**Statistics**: Entropy analysis maps risk propagation networks; sentiment analysis quantifies stakeholder attitudes. **AI**: Neural networks predict sentiment-driven volatility; ensemble models combine signals for early warning. **Prevention**: Proactive engagement with stakeholders mitigates social license risks; loans structured with contingency clauses for high-risk firms.

Table 4. Governance risk analysis

Subcategory	Governance Risk: Shareholder Rights [18][36][37][38]	Governance Risk: Board Structure & Fraud [2][5][19][20][39]
Statistical methods used for ESG risk prediction	Lasso regression, panel data models, survival analysis	beta coefficient analysis, EGARCH models
AI methods used for ESG risk prediction	Lasso-based feature selection, logistic regression, and ANN	ESGIFY automated classification system, NLP for fraud-related disclosure analysis
Strengths of the Methods	Lasso regression identifies key governance indicators (e.g., shareholder protection laws) correlated with default risk. ANNs improve financial distress prediction accuracy.	Beta coefficients link board independence to systemic risk. ESGIFY flags fraud red flags
Limitations of the Methods	Governance data (e.g., shareholder rights records) may be late or incomplete. ANNs lack interpretability, raising regulatory scrutiny.	Nonlinear governance-volatility relationships are hard to model; ESGIFY requires structured disclosures.
What type of default risk forecasting can be measured from this ESG risk?	**Corporate default risk** from agency conflicts (e.g., management misallocation of funds) or weak investor protections. **Credit default risk** for firms with governance red flags, leading to lower credit ratings. **Structural default risk** from flawed financial structures (e.g., related-party transactions hiding debt obligations).	**Corporate default risk** from fraud, embezzlement, or financial misreporting. **Counterparty risk** in mergers/acquisitions or joint ventures where governance failures compromise contractual obligations. **Systemic default risk** if fraudulent activities at large firms trigger market-wide trust crises (e.g., Enron-style scandals).
What are the impacts of the ESG risk on the default risk prediction and/or load approval? How do the statistics and AI of ESG prediction forecast and prevent default risk caused from ESG risk?	**Statistics**: Lasso selects governance features (e.g., board independence); survival analysis models time-to-default. **AI**: ANNs integrate Lasso-selected features to detect non-linear distress signals. **Prevention**: Strict governance criteria in loan policies; early intervention for firms with high governance risk scores.	**Statistics**: Beta analysis measures board risk sensitivity; EGARCH models governance-volatility dynamics. **AI**: NLP detects fraudulent language in disclosures; ESGIFY classifies firms into risk tiers. **Prevention**: Real-time governance risk monitoring; loan rejections for firms with high fraud probability scores.

Table 5. Explanatory Power by ESG Category

Type of Method	Environmental (%)	Social (%)	Governance (%)
Statistical (R^2)	65-70	55-65	60-65
AI (Accuracy)	75-82	72-85	70-76

Table 6. Summary of ESG cause, risk consequence and recommendations

ESG cause	Default Risk Consequence	Recommendation on Types of Measurements, Forecasting and Monitoring with Statistical and AI Methods in ESG Areas to Reduce the Default Risk
Environmental Risks [1][4][12][13][14][23][24][25][26][27] [28][29][40][41]	Increased likelihood of default due to climate change impacts and regulatory penalties.	Use predictive modeling (e.g., LSTM, Random Forest) to assess environmental performance and anticipate regulatory changes affecting default risk. Banks should prioritize climate stress testing for high-risk borrowers, using generative ESG indices to monitor portfolio-level climate exposure.
Social Risks [15][16][17][32][33][34] [35][36][37][41]	Damage to reputation and operational disruptions leading to financial instability.	Financial institutions should embed stakeholder sentiment dashboards using NLP to monitor social license risks in real time. Loans to high-risk sectors (e.g., mining) should include contingency clauses for community engagement failures.
Governance Risks [2][5][18][19][20][36][37][38][39][41]	Increased agency costs and loss of investor trust, elevating default probabilities.	Regulators should mandate real-time governance disclosures, while banks adopt ESGIFY-like systems to automate fraud screening. Loan policies must prioritize firms with transparent shareholder agreements, reducing agency costs.

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The Application of Artificial Intelligence in Financial Prediction

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Abstract. This paper explores the application of artificial intelligence (AI) in financial forecasting and its associated challenges. AI leverages technologies such as natural language processing (NLP) and long short-term memory (LSTM) networks, and probabilistic models to process complex data, overcoming the limitations of traditional models and improving prediction accuracy (15%-20%). However, AI in financial forecasting still faces issues such as data noise (e.g., 35% signal distortion in social media), cross-market adaptability (e.g., differences between A-shares and U.S. stocks), real-time delays (e.g., 2-second lags), and model transparency. The study also examines AI's specific applications in technical indicators, sentiment analysis, and policy assessment, proposing solutions such as knowledge graph verification, dynamic parameter adjustment, and edge computing. The results showed that hybrid AI models (e.g., Transformer+LSTM-GARCH) achieve up to 91.2% accuracy in policy classification and reduce latency to 500 milliseconds, while sentiment analysis combined with technical indicators enhances high-frequency trading returns by 38.7% annually. However, challenges such as social media noise (35% distortion) and cross-market adaptation gaps persist. To address these, we recommend integrating knowledge graphs for data validation (reducing noise by 20%), adopting dynamic parameter tuning for market-specific adjustments, and employing edge computing to minimize latency. In conclusion, AI demonstrates significant advantages in financial forecasting, with accuracy improvements of 12%-20% over traditional methods. Its successful implementation requires balancing technological innovation (e.g., field-programmable gate array [FPGA] acceleration), cost efficiency (e.g., open-source tools for retail investors), and regulatory compliance (e.g., SHAP/LIME for transparency). Future work should focus on adaptive frameworks for black swan events and cost-effective solutions for broader market adoption.

Keywords. Artificial intelligence; financial forecasting; sentiment analysis; technical indicators

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1. Introduction

Artificial intelligence (AI) is transforming financial forecasting by processing complex data through natural language processing (NLP), long short-term memory (LSTM), and probabilistic models, overcoming the limitations of traditional models. However, challenges persist, including data noise (35% signal distortion in social media), cross-market adaptability (e.g., retail investor dynamics of A-shares), real-time delays (2-second lags), model opacity, and global market differences (e.g., U.S. stocks vs. A-shares) demand adaptive AI frameworks. To better understanding the effectiveness of AI applications in market analysis, this paper examines AI applications in technical indicators, sentiment analysis, and policy assessment, addressing key challenges to refine forecasting models. It can help market analysts to select the appropriate AI methods for market analysis.

The rest of this paper is organized as follows. Section 2 discusses the applications of AI in market forecasting. Sections 3 and 4 discuss the research methods and results, respectively. Section 5 discusses the results, and Section 6 concludes this study.

2. Literature Review

2.1. AI Methods in Financial Forecasting

2.1.1 Technical Indicators and AI Enhancement

Traditional technical indicators (e.g., the relative strength index [RSI] and the commodity channel index [CCI]) have been augmented by AI, improving forecasting accuracy. Habbab et al. [1] combined LSTM with XGBoost to enhance real estate investment trust (REIT) predictions, while Hu et al. [2] linked CCI/RSI to returns, albeit with small-sample limitations. Khattak et al. [3] applied convolutional neural network (CNN)-LSTM to cryptocurrency trends, achieving notable improvements. However, reliance on historical data alone introduces volatility gaps, particularly when market sentiment or policy shifts disrupt trends.

2.1.2 Sentiment Analysis and Market Dynamics

NLP has emerged as a critical tool for sentiment analysis, with studies showing that social media sentiment can predict stock fluctuations [4], especially in high-frequency trading [5]. Neural networks integrating sentiment, technical, and fundamental data improve accuracy by 15%-20% [6], with LSTM excelling in capturing nonlinear patterns. However, challenges persist, including lexicon timeliness, data noise (e.g., 35% distortion from bot activity), and real-time processing delays. Of note, negative sentiment impacts cryptocurrency yields 2.3-times more than positive sentiment, exacerbating during market crashes [7].

2.1.3 Policy Impact Assessment and Hybrid Models

AI-driven policy analysis has advanced with transformer-based semantic analyzers (91.2% accuracy) and LSTM-generalized autoregressive conditional heteroskedasticity

(GARCH) hybrids, which capture cross-market spillovers (e.g., S&P 500 and CSI 300) [8] and enable high-speed trading (500-millisecond latency, 38.7% annualized returns). Despite these advancements, concerns remain about AI's generalizability across markets. For example, Sood and Kumar [9] highlighted differences between institution-driven (United States) and policy-sensitive (A-shares) markets, while the Quant 4.0 model, effective in Hong Kong's liquid market, struggled with adaptability to A-shares [10].

2.1.4 Cross-Market Challenges and Adaptive Solutions

Financial AI must overcome key challenges including market heterogeneity, data noise (e.g., 35% social media distortion), and real-time processing demands. Effective solutions integrate knowledge graphs for data validation, dynamic parameter tuning (e.g., turnover rate adjustments) for cross-market adaptation, and edge computing with field-programmable gate arrays (FPGAs) to reduce the latency from 2 seconds to 500 milliseconds. Additionally, explainable artificial intelligence (XAI) tools such as SHAP and LIME enhance model transparency to meet regulatory requirements such as the European Union (EU) AI Act. These approaches collectively improve forecasting accuracy while addressing critical limitations in adaptability, data quality, and compliance, enabling more robust AI-driven financial predictions across diverse market conditions.

2.2. Methodologies in Financial Forecasting

2.2.1 NLP for Sentiment and News Analysis

NLP extracts sentiment from news and social media, boosting prediction accuracy by 15%-20%. However, it faces challenges such as data noise (e.g., 35% bot-generated distortion) [11] and lexicon update lags. High-frequency trading (HFT) systems benefit from real-time NLP but require FPGA acceleration to achieve sub-second latency.

2.2.2 Time Series Models for Trend Forecasting

LSTM networks outperform traditional autoregressive integrated moving average (ARIMA) models by 12.6% in emerging markets, capturing cyclical trends effectively. Yet, they struggle with black swan events, where sudden market shocks cause prediction breakdowns.

2.2.3 Probabilistic Models for Risk Assessment

Bayesian networks and other probabilistic models reduce cryptocurrency pricing errors to 12.7%, offering robust risk quantification. However, they rely heavily on historical assumptions, failing in extreme market conditions.

2.2.4 Hybrid Frameworks and Implementation Challenges

Hybrid AI models (e.g., Transformer+LSTM-GARCH) achieve 91.2% policy accuracy but face computational cost disparities. Institutional investors (e.g., hedge funds)

optimize speed-accuracy via GPU clusters, yielding 38.7% annual returns. Retail investors prioritize interpretability (e.g., LIME tools) using cost-effective open-source solutions (<$1k/month), accepting marginal accuracy trade-offs. This highlights the divide between capital-intensive high-performance systems and accessible transparent alternatives.

2.2.5 Synthesis and Strategic Recommendations

AI financial forecasting employs specialized techniques: NLP (enhanced by noise reduction, e.g., BERT) excels in high-frequency trading, while time series models predict mid/long-term trends but require crisis adaptation. Probabilistic models enable risk assessment yet depend on real-time data. Hybrid frameworks integrating these approaches offer robust solutions by simultaneously addressing short-term movements, long-term trends, and risk exposure. Successful implementation requires balancing accuracy, computational costs, and compliance, particularly for resource-rich institutions.

3. Research Method

We used a comparative analysis approach to compare different AI methods for market forecasting. We considered four types of comparison, including AI method effectiveness, data validity, type of investors, and type of challenge.

Comparative Analysis 1: In the first comparative analysis, we considered the mostly commonly used AI tools for market forecasting: NLP text analysis [12], time series (LSTM), and probabilistic models. We compared their accuracy and effectiveness, advantage and challenge, and best application scenario.

Comparative Analysis 2: Second, we compared the validity of data sources for market forecasting. We compared the marketing forecasting effectiveness of historical data, news data, social media, and financial statements [13], focusing on their predictive value mechanism, empirical case, and risk in prediction.

Comparative Analysis 3: In the third comparative analysis, we considered different types of investors, including hedge fund, wealth managers, and retail investors. We compared their technological choices, core requirements, and cost benefit balance point [14].

Comparative Analysis 4: Finally, we compared the type of challenge—including data quality, cross-market generalization, real-time bottleneck, and regulatory compliance [15]—considering the concrete issue and preamble solutions.

4. Results

The four comparative analyses are summarized in Tables 1-4.

Table 1. Comparison of Financial Forecasting Techniques and Methods

Al techniques used	Accuracy/ effectiveness	Core advantage	Challenge	Best application scenario
NLP text analysis	The decision value in the 12 hour window period after breaking news is significant	Realtime parsing of unstructured data (improved accuracy of 1520% fluctuation recognition)	Data noise, emotion dictionary update lag	High frequency trading, public opinion monitoring
Time series (LSTM)	Forecast medium and long-term trends in market stability	Capture periodic fluctuations (LSTM is better than ARIMA by 12.6%)	The response to emergencies is delayed, and the data fault causes a 30% deviation	Emerging market equity cycle forecast
Probabilistic model	Nonlinear market risk pricing for cryptocurrencies	Quantitative uncertainty (Bayesian network error is 12.7%)	Relying on historical laws, the market changes and fails	Option pricing, risk management

Table 2. Comparison of Validity of Data Sources

Data type	Predictive value mechanism	Empirical case	Risk in prediction
Historical data	RSI overbought/sold signal to guide short-term operations	LSTM+RSI improves the prediction power of emerging markets	The lag is obvious (the error rate of a single index is more than 40%)
News data	Sentiment polarity → stock price moves in 12 hours	Negative news sent shares down instantly	Media bias leads to bias in sentiment analysis
Social media	Collective emotions as the "digital agents" of the market	Positive sentiment on Reddit signals the potential for a rise in stock prices	35% of robot accounts are fake
Financial statements	P/E ratio/earnings indicator to evaluate intrinsic value	Sustainable investment credit risk assessment (renewable energy sector)	Risk of financial statement fraud (such as inflated net profit)

Table 3. User Scenario Adaptation Scheme

Type of investor	Technological choices	Core requirements	Cost-benefit balance point
Hedge fund	Hybrid model + FPGA acceleration	38.7% annualized revenue + millisecond response	$5 million GPU investment vs. tens of millions of excess revenue
Wealth managers	LSTM + visualization tool (LIME)	Decision interpretability (heat map display)	Sacrifice 10% accuracy (75% to 65%) for customer trust
Retail investors	Technical indicators + simplified ARIMA	Zero code implementation + real-time signal prompt	Free open source tools (TensorFlow)

Table 4. Core Challenges and Innovative Solutions

Type of challenge	Concrete issue	Preamble solutions
Quality of data	Social media leads to 35% signal distortion	Knowledge graph validation layer (associate financial statements/policy data)
Cross-market generalization	The characteristics of retail investors in A shares make the strategy ineffective (the transplantation of Hong Kong stocks to A-shares fails)	Dynamic introduction of turnover rate and leverage ratio parameter optimization
Realtime bottleneck	VADER sentiment analysis is delayed by 2 seconds per message	Edge computing + FPGA chip (500 milliseconds/strip)
Regulatory compliance	The EU requires black box models to be interpretable	LSTM integrates SHAP value analysis module (decision traceability)

5. Discussion on the AI Stock Prediction: Advantages, Practices, and Challenges

5.1. Core Advantages of AI Prediction

Processing Massive Heterogeneous Data: Traditional models missed unstructured data insights. AI-powered NLP now analyzes real-time social media sentiment, detecting market anomalies within hours and improving volatility forecasts by 15%-20%. This bridges quantitative analysis with modern information-rich markets.

Capturing Complex Nonlinear Relationships: Traditional linear models cannot adequately capture complex market dynamics involving policy changes, sentiment shifts, and multifactor interactions. Modern AI solutions overcome these limitations: LSTM networks show 12.6% better accuracy than ARIMA for cyclical trends, Bayesian networks achieve an error of just 12.7% in crypto predictions, while hybrid models such as Transformer+LSTM-GARCH facilitate sophisticated cross-market arbitrage strategies.

Enhancing Speed and Automation: Manual analysis cannot meet HFT speed demands. AI solutions now achieve a 500-millisecond latency via FPGA acceleration, generating automated trading signals (like RSI+sentiment combos) while maintaining transparency through explainable AI tools (LIME/SHAP).

Dynamic Market Adaptation: Traditional models fail during market shocks. AI enhances resilience through real-time learning and adaptive parameters (turnover rate), while threshold regression identifies uneven sentimental effects.

5.2. Key Practices for Effective Predictions

AI stock prediction requires: (1) NLP+FPGA for HFT, LSTM for trends, probabilistic models for risk (GPU for institutions, open-source for retail); (2) multisource data integration (RSI/MA + sentiment + P/E) via knowledge graphs; (3) BERT filters 35% of bot noise with dynamic tuning; and (4) SHAP/LIME ensures EU compliance with ~10% accuracy trade-off.

5.3. Critical Challenges

AI stock prediction faces key challenges: 35% of social media noise causes >30% errors; institutional strategies fail in retail markets (e.g., Hong Kong vs. A-shares); millisecond

responses require costly FPGA/GPUs; black-box models conflict with the EU AI Act; historical data fails in crises; and complex models require $100k+ budgets and rare finance and AI skills.

5.4. Summary

AI transforms stock forecasting but faces noise, adaptability, and transparency hurdles. Key solutions include: advanced NLP/knowledge graphs for noise reduction (35% social media distortion), self-tuning models, XAI for compliance (the EU AI Act), and edge computing. Success requires balancing technical innovation with cost (~$100k budgets) and regulatory realities.

6. Conclusion

6.1. Core Advantages of AI Stock Prediction

AI revolutionizes stock prediction by (1) processing multisource data (news/social media and fundamentals) to boost accuracy by 15%-20%; (2) LSTM beats ARIMA by 12.6%, and Bayesian nets reduce crypto errors to 12.7%; (3) FPGA enables 500-millisecond analysis for real-time trading; and (4) dynamic adaptation handles market shifts via turnover ratios and online learning [16].

6.2. Key Practices for Obtaining good prediction results

Optimal results require tailored technology stacks: NLP+FPGA (≤500-millisecond delay) for HFT; LSTM+RSI for mid/long-term forecasts; Bayesian networks for risk quantification [17]. Institutions deploy hybrid models (Transformer+LSTM-GARCH), while retail traders use ARIMA+open-source tools. Multisource integration combines knowledge graphs (verifying financial/policy data) with BERT-optimized sentiment analysis, reducing social media noise by 35% [17]. Compliance demands SHAP/LIME explainability (e.g., LSTM heatmaps), meeting EU regulations despite a 10% accuracy trade-off (75%→65%) for client trust [17].

6.3. Core Challenges and Unsolved Problems

AI stock prediction faces major challenges: 35% social media noise, financial data gaps (>30% errors), and poor cross-market adaptability (e.g., Hong Kong→A-shares failures). High costs ($1M+ hardware, $50k/month NLP) and regulatory issues (the EU AI Act vs. LSTM opacity) compound problems. Most critically, models fail during black swan events (Fed shocks, crises), limiting reliability [17].

6.4. Conclusion: Dynamic Balance of Technology, Cost, and Regulation

While AI surpasses traditional methods in processing complex data and automation, challenges remain. Key advancements require (1) enhanced noise reduction (knowledge graphs + BERT), (2) adaptive architectures with dynamic parameters, (3) cost-efficient

edge computing for real-time analysis, and (4) XAI balancing accuracy with compliance. Successful implementation must optimize technical capabilities, data quality, domain expertise, costs, and regulations [16,17].

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AI's Employment Promotion Mechanism for Chinese College Students in an Aging Society: A Dual-Perspective Study

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Abstract. This project addresses employment challenges university students face under China's delayed retirement policy and AI-driven economic transformation. Given an aging population, academic inflation, and intensified job competition, this study investigated how AI technologies can generate emerging professions (e.g. algorithm engineers, AI maintenance specialists), enhance skills development (personalized learning systems), and optimize job matching (intelligent platforms). Five recruitment experts were interviewed to identify how the AI-driven economic being transformed. The results found that mitigating the employment pressure on college graduates caused by delayed retirement policies, while also innovatively proving that AI is not a "job displacer" but rather a "bridge builder" for youth to break through to new careers in an era of dramatic demographic shifts and technological explosion. It is necessary to continuously promote the deepening of applied technologies and the construction of intergenerational collaboration mechanisms to transform population challenges into innovation dividends. All in all, this project leveraged artificial intelligence to address the employment difficulties of college students in an aging society, precisely targeting the triple challenges of national aging, youth employment, and technological transformation. It combined policy foresight and the promotion of practical value. It provided a demonstrative solution for national universities to tackle employment issues against the background of delayed retirement and promote the transformation from "talent dividend" to "innovation dividend."

Keywords. Artificial Intelligence, Delayed Retirement, University Student Employment, Structural Employment Mismatch, Technology-Driven Solutions

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All authors contributed the same in the research. Dr Adela Education Limited is a HKU startup and spinoff.

1. Introduction

Amid accelerating population aging globally, over 31 Chinese provinces have implemented delayed retirement policies (e.g., extending male retirement to 63 years by 2040), which has exacerbated youth unemployment pressures. The AI revolution—driven by national strategies like the New Generation AI Development Plan—is also reshaping labor markets, creating both opportunities and disruptions. University graduates now face a dual crisis: intergenerational job competition from retained senior workers and structural skill mismatches as AI redefines 65% of traditional roles [1]. This has manifested acutely in China, as youth unemployment reached 21.3% in 2023 [2], while AI-related vacancies grew by 140%. This mismatch highlights a critical tension between labor supply and demand. This project therefore reviewed AI job requirements and provides suggestions on the job opportunities and skills required for students to equip themselves for AI evolution in the job market.

The remainder of this paper is organized as follows: Section 2 discusses the AI-enabled solutions for youth employment amid delayed retirement and skill mismatches. Sections 3 and 4 discuss the research methods and results, respectively. Section 5 presents the results, and Section 6 concludes this study.

2. Literature Review

The implementation of delayed retirement policies [3] has exacerbated youth unemployment pressures [2], while the AI revolution, driven by national strategies like China's New Generation AI Development Plan, is reshaping labor markets, creating both opportunities and disruptions. University graduates now face a dual crisis: intergenerational job competition from retained senior workers and structural skill mismatches as AI redefines 65% of traditional roles [1]. This dual crisis and the resulting mismatch between youth employment and AI-related job vacancies underscores a critical imbalance between labor supply and demand [4]. This study bridges the gap by investigating AI-enabled solutions to reconfigure youth employment pathways under delayed retirement constraints. It proposes a technology-driven framework that includes dynamic skills mapping using AI algorithms [5].

The scale of enrollment in undergraduate and postgraduate programs has been continuously expanding in recent years, and the number of highly educated people has been growing steadily [4]. However, the supply of talent has exceeded market demand, and the advantage of academic qualifications has weakened. The devaluation of academic qualifications has therefore become an increasingly prominent problem [6]. The innovation of this study lies in proposing a solution focused on collaboration among AI, industry, and academia (e.g., smart training bases) to bridge gaps through technology, thus offering new pathways for educational alignment theories [7].

3. Research Method

This study used interview method for data collection. Five recruitment experts were interviewed and the results are summarized below. The inclusion criteria were that the interviewee must have at least 10 years recruitment experience or be in a management

position. Individuals with less than 10 years' experience or had no management or recruitment experience were excluded. The following questions were applied in the focus group discussion:

(1) From the perspective of an employer, what are your core criteria for talent recruitment, especially when there are more candidates as a result of the postponed national retirement age?
(2) As a recruitment expert, how do you think universities should optimize their programs to better prepare their students for the job market amid rapid development of AI technology?
(3) As new positions emerge as result of the rise of AI technology, how do you identify graduate candidates with the right AI skills in an efficient manner?
(4) As AI technology threatens to replace humans in many positions, what is your advice to university graduates to handle a more competitive environment through better personal development planning?
(5) What university subjects and job positions do you think will become the most popular in the next decade, considering both the postponed national retirement age and the rise of AI technology?

4. Result

The results of the interview with five managers are summarized in appendix. To tackle the challenges of this shifting landscape, graduates should integrate domain expertise with AI proficiency, while universities and policymakers need to align educational strategies with labor market demands [8].

4.1. Artificial Intelligence and College Students' Employment

Technology is evolving rapidly, and the knowledge and skills required to engage with this technology are changing frequently. If college students do not keep learning [9], they may have outdated knowledge and skills, which can lead to difficulty adapting to employment. The requirements for comprehensive abilities have also increased. More than professional skills are needed; qualities such as communication, collaboration, and innovation are also necessary to meet the demands of cross-disciplinary cooperation [10]. AI-related majors are also highly sought after, with many students flocking in, thus making the employment competition even fiercer. Even students from non-AI majors have crossed over to join, further intensifying the competition.

4.2. The Development of AI Technology Has Provided Jobs

The development of AI technology has, however, created abundant employment opportunities for college students [11]. New occupations such as AI algorithm engineers and data scientists have emerged, and there is an urgent need for professional college students to fill the job vacancies. PwC's report notes AI exposed roles (e.g., algorithm engineers) grew by 38% [12]. The integration of AI with traditional industries such as healthcare and finance is also promoting their digital transformation. The combination of AI and traditional technologies, as well as cross-border integration, has become an important economic avenue, giving rise to new products and industries such as

unmanned aerial vehicles, intelligent medical diagnostic products, intelligent robots, and machine translation products, thereby increasing related job opportunities [13]. College students can also use AI to optimize business processes and create more job opportunities [14], because AI lowers the threshold and cost of starting a business. This could allow college graduates to carry out entrepreneurial projects and develop new products and services with innovation and technology.

4.3. Challenges Brought in the AI Era

The rapid development of AI has stimulated the social demand for versatile talents [11]. The demand for experts in the field of AI has increased around the world, and the competition for versatile talents has become increasingly fierce. Competitive pressure among college students is increasing [15]. The combination of AI and traditional industries has brought about a new industrial revolution, creating new types of jobs. However, the demand for the newly added positions is insufficient to make up for the demand of the replaced positions. The application of AI technology has accelerated the replacement of human workers, and in many fields, AI will replace assembly line jobs. The use of AI technology can save a large amount of money for workers' wages and manufacturing costs. Enterprises are thus likely to lay off a large number of workers, which would increase the number of unemployed and affect social stability [16]. The re-employment of these unemployed people poses a threat to the employment of college students, just as the emergence of the AI industry has raised the requirements for the employability of college students.

From the perspective of college students themselves, Harvey believes that the employability of college students includes six aspects: professional knowledge, learning willingness, self-management, communication, teamwork, and ability to handle interpersonal relationships. This definition comprehensively summarizes all aspects of skills that college students need to cultivate to achieve employment. College student employability not only refers to their ability to obtain jobs [17], but more importantly, to the ability to maintain employment commensurate with their educational qualifications after finding a job. This definition implies the importance of college students' perception of their own employability and puts forward higher requirements for that employability.

The core of talent development lies in establishing a systematic training mechanism based on strategic guidance, focusing on the dynamic adaptation to improve individual ability while meeting organizational needs. Its core elements cover multiple dimensions such as strategic planning, continuous learning, innovation incentives, person–position matching, and institutional guarantees to achieve the coordinated development of individuals and organizations. In conclusion, to better address employment challenges in the AI era, college students should prepare in advance by, for example, focusing on the study of professional knowledge, strengthening the cultivation of comprehensive abilities, actively participating in practical projects, and keeping an eye on industry trends to enhance their competitiveness and seize the opportunities created in the AI era.

5. Discussion

After collecting the opinion from recruitment experts, several suggestions can be made for college students to equip themselves for the AI revolution [11]. Talent development

needs to establish a strategic-guided systematic training mechanism focused on the dynamic adaptation between enhancing individual abilities and meeting organizational needs. The core elements of such enhancement encompass multiple dimensions—strategic planning, continuous learning, innovation incentives, person–position matching, and institutional guarantees—with the aim of promoting coordinated development between individuals and organizations [18]. Universities should offer AI courses, including core subjects like machine learning, deep learning, natural language processing, and computer vision, to satisfy the market's demand for AI talents. These courses would not only teach students the latest AI technologies but also enhance their practical skills and innovative thinking.

6. Conclusions

The core concept of this project was AI empowerment, and it successfully demonstrated the effectiveness of technological solutions in resolving intergenerational employment conflicts. The research outcomes not only address the original intention of mitigating the employment pressure on college graduates caused by delayed retirement policies, but also innovatively prove that in an era of dramatic demographic shifts and technological explosion [19], AI is not a "job displacer" but rather a "bridge builder" for youth to break through to new careers [20, 21]. In the future, it is necessary to continuously promote the application new technologies and the construction of intergenerational collaboration mechanisms to transform population challenges into innovation dividends.

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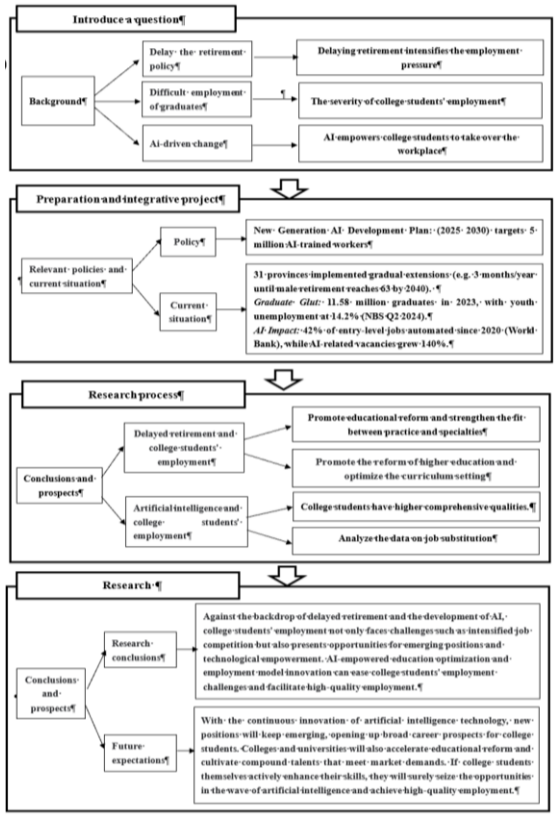
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Appendix



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Use of a Novel Clustered Bayesian 3D-CNN Model for Triage Classification of COVID-19 Mass Casualty Incidents

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Abstract. The first author previously conducted an empirical review of the constructs for determining triage recommendations for COVID mass casualty incidents (MCIs). This research aims to continue that previous study and to implement a novel clustered Bayesian 3D-CNN model for predicting COVID-19 MCI triage classification. An experimental research method is used here. Data were collected from the databases of the COVID Tracking Project, Oxford COVID-19 Government Response Tracker, and OxCGRT. The data samples were then integrated to construct a dataset with the three dominants of severity of infection (signs and symptoms of coronavirus), likelihood of spreading (attitudes towards pandemic spreading, personal behaviors, and government policy), and available resources (availability of physicians and medication, hospital vacancies, and evacuation assets) to train a 3D-CNN model on COVID19 test results, recovery histories and medication outcomes. The output of the model includes categories of triage recommendations entitled "immediate (hospital admission with immediate medical care)", "delayed (quarantine center and observation)", "minimal (home quarantine with medication)", "semi-minimal (home quarantine without medication)", and "no priority (no therapeutic resources)". Experimental results show that the accuracy rate, AUC, precision, recall and F1-score for the COVID19 MCI triage decisions are 82%, 85.8%, 0.835, 0.789, and 0.811, respectively. In addition, our model outperforms other triage decision models for emergency incidents. As a consequence of this study, medical professionals will be able to apply our model to their hospital data for triage decisions involving COVID-19 or other medical incidents.

Keywords. Bayesian network, 3D-CNN model, MCI triage classification, COVID-19

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1. Introduction

Although traditional statistical models provide straightforward implementation and clear interpretability, their reliance on strong parametric assumptions frequently leads to model misspecification, particularly when handling real-world epidemiological data. In an empirical study by Cheung et al. [1], the determinants of pandemic spread were found to include risk perception, hygiene behaviors, attitude towards pandemic prevention programs, culture, health education programs, government policies, technologies, information disclosure, and economic strategy, among others. Prediction of pandemic spread is a complex nonlinear problem that depends on many determinants, and traditional statistical methods cannot model nonlinear situations in a complex environment. Artificial intelligence (AI) can be used to model complex situations through nonlinear modeling; it requires no model assumptions or specific data structures, and can discover hidden patterns and relationships in the data. Thus, machine learning models should be employed for predictive modeling in complex environments.

The spread of a pandemic depends on specific factors such as the signs and symptoms of coronavirus, attitudes towards pandemic spreading and policy, and public resources, and conditional probability relationships exist among these factors and their determinants [1]. The spread therefore depends on combinations of these factors in this complex environment [1]. AI can be used to model both pandemic spread prediction and COVID-19 MCI triage classification. Methods that integrate traditional statistical models with AI methods can improve the accuracy of prediction and classification while minimizing computational complexity.

The following section will discuss the strengths and limitations of statistical and AI methods for prediction, and will discuss the determinants for predicting COVID-19 MCI triage classification. Sections 3 and 4 introduce the research method and the results, respectively. Section 5 contains a discussion of the results, and Section 6 concludes this study.

2. Literature Review

During the COVID-19 pandemic, accurate forecasting of the spread of infection was crucial in order to develop effective public health strategies. Researchers have employed both statistical and AI approaches to predict transmission patterns. Traditional statistical forecasting models have included autoregressive integrated moving average (ARIMA) [2] and susceptible-exposed-infectious-recovered (SEIR) models [3].

The basic idea of the ARIMA forecasting model is to predict future trends based on past time series data. A common assumption in time series models is that all the data are stationary, a mathematical term that refers to data whose statistical properties remain constant throughout the study period. The ARIMA model has been employed to predict the incidence and transmission dynamics of COVID-19 in the five countries with the highest reported caseloads [4]. Although ARIMA modelling yielded a high accuracy, the model failed to capture the complex nonlinear interactions affecting pandemic spread [4]. The study was constrained by the assumption that no vaccines or effective therapeutic interventions were available during the forecasting timeframe [4].

In a classic SEIR model, each individual is classified into one of four categories based on their epidemiological status: susceptible (S), exposed (E), infected (I), and recovered (R). To predict the spread of the pandemic, Huang and Qiao [5] implemented

the SEIR model to project infection trajectories, and estimated a pandemic peak occurring at approximately 14 days. The main limitations of their study were that they assumed unchanging infection rates, no introduction of new pharmaceutical interventions, and consistent medical management capacity throughout the analysis period [5]. In practice, the presence of super-spreaders may elevate COVID-19 transmission rates by up to 85% compared to typical infected individuals [6].

Although these methods benefit from the use of complete population datasets, without requiring additional sampling [7], they become less effective as the parameter complexity increases [8], and struggle with large datasets due to computational limitations [9]. Deep learning (DL) has emerged as a powerful alternative approach, with applications including long short-term memory (LSTM) networks [10], polynomial neural networks [11], and standard neural networks [12]. Comparative studies have demonstrated the superior computational efficiency of DL in processing time-series data [13].

Statistical methods can handle probabilistic relationships while AI captures complex details and nonlinear dynamics. Raddad et al. [14] developed a hybrid COVID-19 severity classification model that achieved an accuracy of 98% with a deep neural network (DNN) and 96% using XGBoost, which was validated using 5,654 patient records with 146 features. However, while AI achieves high classification accuracy, its low level of interpretability remains a fundamental limitation [15].

Bayesian networks offer distant advantages in terms of the graphical representation [16] of variables, although their performance remains contingent on the data dimensions and distributional assumptions [17]. In contrast, three-dimensional convolutional neural networks (3D-CNNs) have specific strengths, particularly for medical imaging analysis [18]. Their capabilities in regard to processing X-ray micro-topography, enabling rapid design iteration, and supporting probabilistic engineering design make them suitable for COVID-19 forecasting [19]. One important aspect is that 3D-CNNs can overcome the limitations of Bayesian networks in handling high-dimensional data. Hence, an integrated approach based on a Bayesian network and 3D-CNN model is recommended for predicting the spread of COVID-19.

In Cheung's empirical review study [20], the major determinants for the prediction of COVID-19 MCI triage classification included the severity of infection, likelihood of spreading and available resources. The determinants for the prediction of severity of infection rely on signs and symptoms of coronavirus, such as fever, cough, and shortness of breath [21]. Attitudes towards pandemic spread, personal behaviors, and government policy are the key determinants for predicting the likelihood of spreading. The availability of physicians and medication, hospital vacancies, and evacuation assets determine the available hospital resources. Hence, we adopt these factors when constructing our novel clustered Bayesian 3D-CNN model for predicting COVID-19 MCI triage classification based on COVID-19 test results, recovery history and medication outcome. The output of the network is divided into four categories of triage recommendations: "immediate (hospital admission with immediate medical care)", "delayed (quarantine center and observation)", "minimal (home quarantine with medication)", "semi-minimal (home quarantine without medication)", or "no priority (no therapeutic resources)".

3. Research Method

3.1 Data Selection

In this study, three publicly available COVID-19 datasets [22,23,24] were integrated to evaluate the severity of infection, likelihood of disease transmission, and availability of healthcare resources across 40 US states and territories, using a Bayesian network model for predicting the risk of COVID-19 positivity. These datasets were the COVID Racial Data Tracker (CRDT) [25], data from state-level testing and outcomes from the COVID Tracking Project [22], and the Oxford COVID-19 Government Response Tracker (OxCGRT) [24]. The selected variables were the three determinant categories of severity indicators, transmission factors, and resource metrics, which were augmented by a derived death rate metric and then used to simulate infection risk through a Bayesian network framework. The categories, units, data types, and descriptions of variables are summarized in Table 1.

The CRDT dataset [25] contains daily cumulative cases and deaths by race/ethnicity. We selected Cases_Total (cumulative confirmed and probable cases), Deaths_Total (cumulative confirmed and probable deaths), and positiveIncrease (daily new cases) as severity indicators, to capture the prevalence of infection and mortality burden. The States dataset, sourced from the COVID Tracking Project [22], offers daily metrics on testing and healthcare utilization; from this, we extracted hospitalizedCurrently (current hospitalizations with COVID-19), inIcuCurrently (current ICU patients), onVentilatorCurrently (current ventilator patients), and totalTestResultsIncrease (daily new tests) to reflect the real-time severity of disease and testing capacity, with information on both severity and transmission dynamics.

The OxCGRT dataset [24], filtered for US subnational data, provides government response policies and indices. We selected StringencyIndex_Average, GovernmentResponseIndex_Average, and ContainmentHealthIndex_Average as aggregate transmission factors, alongside containment policies (e.g., C1M_School.closing, C2M_Workplace.closing, C3M_Cancel.public.events), public health measures (H1_Public.information.campaigns, H6M_Facial.Coverings), healthcare policies (H4_Emergency.investment.in.healthcare, H8M_Protection.of.elderly_people), and economic support (E1_Income.support, E2_Debt.contract.relief) to model transmission risk and resource availability. A derived variable, death_rate (Deaths_Total/Cases_Total), was used to quantify case fatality as an additional metric of severity. The variable H5_Investment.in.vaccines was excluded, as it had zero values across all records, indicating no reported state-level vaccine investment. The period analyzed here was from April 12, 2020, to March 7, 2021, covering 330 days of the initial COVID-19 pandemic wave in the US. This period was selected based on the availability of data and the dynamic evolution of government responses.

We extracted two datasets (CRDT [22] and States [25]) from the COVID Tracking project [26], comprising daily records across 40 states and territories. Fifteen regions (including California and New York) were excluded due to incomplete data availability. The OxCGRT dataset was obtained from the OxCGRT GitHub repository [27], as this offered daily subnational policy data. We processed the data daily to capture rapid shifts in transmission patterns, healthcare burden, and intervention impacts.

The raw datasets were integrated through exact matching of the data and state fields, with all data values standardized to date/time format and state codes made consistent. To ensure data integrity, we filtered the dataset by requiring exact matches between

Cases_Total and ConfirmedCases and between Deaths_Total and ConfirmedDeaths in OxCGRT, thereby eliminating discrepancies. To fill the missing values in the columns entitled hospitalizedCurrently, inIcuCurrently, and onVentilatorCurrently, we implemented k-nearest neighbors (k=3) to preserve data patterns while completing all 2,184 daily records. The final dataset covered 40 states and territories, with approximately 54 observations per state, reflecting filtering constraints. We used data from April 12, 2020, to December 31, 2020 (1,934 samples) for model training and January 1, 2021, to March 7, 2021 (250 samples) for testing, supporting the Bayesian network's predictive analysis.

Finally, we mapped the selected variables to nine sub-factors to simulate patients' risk of infection: severity (X11: fever, X12: cough, X13: shortness of breath), transmission (X21: pandemic attitude, X22: personal behavior, X23: government policy), and resources (X31: physician availability, X32: hospital vacancy, X33: evacuation assets). These were normalized and discretized (threshold=0.15) to construct three Bayesian networks with noisy-OR conditional probability distributions, to estimate the probabilities for the severity $P(X_1)$, transmission $P(X_2)$, and resource $P(X_3)$ levels. A weighted COVID-19 positivity probability was computed as shown in (1), to gain insights into risk assessment and resource allocation.

$$R = 0.5P(X_1) + 0.4P(X_2) + 0.1\big(1 - P(X_3)\big) \quad (1)$$

In summary, the raw independent variables included seven severity indicators, 11 transmission factors, and four resource metrics, drawn from 2,184 daily samples from across 40 US states and territories. This selection supports a robust analysis of COVID-19 dynamics and facilitates the Bayesian network model's evaluation of infection risk.

Table 1. Summary of selected variables for Xs' input

Factor category	Sub-factors	Name	Units	Data type	Description
Identifiers		Date	Date	datetime64[ns]	Date of the record (daily granularity)
		State	N/A	object	State or region name within the USA
X1: Severity of infection		Cases_Total	Count	float64	Total confirmed COVID-19 cases reported in the region to date
		Deaths_Total	Count	float64	Total confirmed COVID-19 deaths reported in the region to date
	Fever	positiveIncrease	Count (daily)	float64	Number of new confirmed positive COVID-19 cases on that day
	Cough	hospitalizedCurrently	Count	float64	Number of COVID-19 patients currently hospitalized
	Shortness breath	inIcuCurrently	Count	float64	Number of COVID-19 patients currently in intensive care units (ICUs)
	Shortness breath	onVentilatorCurrently	Count	float64	Number of COVID-19 patients currently on ventilators
	Fever, cough, shortness breath	death_rate	Proportion (0-1)	float64	Death rate, calculated as Deaths_Total divided by Cases_Total
X2: Likelihood of spreading	Pandemic attitude	StringencyIndex_Average	Index (0-100)	float64	Average stringency of government containment and closure policies
	Pandemic attitude	GovernmentResponseIndex_Average	Index (0-100)	float64	Average government response index, including economic and health policies

	Pandemic attitude	ContainmentHealthIndex_Average	Index (0-100)	float64	Average index of containment and health system policies
		totalTestResultsIncrease	Count (daily)	float64	Number of new COVID-19 tests reported on that day
	Personal behavior	H1_Public.information.campaigns	Ordinal scale (0-2)	float64	Public information campaigns intensity (0: none, 1: limited, 2: extensive)
	Personal behavior	H6M_Facial.Coverings	Ordinal scale (0-4)	float64	Policy on face coverings/mask mandates (0: no policy to 4: required outside home at all times)
	Government policy	C1M_School.closing	Ordinal scale (0-3)	float64	School closure policy (0: no measures to 3: require closing all levels)
	Government policy	C2M_Workplace.closing	Ordinal scale (0-3)	float64	Workplace closure policy (0: no measures to 3: require all but essential workplaces to be closed)
	Government policy	C3M_Cancel.public.events	Ordinal scale (0-2)	float64	Cancellation of public events (0: no measures, 2: require cancellation)
	Government policy	C4M_Restrictions.on.gatherings	Ordinal scale (0-4)	float64	Restrictions on private gatherings (size limits)
	Government policy	C5M_Close.public.transport	Ordinal scale (0-2)	float64	Closure of public transport (0: no measures, 2: require closure)
	Government policy	C6M_Stay.at.home.requirements	Ordinal scale (0-3)	float64	Stay-at-home requirements (0: none, 3: require not leaving home, with minimal exceptions)
	Government policy	C7M_Restrictions.on.internal.movement	Ordinal scale (0-2)	float64	Restrictions on internal movement within the country/region
	Government policy	C8EV_International.travel.controls	Ordinal scale (0-4)	float64	International travel controls (0: no restrictions, 4: total border closure)
X3: Available resources	Physician availability	H4_Emergency.investment.in.healthcare	Ordinal scale (0-2)	float64	Emergency investment in healthcare system (0: none, 2: significant investment)
	Evacuation asset	H8M_Protection.of.elderly.people	Ordinal scale (0-2)	float64	Policies protecting elderly people (0: none, 2: strong protection measures)
	Evacuation asset	E1_Income.support	Ordinal scale (0-2)	float64	Income support policies for households (0: none, 2: generous support)
	Evacuation asset	E2_Debt.contract.relief	Ordinal scale (0-2)	float64	Debt or contract relief measures (0: none, 2: widespread relief)
	Hospital vacancies	Inverse_hospitalizedCurrently		float64	Indicator representing hospital bed vacancy, calculated as $1 - (hospitalizedCurrently_{normalized} + inIcuCurrently_{normalized} + onVentilatorCurrently_{normalized})/3$ A higher value indicates more vacant beds and less pressure on hospital resources. The original data are normalized to the range [0, 1] through min - max scaling.
	Hospital vacancies	Inverse_inIcuCurrently		float64	Indicator representing ICU bed vacancy, calculated using the same method as Inverse_hospitalizedCurrently,

	Hospital vacancies	Inverse_onVentilatorCurrently	float64	reflecting the vacancy status of ICU beds Indicator representing ventilator availability, calculated using the same method as Inverse_hospitalizedCurrently, reflecting the availability of ventilators

Table 2. Summary of selected variables for Ys' output

Y-Score Category	Name	Units	Datatype	Description
Y1: Immediate	Y1_Immediate_Score	Ordinal scale (1-4)	int64	Y1 score for immediate hospital admission with urgent medical care, based on high COVID probability and severe symptoms
	Y1_Probability_Distribution	Probability (0-1)	float64	CNN 4-class SoftMax probability distribution for Y1 immediate triage category, learned from spatial medical patterns
Y2: Delayed	Y2_Delayed_Score	Ordinal scale (1-4)	int64	Y2 score for delayed quarantine center observation, targeting moderate COVID probability cases
	Y2_Probability_Distribution	Probability (0-1)	float64	CNN 4-class SoftMax probability distribution for Y2 delayed triage category for quarantine center placement
Y3: Minimal	Y3_Minimal_Score	Ordinal scale (1-4)	int64	Y3 score for minimal home quarantine with medication support, for low-probability COVID cases with symptoms
	Y3_Probability_Distribution	Probability (0-1)	float64	CNN 4-class SoftMax probability distribution for Y3 minimal triage category for medicated home quarantine
Y4: Semi-minimal	Y4_Semi_Minimal_Score	Ordinal scale (1-4)	int64	Y4 score for semi-minimal home quarantine without medication, for very low-probability COVID cases
	Y4_Probability_Distribution	Probability (0-1)	float64	CNN 4-class SoftMax probability distribution for Y4 semi-minimal triage category for minimal medical intervention
Composite	Max_Y_Score	Ordinal scale (1-4)	int64	Maximum Y-score across all four categories from Bayesian network used to determine final triage priority
	Final_Triage_Category	Categorical (0-3)	int64	Final triage decision determined by CNN Y-score predictions: 0=immediate, 1=delayed, 2=minimal, 3=semi-minimal

3.2 Design of the Clustered Bayesian 3D-CNN model

Step 1: Data collection from various data sources
We first collected the patient symptom data, pandemic behavior factors, and healthcare resource factors, and stored them in the medical database for implementation of the clustered Bayesian 3D-CNN model (see Figure 1).
Step 2: Data preprocessing with Bayesian network
Data on infection factors (i.e., signs and symptoms such as fever indicators, cough, shortness of breath), pandemic spreading factors (i.e., pandemic attitude, personal behavior compliance, effectiveness of government policy), and healthcare resource availability factors (e.g., physician availability, hospital vacancy rates, evacuation asset readiness) were pre-processed. In particular, the X1 signs and symptoms input matrix had three layers to handle the three symptom factors (X11=fever, X12=cough,

X13=shortness of breath), with spatial dimensions of 10×10, representing the geographic distribution of patients measured at the state-day level for one temporal period. Similarly, the X2 pandemic attitudes input matrix had three layers, with spatial dimensions of 10×10, which stored the three pandemic behavioral factors (X21=pandemic attitude, X22=personal behavior, X23=government policy) for the same geographic regions. The X3 available resource matrix contained three layers to handle the healthcare resource factors (X31=physician availability, X32=hospital vacancy, X33=evacuation assets), with spatial dimensions 10×10, representing the regional healthcare infrastructure data.

Step 3: Model design

We expressed the three categories of medical explanatory variables as a clustered 3D matrix, and imported it into the three independent convolutional sub-models described above. To account for medical factors measured across different semantic domains and scales, three clusters are necessary. Otherwise, combining heterogeneous medical factors will constrain the choice of feature extraction patterns, thereby limiting the model's capacity to capture domain-specific medical relationships.

Step 4: Feature extraction with filters

In this step of training, we applied progressive filters **(8→16→32)** with matrix dimensions of 3×3×3 in each of the convolution layers to identify the most important medical patterns.

Step 5: Enhancement of model efficiency with activation function and max pooling

To determine the most significant medical patterns or features, we extracted the convoluted values from the three 3D-CNN models and passed them to their corresponding activation and max pooling functions with dimensions 2×2×2.

Step 6: Model training and optimization with Adam optimizer

Finally, the three 3D-CNN clusters generated hidden representations of the symptom severity, pandemic risk exposure, and healthcare resource availability. These formed a concatenated 96-dimensional feature vector that was used for training. In addition, to train the CNN with a backpropagation model for the Y-score prediction and four-class triage decision making, the COVID probability computed by the Bayesian network was passed to the CNN. The model predicted four separate Y-scores (Y1=immediate, Y2=delayed, Y3=minimal, Y4=semi-minimal) as four-class categorical distributions (probability distributions over severity levels 1 to 4). The Y-scores predicted by the CNN determined the final triage category directly, incorporating medical domain knowledge that Y-scores contain the necessary triage information. The entire medical decision system was trained through backpropagation, using a multi-task loss function (0.5×cross-entropy for triage + 0.5×cross-entropy for Y-scores), in which gradients were propagated backward through all prediction heads to jointly optimize the Y-score learning and four-class triage decisions. The Adam optimizer was used to update the network parameters iteratively, with learning rate scheduling and early stopping to ensure stable convergence while preserving the medical logic hierarchy of the Bayesian COVID→CNN Y-scores→Triage decisions. The details of the structural design of the clustered 3D-CNN model for COVID-19 medical triage are shown in Figure 1.

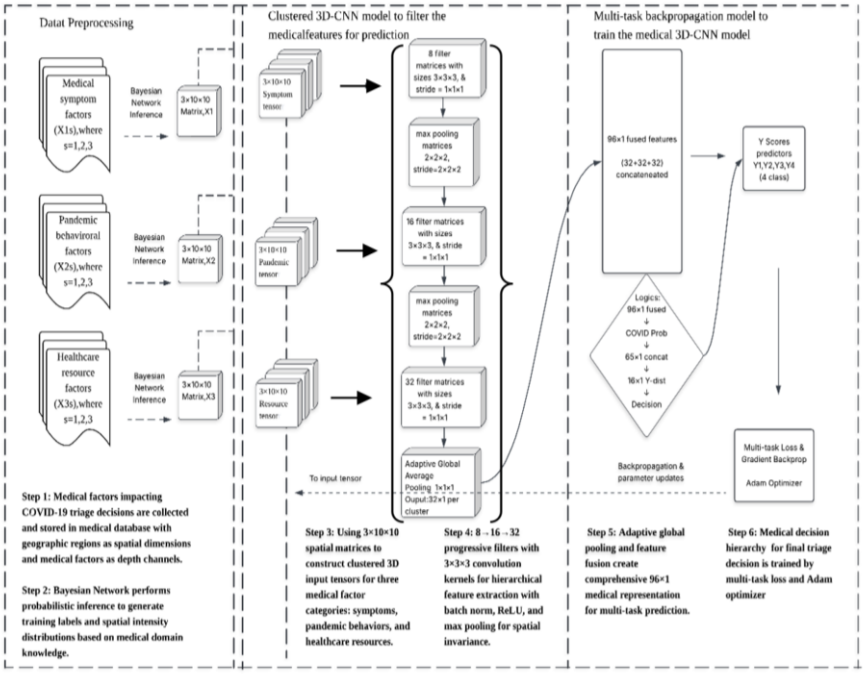


Figure 1. Clustered 3D-CNN model for triage decision prediction.

3.3 Data Pre-processing

The three symptom factors (i.e., $X_{1,i}$), three pandemic behavioral factors (i.e., $X_{2,j}$), and three healthcare resource factors (i.e., $X_{3,k}$) were pre-processed using **Bayesian Network inference** to predict the four Y-score triage categories (i.e., Y_m) for COVID-19 MCI triage decision making. The symptom input matrix has three layers corresponding to the three symptom factors, with spatial dimensions of 10×10, representing the patient distribution across geographic regions for each state-day period. Similarly, the pandemic input matrix has three layers and spatial dimensions of 10×10, storing three pandemic behavioral factors for the same geographic regions. The healthcare resource matrix contains three layers corresponding to the resource availability factors, with spatial dimensions of 10×10, representing the regional healthcare infrastructure capacity.

Symptom factor vector $X_{1,i}$ *= {fever indicator, cough presence, shortness of breath}*

where i = 1, 2, 3

Pandemic behavioral vector $X_{2,j}$ *= {pandemic attitude compliance, personal behaviour adherence, government policy effectiveness}*
where j = 1, 2, 3

Healthcare resource vector $X_{3,k}$ *= {physician availability, hospital vacancy rate, evacuation asset readiness}*

where k = 1, 2, 3

Triage categories $Y_m \in \{Y_1(Immediate), Y_2(Delayed), Y_3(Minimal), Y_4(Semi\text{-}minimal)\}$
where m = 1, 2, 3, 4

3.3.1 Data preprocessing for the Bayesian network

Unlike traditional normalization approaches, our method employs **Bayesian Network inference** with conditional probability distributions (CPDs) to capture medical domain knowledge and uncertainty at the data pre-processing stage.
The **probabilistic pre-processing pipeline** transforms raw medical categorical data into semantically informed spatial representations, as follows:
Raw Evidence → Bayesian Inference → Spatial Clustering → Domain Normalization
This approach enables the clustered Bayesian 3D-CNN to learn from medically meaningful spatial patterns, rather than arbitrary categorical encodings, while maintaining inference consistency across the training and validation datasets.
Probabilistic Medical Inference Framework
The Bayesian network establishes causal medical relationships through a structured probabilistic model, a hierarchical medical decision framework. Given patient evidence **E = {X1, X2, X3}**, inference proceeds through the following intermediate medical constructs:
The formula for exposure risk assessment from pandemic behavioral factors is as follows:

$$P(Exposure_{risk}|X_{2,j}) = TabularCPD(exposure_{risk}|X_{21}, X_{22}, X_{23})$$

$$Risk_{score} = 0.4 \times X_{21} + 0.4 \times X_{22} + 0.2 \times X_{23}$$

$$Exposure_{risk} = 0.2 + Risk_{score} \times 0.6$$

where $TabularCPD$ Stands for the tabular conditional probability distribution.
The detection quality is calculated from the healthcare resource availability as follows:

$$P\left(Detection_{quality}\middle|X_3\right) = \text{TabularCPD}\left(detection_{quality}\middle|X_{31}, X_{32}, X_{33}\right)$$
$$Quality_{score} = 0.3 \times X_{31} + 0.4 \times X_{32} + 0.3 \times X_{33}$$
$$Detection_{quality} = 0.3 + Quality_{score} \times 0.5$$

The COVID probability integrates symptom evidence with exposure context, as follows:

$$P(COVID|X_1, Exposure_{risk}) = \text{TabularCPD}(covid|X_{11}, X_{12}, X_{13}, exposure_{risk})$$
$$Symptom_{score} = 0.2 \times X_{11} + 0.18 \times X_{12} + 0.25 \times X_{13}$$
$$COVID_{prob} = 0.15 + Symptom_{score} \times 0.6 + Exposure_{risk} \times 0.3$$

Medical Domain Normalization

Different medical parameters are evaluated using separate semantic domains and probabilistic scales, causing heterogeneous input characteristics. When modelling a medical neural network, the use of normalized spatial data typically accelerates the learning process and leads to faster convergence while preserving the medical semantic relationships.

In our clustered spatial representation, we perform **clipping normalization** to ensure numerical stability and preserve the medical semantic relationships, as follows:

$$X' = clip(X, 0,1) = max\big(0, min(X, 1)\big)$$

In this approach, all spatial intensity values are bounded within the range [0,1] while the relative relationships between active and inactive medical factors are preserved.

3.3.2 Model Design

Three clustered 3D-CNN models were developed to reflect the three medical factor categories (symptoms, pandemic behaviors, healthcare resources). A total of 60% of the dataset was used for training, 20% for validation, and 20% for testing. The dimensions of the three input matrices were 3×10×10, 3×10×10, and 3×10×10, and the predicted outputs were four-class categorical distributions for the scores Y1 to Y4, with dimensions of 1×1 (COVID probability), and 1×1 (send-home decision). The structural details of the clustered 3D-CNN are shown in Figure 1.

Convolution Layer

The convolution layer takes as input a matrix with dimensions M rows, N columns, Q slices. In the first layer, there are **eight** filters (kernel), each with dimensions of m rows, n columns, and q slices, followed by **16** and **32** filters in the subsequent layers. The size of each convolution stride is $s_1 \times s_2 \times s_3$. Consequently, the output size of the convolution layer O(i,j,k) is $[(M-m)/s_1]+1$ rows, $[(N-n)/s_2]+1$ columns, and $[(Q-q)/s_3]+1$ slices. The equation used to compute the output of the convolution layer is shown below:

$$O(i,j,k) = \sum_{a=1}^{m}\sum_{b=1}^{n}\sum_{c=1}^{q} f(\, i+a-1, j+b-1, k+c-1)\; \mathrm{g(a,b,c)}$$

where i ranges from 1 to $[(M-m)/s_1]+1$, j ranges from 1 to $[(N-n)/s_2]+1$, and k ranges from 1 to $[(Q-q)/s_3]+1$.

Activation Function

To determine whether to pass onward information, and how much to transfer, the output of the convolution layer is fed to an activation function ReLU = max(x,0).

$$R(x) = \begin{cases} x & x > 0 \\ 0 & x \le 0 \end{cases}$$

where x is an element of the convolution result $O(i,j,k)$.

Batch Normalization Layer

Each convolution block includes batch normalization to stabilize medical feature learning:

$$BN(x) = \gamma \times (x-\mu)/\sigma + \beta$$

where μ and σ are the batch mean and standard deviation, respectively, and γ and β are learnable parameters.

Max Pooling Layer

A max pooling matrix has x rows, y columns and z slices, with a stride of size $t_1 \times t_2 \times t_3$. The output max pooling matrix M(u,v,w) has dimensions f×g×h (rows×columns×slices), where $f = [(M-x)/t_1]+1$, $g = [(N-y)/t_2]+1$, and $h = [(Q-z)/t_3]+1$. The equation used to compute the max pooling output is:

$M(u,v,w) = max_{c=0\ldots x-1,d=0\ldots y-1,e=0\ldots z-1} O(u+c, v+d, w+e)$
where u ranges from 1 to f, v ranges from 1 to g, and w ranges from 1 to h.

Adaptive Global Average Pooling Layer
Following the max pooling operations, adaptive global average pooling is applied to generate translation-invariant feature representations. For each channel i of the final feature map F with dimensions D×H×W, the adaptive global average pooling output GAP(i) is computed as:
$\text{GAP}(i) = \frac{1}{D\times H\times W} \times \sum_{d=1}^{D}\sum_{h=1}^{H}\sum_{w=1}^{W} F(i,d,h,w)$

Fully Connected Layer and Sigmoid Function
The outputs of the max pooling layers from the three medical clusters are concatenated into a feature input vector **with dimensions 96×1**, which serves as input to the fully connected layer. The aim is to train the clustered 3D-CNN model with backpropagation for medical triage prediction. Medical features are processed through multiple specialized prediction heads, where each medical task has its own dedicated pathway: the Y1–Y4 scores use four-class SoftMax classification, COVID probability uses sigmoid activation, and COVID-19 MCI triage decision uses sigmoid activation. This allows the model to learn task-specific medical patterns in a natural way.
For Y-scores, $\text{SoftMax}(x_i) = \frac{e^{x_i}}{\sum_{j=1}^{4} e^{x_j}}$, where x_i is the raw logit/score for class *i* before activation, which ensures that each Y-score is a probability distribution over four severity levels (1–4).
For probabilities, $\text{Sigmoid}(x) = \frac{1}{1+e^{-x}}$, where x is the output from each medical prediction head, ensuring COVID and COVID-19 MCI triage decision probabilities are bounded between zero and one.

3.3.3 Model Training

Figure 2 illustrates the training process of the clustered 3D CNN model.

3.3.4 Complexity Analysis

The following 3D convolution formula shows how the computational complexity of the proposed medical clustered 3D-CNN model is computed, accounting for each convolution cluster:

$$K1 \times K2 \times K3 \times C_{in} \times D_{out} \times H_{out} \times W_{out} \times C_{out}$$

where the kernel size is $K1 \times K2 \times K3$; C_{in} and C_{out} are the number of input and output channels, respectively; and D, H, and W are the depth, height, and width of the 3D feature map.
For the medical symptom factors, the $3 \times 3 \times 3$ convolution with **eight filters** on a $3 \times 10 \times 10$ feature map with three input channels requires $3 \times 3 \times 3 \times 3 \times 3 \times 10 \times 10 \times 8 = 194{,}400$ multiply-accumulate operations. Similarly, for the first convolution layer, which processes the pandemic factors, the same 194,400 operations are required, and for the resource factors, another 194,400 operations are involved, giving a total of **583,200 operations** for the first convolution layer across all three clusters.

The subsequent layers with 8→16 and 16→32 channel progressions follow similar computational patterns, with reduced spatial dimensions due to pooling. Overall, the complexity of the clustered 3D-CNN model is O(K³NC), where K = max(K_1, K_2, K_3) = 3 (kernel size), C = max(C_{in}, C_{out}) = 32 (max channel count), and N = max (D_{out}, H_{out}, W_{out}) = 10 (max feature map dimension).

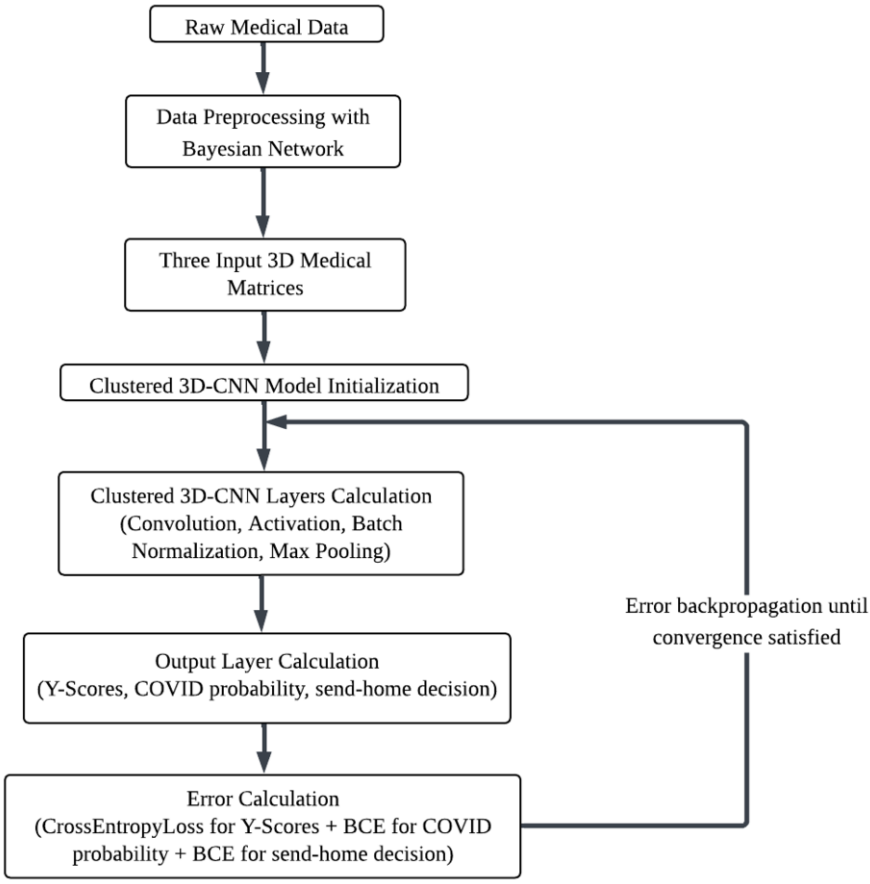


Figure 2. Training processes of the Clustered 3D-CNN model.

The evaluation metrics for medical triage performance are listed in Table 3.

Table 3 Evaluation metrics for medical triage performance

Evaluation metrics	Formula
Y-score accuracy	$\frac{1}{T}\sum_{i=1}^{T} 1[\hat{y}_i = y_i]$
Y-score cross-entropy loss	$-\frac{1}{T}\sum_{i=1}^{T}\sum_{j=1}^{4} y_{i,j}\log(\hat{y}(i,j))$

COVID Prob MAE	$\frac{1}{T}\sum_{i=1}^{T}\widehat{p_i} - p_i$
COVID-19 MCI triage classification accuracy	$\frac{TP + TN}{TP + TN + FP + FN}$

4. Results and Discussion

Table 4 summarizes the results for the accuracy of COVID-19 prediction, triage decisions, the overall performance, and the significance analysis of the clustered Bayesian 3D-CNN model, a traditional machine learning ensemble, and a standard CNN.

Table 4. Results of COVID-19 triage predictions with Clustered Bayesian 3D-CNN, traditional ML ensemble, and Standard CNN.

Model	Average accuracy	Average AUC-ROC	Average precision	Average recall	F1 score	p-value	Cohen's d	95% CI
Clustered Bayesian 3D-CNN	0.820	0.858	0.835	0.789	0.811	-	-	-
Traditional machine learning ensemble	0.742	0.781	0.756	0.698	0.726	<0.001	0.73	[0.062, 0.094]
Standard CNN	0.734	0.776	0.748	0.691	0.719	<0.001	0.68	[0.071, 0.101]

We used McNemar's test comparing against the clustered Bayesian 3D-CNN (reference model). We also examined the effects using Cohen's conventions as well as a 95% confidence interval for the difference in accuracy from the reference model.

5. Discussion

The superior accuracy of the proposed clustered Bayesian 3D-CNN model in regard to triage classification (see Table 4) stems from its innovative integration of Bayesian inference with 3D CNNs. This architecture effectively captures the complex spatial-temporal and probabilistic relationships among heterogeneous forms of COVID-19 patient data, including symptoms, pandemic behavior, and healthcare resource availability. Unlike traditional machine learning models that assume conditional independence, our model leverages clustered data representations to preserve domain-specific parameter correlations, with a statistically significant although modest improvement in accuracy.

The statistically validated performance improvements translate directly to meaningful clinical benefits. The improvements in accuracy for our model of 7.8–8.6% represent approximately 78–86 correct triage decisions per 1000 patients, corresponding to substantial improvements in the efficiency of the emergency department. The improvement in precision of 0.079 over traditional machine learning reduces false

positive admissions by nearly 8%, potentially preventing unnecessary resource utilization during pandemic surges.

The effect sizes of 0.73 and 0.68 for Cohen's d exceed the 0.5 threshold that is typically considered as practically significant in medical decision support systems, thus confirming that our architectural innovations provide tangible clinical benefits beyond statistical significance. The consistent improvements across multiple metrics (accuracy, precision, recall, and AUC-ROC) represent robust performance advantages compared to single-metric optimization.

Tuning of the model involved iterative optimization of convolutional kernel sizes, channel depths, and batch normalization layers to improve feature extraction and reduce overfitting. We also applied max normalization and an 80/20 training-testing split, to ensure stability and generalizability across diverse patient profiles.

Key challenges included the management of heterogeneous data sources, taking into consideration the uncertainty inherent in medical data, and preventing overfitting of the model when trained on limited samples. These issues were addressed by using Bayesian pre-processing to embed causal knowledge and uncertainty, designing specialized CNN clusters for each data domain, and employing normalization and regularization techniques.

Overall, as shown in Table 3, our approach significantly outperformed the baseline models in terms of accuracy, AUC-ROC, precision, and recall, thus demonstrating its effectiveness for COVID-19 triage decision support.

However, in Almulihi's [28] study, focusing on traditional machine learning approaches for medical triage systems, our model's 78.9% recall for COVID-19 MCI triage decision is consistently lower than precision-optimized models. A comparative analysis of the recall results against a random forest-based model, an SVM-based model, and an ensemble NN-based model is provided in the last two rows of Table 4. This occurs mainly because simulated and real-world clinical datasets are used. In controlled clinical environments, patient presentations follow more predictable patterns, with standardized diagnostic protocols, while real-world emergency triage involves more complex patient interactions with comorbidities, symptom variability, and resource constraints [29]. Moreover, COVID-19 triage is more strongly influenced by the timing of symptom onset than symptom severity alone, due to the dynamic nature of viral progression and infectivity windows [29]. Notably, our test period covers the early pandemic phase in 2020–2021. The emergence of COVID-19 variants significantly influenced the clinical presentation and transmission patterns of patients worldwide; however, traditional models cannot adequately learn these evolving epidemiological scenarios from pre-pandemic training data.

6. Conclusion

This study has introduced a clustered Bayesian 3D-CNN model, thereby enhancing the interpretability and scalability of COVID-19 triage, using simulated patient data. As it includes a Bayesian network with 3D convolutional layers, our model can learn joint spatial-temporal and uncertainty patterns from mixed inputs such as symptom levels, public behaviors and the availability of health care tools, laying down a flexible engine that hospitals can scale up or down as demand shifts. The model achieves values for the accuracy of 82.0%, AUC-ROC of 85.8%, precision of 83.5%, recall of 78.9%, and F1-score of 81.1% (see Table 5). These values exceed the results attained by standard

benchmarks such as a full-learning ensemble, a typical 2D-CNN setup, an ARIMA pipeline, and an SVR approach. The recall rate still represents a notable shortfall, a discrepancy that is attributable to the noise inherent in field data and the rapid proliferation of novel variants. Hence, future versions of the model will need to target these strains more carefully. In general, the platform offers frontline clinicians a robust, data-driven methodology for expediting patient triage in time-critical scenarios.

Table 5. Comparison of our model with other models as benchmarks

Model Type	ARIMA-based model for emergency incident triage classification	SVR-based model for emergency incident triage classification	NN-based model for emergency incident triage classification	Clustered Bayesian 3D-CNN (ours) for COVID-19 MCI TRIAGE CLASSIFICATION
Accuracy	72.4%	–	75.8%	82.0%
COVID-19 MCI Triage F1-Score	68.2%	71.5%	69.7%	81.1%
COVID-19 MCI Triage AUC-ROC	0.742	0.758	0.771	0.858

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A Novel Lightweight Framework Using Zero-DCE and Epsilon Sampling Strategy for Improving Dark Object Recognition

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Abstract. The paper presents a novel lightweight framework for real-time human detection, tracking, and action recognition in low-light environments, addressing critical challenges of poor visibility and noise in surveillance and autonomous systems. Key problems tackled are insufficient image contrast, real-time detection misses, high computational load, and class imbalance. We propose: Zero-Reference Deep Curve Estimation (Zero-DCE) for dark region contrast enhancement; an optimized YOLOv5 detector with cascaded 3×3 max-pooling stacks; a core Epsilon sampling strategy ensuring temporal diversity and computational efficiency by strategically selecting frames to avoid omitting semantically critical content; a ResNet-34-based R(2+1)D network combined with a Transformer-style BERT module for robust action recognition under occlusion/low contrast; and a "deep compression" pipeline. Focused loss and data augmentation mitigate class imbalance. Evaluated on low-light datasets (ARID, HMDB51, synthetic HMDB51-dark), our framework achieves state-of-the-art performance. It reduces model size by 50% and inference latency by 28% while maintaining near-original accuracy.

Keywords. Dark object recognition; Edge deployment; Deep compression; Lightweight framework; Zero-DCE; Epsilon sampling strategy

1. Introduction

Currently, video analysis struggles under low-light or dark conditions, where poor visibility and noise disrupt the accuracy of the recognition. This limits its application in

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critical fields such as security monitoring and autonomous driving. The objective of this study is to develop a lightweight framework for improving human tracking and action recognition under low-light conditions, while maintaining high efficiency and real-time performance on embedded devices. The following chapter discusses the AI techniques to solve the problems arising for video detection under low-light conditions. Section 3 discusses the research methods. Section 4 and 5 are the results and discussion. Section 6 summarizes the conclusions.

2. Literature Review

In the field of low-light video enhancement and action recognition, there are several challenges including insufficient contrast in dark environments, high computational load, real-time detection misses and class imbalance. Several AI techniques have attempted to solve these problems and are discussed in the following.

2.1. Zero-DCE Data Augmentation for Video Enhancement

There are three categories of methods to solve the problem of images having insufficient contrast: spatial domain methods, frequency domain methods and transform based methods [1,2]. Gamma Image Correction (GIC) [3], EnlightenGAN [3], and Zero-DCE [4] are the most commonly used. GIC is a traditional image enhancement method that increases the contrast of the image, and is commonly used to adjust the brightness. EnlightenGAN was the first successful approach to introduce unpaired training for low-light image enhancement. This training strategy eliminates the need for paired training data, allowing the use of a wider variety of images from different domains. Zero-DCE (Zero-Reference Deep Curve Estimation) is a novel and high-performing method for enhancing the quality of low-light images. Guo [4] used a Zero-DCE to enhance video frames under low-light conditions, which significantly improves visibility by enhancing contrast and brightness. This approach effectively handles low-light conditions by enhancing the contrast of dark regions without requiring reference images.

2.2. YOLO Network for Human Detection and Epsilon Sampling Strategy for Computation Efficiency

To solve the problems of real-time detection misses and high computational load, YOLO (You Only Look Once) is employed for real-time human detection on the enhanced frames. It offers high-speed performance and accuracy in detecting objects [5]. YOLO is efficient in detecting humans in real-time, enabling swift processing of video streams. To improve the computational efficiency, Shorten & Khoshgoftaar used the epsilon sampling strategy for improving the frame selection and sampling [6]. By adaptively selecting semantically important frames, it effectively preserves critical action information, reduces the computational load, and avoids missing important frames, thereby improving the accuracy and robustness of action recognition in low-light videos without sacrificing efficiency.

2.3. R(2+1)D-BERT network for Action Recognition

For action recognition and tracking, traditional methods include RGB-based neural networks, skeleton-based networks, and advanced pose estimation methods [7,8]. The R(2+1)D-BERT network of [9], with a ResNet-34 backbone, is used for recognizing human actions. This method incorporates BERT for better temporal attention mechanisms and position encoding. BERT's self-attention mechanism improves the learning of temporal features, while the ResNet backbone enhances the feature extraction.

2.4. Focused Loss and Data Augmentation Techniques for Training on Imbalanced datasets

Focal loss has demonstrated its effectiveness for training, especially for imbalanced datasets, allowing the model to focus on hard-to-classify examples [10]. It reduces the impact of easy examples, leading to improved performance in challenging cases. In addition, data augmentation methods like horizontal flip, random rotation, and mix-up are used to increase the robustness of the model and its generalizability to diverse scenarios [6].

Therefore, techniques for image enhancement (Zero-DCE), object detection (YOLO), frame sampling (Epsilon), temporal modeling (R(2+1)D-BERT), loss functions (Focal Loss), and data augmentation that overcome existing challenges in low-light video analysis will be used to design the lightweight framework of this study. Some experiments will be done so as to design the model and evaluate its performance.

3. Research method

3.1. Data Selection

The ARID dataset includes 11 categories of common human actions [11]. These can be divided into two types: one is individual actions, including jumping, running, turning, walking, and waving; the other is interactions between a person and an object, including drinking, picking up an object, pouring, pushing an object, sitting down, and standing. Example frames from the ARID dataset are shown in Figure 1.



Fig. 1. Examples of frames from the 11 action categories in the ARID dataset (all frames have been manually brightened)

The ARID dataset was collected using three different commercial cameras, all recorded at night. It includes 11 volunteers: 8 males and 3 females. Each scene has different

lighting conditions, but in almost all videos, there is no direct lighting on the actors. In many cases, it is difficult to recognize human actions even with the naked eye without adjusting the original videos.

The ARID dataset contains a total of 3,784 video clips, with no fewer than 110 clips per category. The dataset is split into training and testing sets at a ratio of 7:3. The overall data distribution is shown in Figure 2.

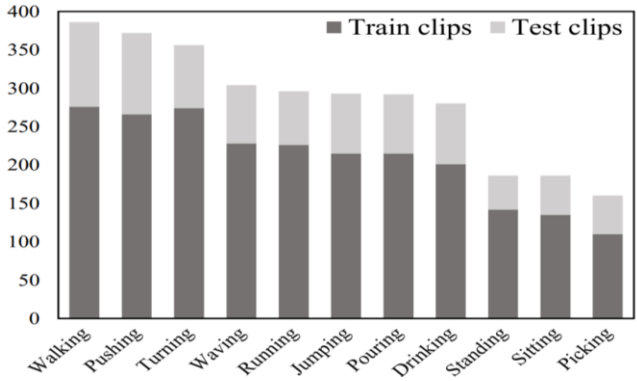


Fig. 2. Distribution of all action categories in ARID (with dark gray representing the training set and light gray representing the test set)

For the human tracking dataset, we manually annotated frame-by-frame data from the ARID dataset. To accelerate the labeling process, we further adopted a semi-supervised approach, resulting in the construction of a human tracking dataset under dark conditions. To enable the model to better recognize actions under dark video conditions, an intuitive strategy is to enhance each dark video frame so that the person and their actions become visually clearer.

3.2. Experiments for the Sake of Designing the Model

Experiment 1: To select the image enhancement, we applied three common frame enhancement methods: Gamma Image Correction (GIC), EnlightenGAN, and Zero-DCE for comparative analysis. We conducted data enhancement experiments on a sample image under dark conditions using all three methods. As observed, the original image is taken under low-light conditions, where the human figure is barely visible.

Experiment 2: To select the object detection method, the mainstream object detection algorithms are mainly based on deep learning models, which can be divided into two categories: two-stage detection algorithms and one-stage detection algorithms. The main performance indicators of object detection models are detection accuracy and speed. For accuracy, object detection needs to consider the accuracy of object localization, not just classification accuracy. Generally, two-stage algorithms have an advantage in accuracy, while one-stage algorithms excel in speed. In the experiments, we tested both models.

3.3. Model Design and Evaluation

After running the above experiments, we chose Zero-DCE for the image enhancement, YOLO for the object detection, Epsilon for the frame sampling, R(2+1)D-BERT for the

extraction of the temporal features, Focal Loss for the loss functions, and data augmentation to constitute the lightweight framework of this study. We then used the ARID and HMDB51 datasets to evaluate the model.

4. Results

To better understand videos under dark conditions, we computed and compared the ARID dataset with the HMDB51 dataset and the synthetic HMDB51-dark dataset. Figure 3 presents the ARID, ARID-GIC, HMDB51, HMDB51-dark, and HMDB51-dark-GIC datasets, along with bar charts depicting their means and standard deviations. The values of gamma for ARID-GIC and HMDB51-dark-GIC were both set to $\gamma = 5$.

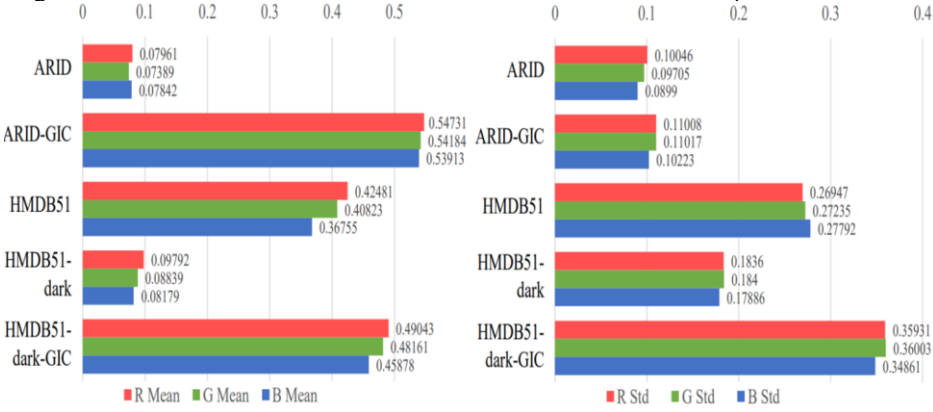


Fig. 3. Bar charts of the RGB means (left) and standard deviations (right) for the datasets (normalized to [0, 1]).

4.1. Experiment 1: Video Enhancement

For the Gamma Enhanced method, regardless of the gamma value applied, gamma correction failed to improve the result—likely due to the variation in the degree of darkness across the dataset, which gamma correction cannot accurately capture. From the Gamma Enhanced results, we also observed that while it evenly brightens the image, the EnlightenGAN method introduces many artifacts and does not adequately consider the existing bright regions of the image when applying illumination. In contrast, the results from the Zero-DCE enhancement method demonstrate its ability to address both issues mentioned above. Zero-DCE generates dynamically illuminated images and thus was chosen as our preferred method for data enhancement.

4.2. Experiment 2: Object Detection

A comparison between one-stage and two-stage models is shown in Table 1. In terms of how the object detection problem is handled, two-stage detection algorithms divide the detection process into two stages: first, generating region proposals, and then classifying the candidate regions (which often requires additional location refinement). The final detection result is obtained by accurately classifying and refining the candidate regions,

leading to more accurate model predictions. In contrast, one-stage detection algorithms do not require a region proposal phase: they directly produce object category probabilities and location coordinates. The final detection result is obtained through a single detection, thus offering faster detection speed, but the model predictions are often less accurate.

Table 1. Comparison of One-Stage and Two-Stage Models.

	One-stage	Two-stage
Testing accuracy	Higher	High
Detection speed	Fast	Relatively fast
Representative algorithm	SSD, YOLO	Faster RCNN, Mask RCNN

4.3. Model Design, Implementation and Evaluation

The PyTorch deep learning framework is used for model training. The trained model was then converted to ONNX and RKNN formats for deployment on edge devices. For the R(2+1)D architecture, we selected ResNet-34 as the backbone network. The output of the R(2+1)D branch is a feature map of size 512×8×7×7. It is then spatially average-pooled to reduce the dimensions to 512×8×1×1. The features are subsequently normalized along the temporal domain and passed to the BERT model, which generates the final classification output. The BERT model uses a hidden size of 512 and consists of one layer with 8 attention heads. The large kernel size of 3×3 MaxPooling stack structure was then used. By applying Movement Pruning for model pruning, knowledge distillation, and the Learned Step Size Quantization (LSQ) algorithm for quantization-aware training, the model is compressed to 50% of its original size, with inference latency reduced to 72% of the original, while maintaining accuracy. The model also supports INT8 storage and inference. The innovation of this study is using the Epsilon sampling strategy for video frame selection. Experimental results show that this strategy delivers better performance under these specific conditions. We replaced the GTAP component in the R(2+1)D model with BERT to further improve the model's ability to capture spatio-temporal information. Experimental results demonstrate that the R(2+1)D-BERT model offers greater robustness for action recognition under dark conditions.

5. Discussion

5.1. System Architecture

The system addresses the underexplored yet critical challenge of human tracking and action recognition in low-light environments. To achieve this, it introduces a lightweight and efficient pipeline optimized for edge deployment by integrating state-of-the-art

detection and recognition models. YOLO v5 is employed as the core object detection module due to its high speed and efficiency as a one-stage detector. To further enhance inference performance, the system replaces computationally expensive large-kernel MaxPooling operations with stacked 3×3 MaxPooling layers. This modification significantly reduces the computational load while maintaining comparable detection accuracy, making it more suitable for real-time edge deployment.

For action recognition, the system utilizes the R(2+1)D-BERT architecture, which effectively combines the strengths of convolutional and transformer-based approaches. R(2+1)D decomposes 3D convolutions into separate spatial and temporal components, enabling efficient extraction of spatio-temporal features. These features are then fed into a BERT-based transformer model, which excels at capturing long-range temporal dependencies. This hybrid architecture merges the spatial understanding capabilities of CNNs with BERT's superior temporal modeling, enabling robust recognition of human actions even in the presence of occlusion, noise, or limited lighting.

Overall, the system's design offers a cohesive and computationally efficient solution for real-time human tracking and action recognition under challenging visual conditions. Its modularity allows for scalable improvements, while its optimized performance makes it practical for deployment on edge devices where computational resources are limited. By integrating fast object detection with deep temporal reasoning, the system not only enhances the accuracy of the tracking but also improves the interpretability of human behavior in low-visibility environments.

5.2. Low-Light Video Enhancement

To enhance the visual quality of images taken under low-light conditions, three image enhancement strategies were evaluated within the system. The first approach, Gamma Image Correction (GIC), is a classical technique that applies a non-linear correction to brighten images. While computationally simple, GIC lacks adaptability to varying lighting scenarios and often results in over- or under-enhancement, making it less suitable for complex, real-world environments.

The second method, EnlightenGAN, leverages generative adversarial networks to improve image brightness and contrast without requiring paired training data. Although EnlightenGAN produces visually pleasing results in many cases, it tends to introduce artifacts and noise, particularly in severely underexposed areas, which can hinder downstream tasks like detection and action recognition.

The third strategy, Zero-DCE, adopts a zero-reference deep curve estimation approach to dynamically enhance the brightness. Unlike GIC, Zero-DCE learns to adaptively adjust the enhancement curves based on the input image's characteristics, and unlike EnlightenGAN, it avoids reliance on adversarial training, thus minimizing artifacts. Through experimental comparison, Zero-DCE was ultimately selected for integration into the system due to its superior balance between the quality of the enhancement, its computational efficiency, and its stability across varying lighting conditions.

This comparative analysis and final selection of Zero-DCE constitutes a thoughtful approach to overcoming the limitations of traditional and GAN-based methods, ensuring robust performance in real-world low-light scenarios.

5.3. Annotation and Preprocessing of a Custom Dataset

The ARID dataset, originally created for action recognition in low-light conditions, was meticulously re-annotated on a frame-by-frame basis to establish one of the first open benchmarks for human tracking under poor illumination. By leveraging semi-supervised learning techniques, the annotation process was significantly accelerated, enabling accurate, large-scale labeling with reduced manual effort. This newly generated dark-condition tracking dataset addresses a critical gap in the field, providing a valuable resource for developing and evaluating algorithms designed to operate reliably when visibility is extremely limited.

5.4. Innovative Epsilon Sampling Strategy

The Epsilon Sampling Strategy dynamically selects frames in a way that balances computational efficiency with temporal coverage. It first computes a base sampling rate, $\alpha = N / L$, where N is the desired frame count and L is the sequence length. A non-negative perturbation, $\beta \geq 0$, is then added to α for each segment, introducing slight variability without risking the exclusion of critical frames. By maintaining a consistent input length while varying the exact frame positions, this approach prevents overfitting to rigid frame distributions and promotes temporal diversity. As a result, the model generalizes more robustly to action sequences of variable durations and pacings.

5.5. Model Compression and Edge Deployment

To enable real-time inference on resource-constrained edge devices, the system incorporates several model optimization techniques. First, movement pruning removes unimportant weights and channels to streamline the network. Next, knowledge distillation trains a compact student model to mimic the behavior of a larger, high-accuracy teacher model. Finally, Learned Step Size Quantization (LSQ) is applied during quantization-aware training to reduce the precision to INT8, shrinking the size of the model and accelerating the computation. Together, these methods halve the model's storage footprint and cut inference latency by 28%, while retaining competitive accuracy. The optimized model is exported in both ONNX and RKNN formats, facilitating deployment across a range of hardware platforms. This engineering-focused pipeline strikes an effective balance between performance and efficiency, making it well-suited for embedded and real-time applications where computational resources are limited.

5.6. Fusion of R(2+1)D and BERT

The R(2+1)D module produces a spatio-temporal feature tensor of size 512×8×7×7, which is then spatially averaged to a compact 512×8×1×1 representation. After applying temporal normalization to this sequence of eight feature vectors, the resulting 512-dimensional embeddings are fed into a BERT encoder configured with a hidden size of 512 and eight self-attention heads. By replacing conventional temporal pooling methods (such as global temporal average pooling) with a Transformer-based approach, the model gains context-aware attention across time steps, enabling it to capture subtle, long-range dependencies and nuanced action dynamics. This improvement allows the system to focus on the most informative frames and motion patterns, significantly enhancing its

ability to distinguish complex human activities in video sequences under challenging conditions.

5.7. Comparative Evaluation

We bolster our contributions with a quantitative comparison of the ARID and ARID-GIC datasets against the standard HMDB51 benchmark and a synthetically darkened HMDB51-dark variant via analyses of the RGB means and standard deviations, vividly illustrating the pronounced distribution shifts and noise characteristics endemic to true low-light footage. Among the system's strengths is its pioneering focus on joint human tracking and action recognition in genuine dark environments, achieved through a thoughtfully engineered hybrid architecture that combines YOLOv5 for rapid detection with an R(2+1)D-BERT module for rich spatio-temporal and contextual modeling. Its robustness and efficiency are further enhanced by the Epsilon sampling strategy, which injects a controlled temporal variability to preserve essential frames and prevent overfitting to rigid sampling patterns. Deployment on edge hardware is made feasible by a suite of optimizations—movement pruning, knowledge distillation, and Learned Step Size Quantization—resulting in a 50% reduction in model size and a 28% reduction in inference time, with ONNX and RKNN formats ensuring broad compatibility. Looking ahead, the authors acknowledge that true real-time performance remains just out of reach, suggesting the desirability of future work on operator-level acceleration, pipeline parallelization, or NPU-specific tuning. They also note the value of expanding the diversity of the dataset to include outdoor night scenes for better generalizability and of incorporating unsupervised or few-shot learning components to enable anomaly detection in surveillance applications.

6. Conclusion

In this work, we have presented an end-to-end framework for human detection, tracking, and action recognition in low-light video. Our system integrates several key innovations: a YOLOv5-based detector, a ResNet34 R(2+1)D-BERT network for spatio-temporal recognition, an "epsilon" sampling strategy during training, and a Zero-DCE-based frame enhancement module. To enable real-time inference on edge devices, we applied aggressive model optimizations including pruning, quantization, and knowledge distillation. We also developed a new annotated low-light video dataset derived from ARID (Action Recognition in the Dark) to support training and evaluation. Together, these contributions significantly improve the ability to analyze human activities under challenging illumination while meeting the latency requirements of practical deployment. We utilized this model, achieving an accuracy of 95%.

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Development of a Novel Integrated Ontology-Based ESG Assessment Tool with AI Assistance for SMEs

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Abstract. Existing environmental, social, and governance (ESG) standards and guidelines are difficult to assess and compare the ESG performance without a standardized and integrated framework. A comprehensive assessment tool is required to integrate these standards and guidelines into a consistent list for assessment; this is especially true for SMEs. The problem arises as to how these ESG standards and guidelines can be connected and interrelated to each other. This paper therefore aims to review the existing ESG standards and guidelines, and to propose an integrated ontology-based ESG assessment tool. The research method involves empirical review, content analysis and pilot testing. The proposed instrument includes three modules of the UN Sustainable Development Group (UNSDG) model, an UNSDG maturity model, and an ESG ontology A questionnaire and a rule-based AI recommendation assistant are developed. The instrument's validity and reliability testing are done with five companies (30 samples). The results indicate that the content validity has values of 0.909 for S-CVR, 0.964 for S-CVI/UA, and 0.982 for S-CVI/Ave. The construct validity has a Pearson's R of 0.7737, convergent validity of 0.983, divergent validity of −0.1, and construct validity of 0.883. The face validity has a Pearson's R of 0.7147 at a confidence level of 95%. The internal reliability has an alpha value of 0.902. Pre-post reliability testing of the instrument shows no significant difference between the two periods ($r=0.965$, $p<0.05$, $N=30$), indicating that the instrument is well designed. The future assessment of the instrument will be extended to 30 company cases and 77 industries.

Keywords. ESG assessment; CMM model, ESG ontology; UNSDG; rule-based system, AI recommender

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ESG Innovations Company Limited is a HKU startup and spinoff.

1. Introduction

Since 1890, many environmental, social, and governance (ESG) standards and guidelines have been developed in different countries, which relate to carbon emissions, climate risks, responsible investment in sustainability, social health and safety, human rights and intellectual capital, product and consumer quality, data integrity, sustainable finance disclosure, and sustainability accounting. However, there is no unified standard for SMEs, and no clear direction for developing ESG activities. To perform a benchmarking comparison, an AI assistance tool is needed to assist in a systematic assessment across companies for comparison. The objectives of this study are therefore to review different existing standards and guidelines, to develop an ESG ontology for assessment, and to design and validate the instrument. A system architecture for the ontology-based integrated ESG assessment tool will be proposed.

2. Existing Standards and Methods for ESG Ontology

The following sections will discuss the existing ESG standards and guidelines, and related theories for the development of an ESG ontology.

2.1 Existing ESG Standards and Guidelines

There are several well-known standards and guidelines for ESG assessment. The GRI standards are widely recognized for their comprehensive approach to sustainability reporting and are used by numerous national and institutional organizations [1]. They primarily cover environmental and social issues, with some aspects of governance, and reflect a broad range of ESG topics, from environmental impact and labor practices to governance issues. They are also aligned with other common frameworks, such as SASB and TCFD. Some frameworks, such as the ESG reporting guide from HKEX and TCFD, directly reference GRI for alignment. However, this approach focuses only on qualitative disclosures, and most of the disclosures are based on textual information rather than quantitative measurements. The G20/OECD, a broad, global framework focusing on environmental and social issues, has similar problems to those of GRI, as it only provides high-level guidance rather than specific, detailed criteria [2].

The Corporate Sustainability Reporting Directive (CSRD) is an EU regulation, and mandates companies to report on their ESG impacts to promote sustainable practices and investments [3, 4]. It is used to assess a company's sustainability and its internal management's efficacy and ethical practices [5] and provides quantitative measurements covering various industries and sectors. However, it does not narrowly define specific ESG performance metrics but instead focuses on meeting various standards and regulations across European countries. The SFDR, introduced by the European Commission [6], is targeted at financial market participants, and provides unified rules on sustainability-related disclosures with similar problems. It provides quantitative measurements and covers various industries and sectors but does not provide detailed measurement metrics.

The ESG reporting guide and regulations published by HKEX were developed to fill this gap [7]. These regulations cover most governance issues, with detailed definitions of measurement, and were utilized in designing the questionnaire. The HKEX reporting guide requires listed companies to disclose their ESG performance, and provides suitable

regional alignment with global ESG guidelines, integrating ESG considerations into broader corporate governance practices to complement the Corporate Governance Code. Similarly to SASB, the HKEX guide emphasizes materiality, requiring companies to report on the ESG issues that are most relevant to their business and stakeholders. However, the mandatory nature of this guide may lead companies to focus on compliance, with priority given to meeting the minimum requirements rather than pursuing higher standards of ESG performance. In addition, ISSB [8] is included in the HKEX guidelines, which requires a company to assess climate-related risks to their business and opportunities, such as climate-related transition risks, opportunities, and physical risks.

Although specific governance issues are addressed in different frameworks, these are not sufficiently detailed for concrete measurements. In a study by Cort and Esty, a validation procedure was presented for measuring sustainable measurement metrics and timelines [9]. An ontology that integrates all these standards and guidelines was therefore designed in this study, and an ESG questionnaire was developed based on this ontology. The determinants and constricts of the ontology are discussed below.

2.1.1 Environmental Assessment Construct

In the resource-based view theory [10], companies are assumed to gain a competitive advantage by developing unique and valuable resources. ESG initiatives, such as recycling waste, managing hazard waste, and reducing energy and water usage, can improve the operational efficiency and reputation of a company. SECR is a UK government initiative that was introduced in 2019 for large companies and large limited liability partnerships (LLPs) in the UK [11]. It involves actions on energy consumption, greenhouse emissions, and energy efficiency in annual reports, provides quantitative measurement metrics, and covers various industries and sectors. The scope is limited to a few criteria and large enterprises.

TCFD provides a framework for disclosing climate-related risks and opportunities, and emphasizes the importance of governance, strategy, risk management, metrics and targets in regard to understanding and reporting the financial impact of climate change [12]. It covers issues such as emissions, climate change, and supply chain management, and focuses primarily on environmental topics, although it also covers several areas of disclosure, including governance (e.g., climate-related risks and opportunities), strategy, risk management, and metrics and targets. The metrics and targets section focuses on the measurement of specific criteria and how these measurements can be assessed. The other climate risk standard, CPG229 Climate Change Financial Risks, for which a practice guide has been released by the Australian Prudential Regulation Authority (APRA), defines some frameworks for ESG disclosures, and particularly climate change. GRI and SASB cover most of the frameworks proposed by CPG229 [13].

SASB provides industry-specific standards that focus on financially material ESG issues, with 77 standards tailored to different industries. SASB standards typically emphasize quantitative metrics, making it easier to compare ESG performance across companies and industries [14]. This framework also covers environmental and social issues with more fine-grained definitions of measurement metrics. SASB emphasizes materiality, with a focus on the ESG factors that are most likely to impact a company's financial performance. SASB prioritizes the most critical sustainability metrics, leading to more meaningful and actionable ESG insights. However, SASB is less quantifiable aspects of sustainability, such as governance measurement metrics, and less measurement of broader social or environmental impacts.

Finally, the ESG-Related Investment Fund Disclosure from the Canadian Securities Administrators (CSA) does not provide a framework for companies to disclose their ESG performance [15]; instead, it offers practical guidance for investment funds, particularly ESG-related funds, in terms of compiling their regulatory disclosures in a way that is consistent with any ESG-related offerings.

From the above study, we suggest that the determinants for measuring environmental performance are resource management, GHG emissions, environment compliance and opportunities. Energy management, water management, waste management, hazard management, and biodiversity are the determinants for resource management, while GHG emissions and climate risk, environmental standards and measurement are determinants for environmental measurement. Environmental certificates, research and opportunity are the determinants for environmental opportunities.

2.1.2 Social Assessment Constructs

Stakeholder theory states that companies have responsibilities to employees, customers, and communities, beyond simply the company's shareholders [16]. An evaluation of how well these relationships are managed and stakeholder concerns are addressed is an essential aspect of a company's success in ESG development. Product quality and data security are the determinants for customer and product construct. Drawing from Maslow's pyramid of needs theory and motivator-hygiene theory, the major factors affecting employee satisfaction are assumed to be related to hygiene, social needs, and job competence. Thus, staff training, health and safety, and labor diversification are the major determinants for human capital constructs. In regard to improving community relationships, community engagement, investment and charity and social-related certificates can demonstrate the company's community contributions, and are the determinants for community constructs. Hence, the ontology proposed in this study uses these determinants for the community, human capital, and product and customer constructs.

2.1.3 Corporate Governance and Operations Constructs

A successful corporate operation requires a set of ESG guidelines and documentation for staff to follow. As described by agency theory, ESG disclosures provide information asymmetry and promote accountability, thereby overcoming potential conflicts of interest between company management and shareholders [17]. Corporate governance issues, such as shareholder rights, ownership and board disclosure, are essential for ESG disclosures. The involvement of stakeholders in voting enhances corporate governance. In contrast, the supply chain's ability for an ecosystem is the critical success factor for sustainability development [18]. When integrated into supply chain management, ESG processes can be streamlined horizontally, resulting in more effective sustainability development. ESG disclosure has become compulsory under modern regulations, and many companies underestimate the impacts of ESG risks, resulting in the company defaulting [19]. The integration of ESG risks into a company's overall risk management framework is required, as well as the development of strategies to migrate risk and capitalize on ESG opportunities [20]. Hence, in this study, the determinants of board disclosure, ownership, and shareholder rights are used to determine corporate governance performance. Guidelines and documentation, supply chain management, risk

management, and related certificates are the determinants for the corporate operation construct.

2.2 Ontology and AI Methods for ESG Assessment

An ontology is a knowledge representation that allows a set of concepts, relationships, and axioms in a specific domain to be grouped together and stored [21]. A user can apply the concepts and rules in the ontology for knowledge extraction, mapping, reasoning and representation [22]. It provides a controlled vocabulary and framework for communication, data integration, knowledge sharing and exchange between people and systems [23], improves data consistency, and supports information filtering, extraction, collaboration, personalization and decision making [24]. An ontology can be used to integrate the ESG standards and guidelines together into a single format. The attributes of the ontology can be defined by using the ESG standards and guidelines, while the rules of the ontology can be used to group the semantic meanings of the ESG terms or objects together by using controlled vocabulary, term relationships, and hierarchical subclass relationships between classes, properties and constraint specifications in classes. With this ontology, users can extract the required ESG standards by using the semantic rules in the ontology to meet the specific ESG requirements of their clients or suppliers for its sustainability supply chain collaboration [25].

To collect, process, organize and extract information from the ESG ontology, artificial intelligence (AI) can be used to gather and filter the data and communicate the extracted information to users. AI excels in data processing, intelligent decision making, process optimization, and recommendation [25]. Current AI techniques, such as machine learning, data mining, and natural language processing, primarily focus on how computer systems emulate human intelligence, learn, adapt to their environments and enable communication between humans and computers [26]. Researchers have recently used natural language processing and text analysis methods to extract information from annual reports for ESG analysis, and have developed AI chatbots for communicating with users with regard to ESG enquiries [27]. Several rule-based systems have been designed for ESG recommendation and decision making, and data mining methods have been developed for ESG risk forecasting and knowledge discovery [27]. The use of AI improves the efficiency and effectiveness of ESG assessment and ESG prediction. Hence, this study will investigate how AI can be used in the proposed ESG ontology for knowledge integration, filtering and communication.

2.3 Proposed Ontology-Based Integrated ESG Assessment Tool for SMEs

SMEs play important roles in sustainability supply chain management. These companies are vital to the economy in terms of employment, supplier support, production and distribution, sales and marketing, and customer services. They have a major economic impact, and are essential for environmental and social change. Investors and banks prioritize ESG factors as being particularly important for investment or loan approval decision making, and select companies with strong ESG performance for investment or loan approval. The adoption of sustainable practices in order to attract investment or loan approval is a new trend and requirement; customer purchasing behavior has also changed, with customers tending to be more environmentally friendly, with more emphasis being placed on sustainability in their purchasing decisions, thus pushing SMSs to align with these values. Most importantly, there are more local and global regulatory requirements

on ESG for SMEs. The greater numbers of ESG reporting demands and transparency requirements for environmental, social, and governance practices result in an urgent need for SMEs to carry out ESG assessments for reporting. By integrating ESG into an SME's business process, the company can mitigate business risks, improve its reputation, foster innovation, attract capital, and contribute to a more sustainable world. However, the main problems faced by SMEs in terms of ESG development are limited knowledge, skills and resources [28]. In this study, we therefore integrate the key components of the existing ESG standards and guidelines to develop an ESG ontology framework, and use an ontology-based rule-based system to define and relate the integrated ESG knowledge for personalized ESG assessments and decision making.

2.4 UNSDG Goals and the Capability Maturity Model

The UNSDGs include 17 goals that companies must achieve in regard to ESG assessment. These 17 goals represent a globally recognized framework for addressing critical sustainability issues, and will therefore be used in this study to align the activities in our ontology framework for ESG assessment. In addition, to assess the ESG performance of a company, the maturity levels of ESG governance practices will be considered. The capability maturity model (CMM) is a key indicator for organizational performance [29]. This is a traditionally used framework in which a classification of five levels of process maturity guides organizations towards improving their software processes [30]. It provides a roadmap for organizations to enhance their practices by moving from ad hoc processes to more mature and optimized ones that are defined with measurable items. This framework is integral to most management systems for improving the quality of development and delivery for all products and services. In this study, these categories are adopted and revised to classify the performance of a company in terms of maturity in ESG development. A five-level UNSDG-CMM is are defined in our instrument, in which a company moves from building to implementing best practices, standardization and continuous improvement, integration and alignment, and continuous innovation. At each UNSDG-CMM level, an ESG score is calculated based on the results of the questionnaire.

3. Research Methods

Based on the review presented above, an ESG ontology was developed to group together similar ESG components in a unified view. A questionnaire was devised based on this ontology framework for assessing the achievements of the companies in terms of ESG activities. Five companies with 30 samples were selected to form the ESG committee for this pilot study. Content validity, construct validity, criteria validity, face validity, internal reliability testing and pre-post reliability testing were done.

3.1 Development of the ESG Ontology

Figure 1 shows an overview of the integrated ESG ontology based on existing standards and guidelines, in which ESG issues are classified into three categories. The first layer represents the ESG categories, while the second layer shows the ESG areas to be measured, and the third layer represents the ESG assessment components.

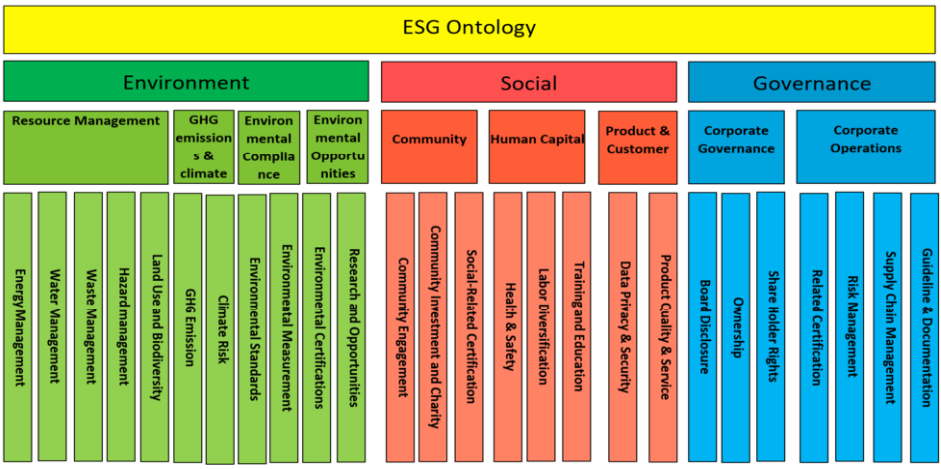


Figure 1. Overview of the integrated ESG ontology.

3.2 Questionnaire Design for the Instrument

To measure these ESG components, a questionnaire was designed based on the above ontology framework and existing ESG guidelines and standards, as shown in the Appendix.

3.3 ESG Score Measurement Methods

Three aspects are measured in this ESG assessment: the UNSDG maturity, achievement of UNSDG goals, and ESG activity performance. To measure the UNSDG maturity performance, an ESG maturity model is developed on this study. To measure how well the ESG activities are being carried out by the company, an ESG ontology is derived from the worldwide ESG standards and guidelines for different countries, and mapped to the 17 UNSDG goals.

- To assess the UNSDG maturity performance, five levels are used, which are quantified by the descriptors in Table x (see Table A.1) to assess the development status of the 17 UNSDG goals (see Table A.2).
- To assess how well the UNSDG goals are being achieved, a set of questions are used to quantify the performance for the 17 goals (see Table A.3). The average of the question scores for each UNSDG sub-target is used to assess whether the sub-target has been achieved, and to provide recommendations. The sub-target score is calculated by averaging the scores for all questions for the sub-target. Each question has a score of either one or zero. The score for each goal is finally calculated by averaging the scores for the sub-targets.
- To assess how well the ESG activities have been carried out to achieve the UNSDG goals, the average score is calculated for all the questions for each ontology component.

3.4 Implementation of AI Rules

Using the proposed ESG ontology and UNSDG sub-targets, the questions are mapped to the UNSDG sub-targets and ESG ontology components. A rule-based system is used to determine the score corresponding to each question for assessment of the ESG ontology scores and UNSDG scores by the experts.

3.5 Validation and Verification of the Instrument

To validate and verify the instrument itself and the content validity, construct validity, criteria validity, and face validity, inter-reliability testing and test-retest reliability testing were done with a confidence level of 95% [31]. For focus group and expert evaluation, the minimal sample size is five [32], while the minimal sample size for a survey is 30 subjects [33].

3.3.1 Content Validity Testing

Purpose: The purpose of content validity testing is to evaluate how well an instrument covers all relevant parts of the ESG construct (i.e., ESG ontology components) it aims to measure.
Sample size: The content validity was tested by five company experts, which is the minimal sample size for expert evaluation.
Sample selection: The inclusion criterion was that the subject had a basic ESG knowledge, whereas the exclusion criterion was that the subject had no ESG knowledge.
Method:
Step 1: Calculate the content validity ratio
The following formula was used to calculate the item content validity ratio (I-CVR) for each question and scale content validity ratio (S-CVR) for the instrument. The critical values for item content validity ratio and scale content validity ratio with five samples were 0.99 and 0.8, respectively. Values closer to one denote a higher content validity.
Item content validity ratio (I-CVR) = (ne − N/2) / (N/2)
where ne = number of SME participants indicating “measurable”
N = total number of SME panelists
Scale content validity ratio (S-CVR) = Mean of (ne/ N)
where ne = number of SME participants indicating “measurable”
N = total number of SME panelists
Step 2: Calculate the content validity index
The following formula was used to calculate the item content validity index (I-CVI) for each question and scale content validity index (S-CVI) for the instrument. The critical value for content validity with five samples is 0.8.
I-CVR = ne / N
where ne = number of SME participants indicating “measurable”
N = total number of SME panelists
The scale-level content validity index based on universal agreement (S-CVI/UA) is calculated by averaging all I-CVR values.

The scale-level content validity index based on average (S-CVI/Ave) is calculated by averaging the averaged item scores for the samples.

3.3.2 Construct Validity Testing

Purpose: Construct validity is used to determine how well the instrument measures the construct that it is intended to measure. There are two types of measurement, called convergent and discriminant validity. Convergent validity measures the extent to which a given measure corresponds to measures of related constructs, whereas discriminant validity measures the extent to which the measure is unrelated or negatively related to measures of distinct constructs.
Sample size: The content validity was tested based on a total of 30 samples from the five pilot companies, which is the minimal sample size for validation of a questionnaire.
Sample selection:
The inclusion criteria were that the subject had over two years of work experience at management level, and had some basic ESG knowledge. The exclusive criteria were that the subject had no ESG knowledge or less than two years of work experience.
Method
Convergent validity
A correlation analysis of the questions was carried out to measure each construct. We calculated the correlation coefficients between the results of the assessment and the results of assessments designed to measure the same constructs. Each correlation coefficient took a value of between −1 and +1. Finally, we took the average of the correlation coefficients. A high average correlation coefficient (i.e., close to +1) indicates high convergent validity, and the cut-off point for an acceptable convergent validity is generally considered to be +0.70.
Discriminant validity
To quantify the discriminant validity, we calculated the correlation coefficients between the results of the assessment and the results of other assessments designed to measure completely different constructs. Each correlation coefficient took a value of between −1 and +1. Finally, we took the average of these correlation coefficients. A correlation coefficient of close to zero indicates high discriminant validity, whereas if the value is close to −1 or +1, then the assessment has very low discriminant validity.
Combining convergent and discriminant validity
The following formula was applied to calculate the construct validity.

$$\text{Construct validity} = \text{Convergent coefficient} - |\text{Discriminant coefficient}|$$

A value close to one indicates very high construct validity, while any value less than 0.5 indicates a limited construct validity. Negative values represent an assessment with very low construct validity.

3.3.3 Criteria Validity Testing

Purpose: Criterion validity evaluates how accurately an instrument measures the outcome it was designed to measure. The criterion variable measures whether it has the same construct, conceptually relevant constructs, and conceptually relevant behavior or performance as similar instruments.
Sample size: The content validity was tested by five company experts through focus group discussion.
Sample selection: The inclusion criterion was that the subject had two years of ESG knowledge. The exclusion criterion was that the subject had no ESG knowledge.
Method: To establish criterion validity in this study, we compared the constructs in the proposed instrument with those of existing standards and guidelines in a comparative

study. In addition, five expert evaluations were done to compare the constructs of our ontology and the existing standards and guidelines.

3.3.4. Face Validity Testing

Purpose: Face validity aims to assess whether the instrument measures what it is intended to measure.
Sample size: The five companies in each case were used to validate whether the instrument could measure the company's ESG performance at the pilot testing stage.
Inclusion criteria for participants:

- General manager (company policy and operation, training, etc.)
- Project director/manager and/or procurement staff (vendor ESG requirement and operation, procurement, etc.)
- Administration staff and/or HR staff (special leave, training, policy, etc.)
- Accounting staff (annual report, profit and loss, paper-related payment, data extraction e.g., funding and donation to in-need community, etc.)
- Marketing staff
- Problem marker/key influencer (if appropriate)

Exclusion criterion for participants: People who were not on the ESG committee for the company.
Method: A focus group discussion was conducted to receive feedback from the five companies (a total of 30 participants) to see whether the instrument could measure what was intended.

3.3.5. Internal Consistency Reliability Testing

Purpose: Internal consistency ensures that each item on a test is related to the topic under research.
Sample size: The content validity was tested using 30 samples, the minimal sample size for questionnaire validation.
Sample selection: The inclusion criteria were that the participant should be an ESG committee member of a company and have at least two years of experience working in the company. The exclusion criterion was that the subject was not an ESG committee member of a company.
Method: The questions or items used to measure a given construct in the ESG ontology are used to measure the same and the difference among the answers. Cronbach's alpha is calculated to give the internal consistency value. A value for Cronbach's alpha of 0.70 or higher is generally considered acceptable for internal consistency
The following formula for Cronbach's alpha was used:

$\alpha = (k / (k - 1)) * (1 - (\Sigma\sigma^2_i / \sigma^2))$:

where α is Cronbach's alpha;

k is the number of items on the test;

$\Sigma\sigma^2_i$ is the sum of the variances for each individual item;

σ^2 is the variance of the total scores on the test.

3.3.6 Test-Retest Reliability

Purpose: The aim of test-retest reliability is to assess the consistency of the measurement instrument by applying the same test to the same individuals at two different times.
Sample size: The content validity was tested with 30 samples, the minimal sample size for questionnaire validations.
Sample selection: The inclusion criteria were that the subject should have over five years of working experience at management level, and some basic ESG knowledge. The exclusion criteria were that the subject had no ESG knowledge or less than five years' working experience
Method: We used the answers from the same responders as in the pre-post pilot testing, with a time interval of one week, to calculate the Pearson's R value. A Pearson's R correlation test with 30 samples (degrees of freedom = 28), the critical value for a one-tailed test at the same significance level, the critical value is 0.306.

4. Results

After the instrument validation and reliability testing was complete, the 88 questions and ontology rules were summarized as given in the Appendix. The following tables present the results for the instrument validation and reliability testing.

4.1 Content Validity

Table 1 presents the content validity testing results.

Table 1. Summary of results for content validity

I-CVR (Item-level Content Validity Ratio)	S-CVR (Scale-level Content Validity Ratio)	I-CVI (Item-Level Content Validity Index)	S-CVI/UA (Scale-level Content Validity Index based on Universal Agreement)	S-CVI/Ave (Scale-level Content Validity Index based on Average)
Critical value > 0.99	Critical value > 0.8	Critical value > 0.8	Critical value > 0.8	Critical value > 0.8
• 80 items have an I-CVR value of one. • Eight items have an I-CVR value of 0.6.	0.909 (80 out of 88)	• 80 items have an I-CVI value of one. • Eight items have an I-CVI value of 0.8	0.964	0.982

4.2 Construct Validity

Pearson correlation was calculated to compare the difference between the scores of the determinants and constructs of the ESG ontology. Table 2 shows that the values of convergent validity, divergent validity, and construct validity are 0.983, −0.1, of 0.883 respectively. Table 3 shows that Pearson's R is 0.7737 at a 95% confidence level.

Table 2. Results of the convergent validity, divergent validity, and construct validity.

Convergent validity	Discriminant validity	Construct validity
0.983	−0.1	0.883

Table 3. t-Test: Results of a paired two-sample test for means for comparison of the overall correlation of the constructs and determinants.

	0.95	*0.74934*
Mean	0.57718	0.592865
Variance	0.09558	0.058164
Observations	25	25
Pearson correlation	0.77377	
Hypothesized mean difference	0	
df	24	
t Stat	−0.40047	
P(T<=t) one-tail	0.34618	
t Critical one-tail	1.71088	
P(T<=t) two-tail	0.69235	
t Critical two-tail	2.0639	

4.3 Criteria Validity

Table 4 shows the results of a gap analysis of the existing standards and guidance for criteria validity testing. Our instrument covered all these ESF issues. In addition, we also introduce environmental, social and government certificates as an assessment criterion to measure the company's ESG performance.

Table 4. Gap analysis of existing ESG standards and guidelines

Construct name	**TCFD**	**CSRD**	**SEC**	**CGP229**	**SASB**	**HKEX/ ISSB**	**GRI**	**G20/ OECD**	**Our UNSDG-CMM**
Energy management					Yes	Yes	Yes		Yes
Water management	Yes	Yes			Yes	Yes	Yes		Yes
Waste management		Yes			Yes	Yes	Yes		Yes
Hazard management		Yes				Yes	Yes		Yes
Land use and biodiversity					Yes	Yes	Yes		Yes
GHG emission	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes
Climate risk	Yes	Yes		Yes	Yes	Yes	Yes		Yes
Environmental standards	Yes	Yes					Yes		Yes
Environmental measurement	Yes		Yes						Yes
Environmental certifications									Yes
Research and Opportunities							Yes		Yes
Community engagement	Yes								Yes
Investment and charity							Yes		Yes
Social-related certification									Yes
Health & safety					Yes	Yes	Yes		Yes
Labor diversification		Yes			Yes	Yes	Yes		Yes
Training and Education		Yes			Yes	Yes	Yes		Yes
Data privacy & security					Yes	Yes	Yes	Yes	Yes
Product quality & service					Yes	Yes		Yes	Yes
Board disclosure		Yes				Yes	Yes	Yes	Yes
Ownership								Yes	Yes

Shareholder rights					Yes	Yes
Related certification						Yes
Risk management	Yes	Yes	Yes	Yes	Yes	Yes
Supply chain management	Yes	Yes	Yes	Yes	Yes	Yes
Guidelines & documentation		Yes	Yes	Yes	Yes	Yes

4.4 Face Validity

Five pilot companies used the instrument to assess their ESG performance, and a focus group discussion was carried out to verify whether the assessment outcomes were aligned with the existing ESG situation in their company. The user satisfaction with the accuracy of the assessment results had a mean value of 0.7147 and standard deviation of 0.0788.

4.5 Internal and Test-Retest Reliability Testing

For internal reliability testing, the value of Cronbach's alpha value was 0.905. Table 5 summarizes the test-retest reliability results with a value for Pearson's R of 0.965 at a confidence level of 95%.

Table 5. t-Test: Paired two-sample for means

	Variable 1	*Variable 2*
Mean	53.1	54
Variance	72.3	81.517
Observations	30	30
Pearson correlation	0.9652605	
Hypothesized mean difference	0	
df	29	
t Stat	−2.081174	
P(T<=t) one-tail	0.0231777	
t Critical one-tail	1.699127	
P(T<=t) two-tail	0.0463554	
t Critical two-tail	2.0452296	

5. Discussion

The proposed ESG instrument was developed by integrating current ESG standards and guidelines. Five companies with 30 samples and similar ESG performance were selected to test the instrument. The following sections present the results for instrument validation and verification.

5.1 Content Validity Testing

The values of S-CVR, I-CVI, S-CVR, S-CVI/UA, and S-CVI/Average were calculated to assess the relevance and clarity of questionnaire items by five company experts. The results for the overall S-CVR, S-CVI/UA, and S-CVI/Average were 0.909, 0.964, and 0.982 respectively, all of which exceed the minimum required threshold of 0.8, thus confirming the overall validity of the scale. A total of 80 out of 88 questions had an I-CVR of one and an I-CVI of one, and for eight out of 88 questions the I-CVR was 0.6, i.e., less than the minimum threshold of 0.99, and the I-CVI was 0.8, i.e., equal to the minimum threshold of 0.8. The eight questions that were unclear were revised to improve the questionnaire. The high value of S-CVI indicates the strong content validity of our instrument.

5.2 Construct Validity Testing

The value of Pearson's R was 0.7737, greater than the critical threshold of 0.7. The value of the convergent validity was 0.983, i.e., greater than the critical threshold of 0.7 and close to one. The value of the divergent validity was −0.1, in other words, close to zero and less than 0.5. The value of the construct validity was 0.883, greater than the critical threshold of 0.7. The results therefore showed that the determinants and constructs have a high positive correlation, supporting the convergent validity of the instrument.

5.3 Criteria Validity Testing

The criterion variable measures whether it has the same construct, conceptually relevant constructs, and conceptually relevant behavior or performance of similar instruments. To establish the criterion validity, we compared the constructions of the instrument with those of existing standards and guidelines via a gap analysis. The criteria for this gap analysis were based on the determinants of the constructed ESG ontology. The comparative table shows that our instrument covers all the major components of the existing ESG standards and guidelines and filling the gaps of those blank items. Our ontology overcomes the limitations of inconsistency and incompleteness of the existing standards and guidelines to provide a unified set of activities that are required to achieve ESG goals.

5.4 Face Validity

The results of the focus group showed that all company representatives agreed that the assessment outcomes were aligned with their company's existing ESG situation. The value for user satisfaction with the assessed results was 0.717 on average. In future work, an additional user satisfaction survey could be done for face validity, in order to assess whether the instrument can measure what it is intended to measure. The companies could also be re-assessed in regard to ESG performance with the existing instrument for comparison. However, the main challenge is that there are no similar instruments to be opened to the public in the market, which results in difficulty in comparison.

5.5 Internal and Test-Retest Reliability Testing

The internal reliability was 0.902, and the test-retest reliability showed no significant difference between the two periods ($r=0.965$, $p<0.05$, $N=30$). These results indicate that the instrument can produce similar results under similar conditions: in other words, the instrument is stable and repeatable and provides consistent measurements. In future work, the interrater reliability could be used to assess the effect of several assessors using the same instrument, to further ensure the consistency and accuracy of the instrument.

5.6 Increased Sample Size in Future Work for Future Instrument Validation

Since the sample size was five companies, whereas the number of SMEs in Hong Kong is 360,000, we conclude that the confidence level of this pilot experiment was 80% and the marginal error was 32% for 50% of the accuracy of the instrument (i.e., unknown

population). In other words, if we randomly select a sample to conduct a survey with the proposed instrument, the accuracy rate will fall between 28% to 82% at an unknown proportion of the population (at true value 50%) of the accuracy of the instrument at a confidence level of 80%.

The acceptable margin of error used by most survey researchers typically falls between 4% and 8% at a 95% confidence level for an unknown proportion of the population (i.e., true proportion of population at 50%) [32,33]. For further tests of the instrument, Table 6 shows the sample size that should be considered in the future based on the expected margin error at a confidence level of 95%, with an SME population size of 360,000 and an unknown proportion of the population (i.e., true value at 50%) [32,33]. Alternatively, a known accuracy rate from previous research could be used to replace the unknown proportion of the population to recalculate the sample size [32,33].

Table 6. Sample size calculations at 95% confidence level for an unknown proportion of the population

Sample size of companies
600
384
150
30

5.7 System Architecture Design and Comparative Advantages over Existing Tools

Figure 2 shows the system architecture for the proposed ontology-based integrated ESG assessment platform. The architecture includes three layers: the ontology application layer, ontology knowledge layer, and ontology data layer. The ontology data layer collects the ESG document and information and provides virtual meeting rooms and an AI chatbot for interaction with users, in order to collect ESG data from company via the e-questionnaire. This layer pre-processes and stores the structured ESG data in the ontology database. The ontology knowledge layer applies statistics, data science, and AI methods to extract the ESG data, and provides rules for reasoning and deducting the ESG knowledge. A text summarization module uses the extracted knowledge for reporting. The ontology application layer creates dynamic ESG reports based on the company's needs. A recommender provides the ESG predictive models and knowledge rules for ESG strategy recommendations. Using Web 6.0 and IoT devices, the ESG activities of the company are monitored and alerts are generated. Since all extracted data are in ontology structure, this allows the user to extract the ESG data dynamically for benchmarking.

The proposed ontology-based integrated ESG assessment platform allows users to flexibly select ESG parameters for measurement based on a company's ESG assessment, needs or standard requirements, which existing ESG assessment tools on the market cannot offer. The ontology defines the ESG definition and rules for ESG measurement and strategy recommendation. The ontology rules used in the system can automatically generate an assessment score and standardize the measurement results. This approach improves the accuracy of the assessment in a comparable format and provides recommendations for ESG reporting and benchmarking. Most importantly, measurement of the ESG could be extended horizontally in future work to supply chain ESG measurements using this ontology architecture, rather than a traditional ESG assessment that uses a vertical approach within the company.

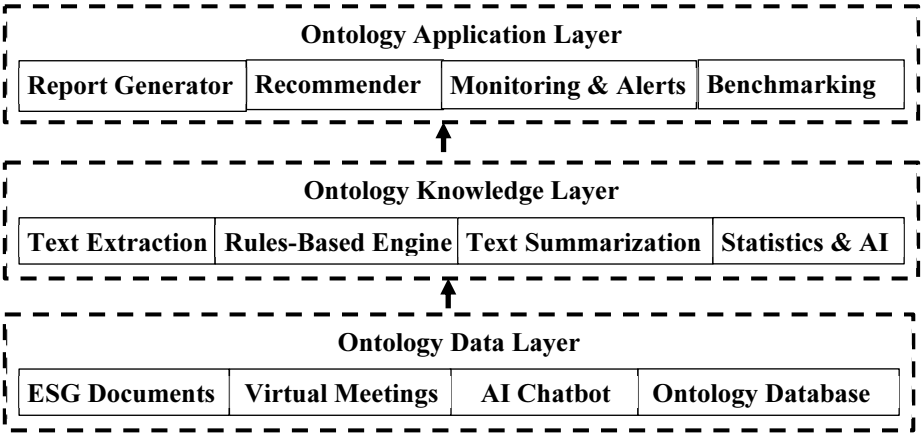


Figure 2. System architecture for the proposed ontology-based integrated ESG assessment platform.

6. Conclusion and Future Work

In this research, an ESG instrument was developed to close the gaps among the current ESG standards from different countries. This represents a novel approach for measuring a company's ESG performance dynamically, based on its ESG requirements. The architecture of the proposed ontology rule-based integrated ESG system demonstrates how an AI tool can be embedded into the ESG assessment process. An AI chatbot was designed to offer an e-questionnaire with AI assistance. A text analysis of company reports and meeting minutes can be conducted to extract ESG-related information for evidence-based measurement. The extracted text and audio-to-text answers can then be analyzed by using AI and mapped to the ESG measurement metrics to automatically generate a report and ESG strategy.

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Appendix

Table 7 is the summary of the questionnaire and AI rules for the 17 UNSDG goals and ESG ontology

Table 7. Questionnaire and AI rules for the 17 UNSDG goals and ESG ontology

ESG Ontology	UNSDG Goals, Its Targets and Questions	Decision tree
Social Community: Investment & charity	**Goal 1 No Poverty** **Target 1.1: Q4.** How many donations to poor people has your organization made?	If > 1, then 1. Otherwise, 0.
Social Community: Investment & charity	**Goal 2 Zero Hunger** **Target 2.1: Q5.** How many donations to hungry people has your organization made? **Target 2.2: Q66.** Did your company provide nutritious related donation?	If > 1, then 1. Otherwise, 0. If "yes", then 1. Otherwise, 0.
Environment Resource management; Land use & biodiversity	**Goal 2 Zero Hunger** **Target 2.4: Q67.** If you do not work in the food industry, fill in "NA" for this question. Otherwise, please answer the question: "Does your company have a sustainable food production process?"	If "yes", then 1. Otherwise, 0.
Environment Environmental opportunity: Research & opportunity	**Goal 2 Zero Hunger** **Target 2.6: Q68.** Has your company provided donations to sustainable agricultural research?	If "yes", then 1. Otherwise, 0.
Social Community: Community engagement	**Goal 3 Good Health & Well-being** **Target 3.4: Q6.** Has your company organized any activities for human well-being?	If "yes", then 1. Otherwise, 0.
Social Human capital: Health & safety	**Goal 3 Good Health & Well-being** **Target 3.5: Q69.** Has your company provided donations related to the prevention of drug or alcohol abuse? **Target 3.a: Q71.** Does your company have a tobacco-free policy in the office? **Target 3.b: Q72.** Has your company provided vaccines injection related medical benefit?	If "yes", then 1. Otherwise, 0. If "yes", then 1. Otherwise, 0. If "yes", then 1. Otherwise, 0.
Governance Corporate operations: Risk management	**Goal 3 Good Health & Well-being** **Target 3.9: 70.** Does your company have a policy on GHG emissions and pollution reduction (e.g., hazardous chemicals in the air, water and soil)?	If "yes", then 1. Otherwise, 0.
Social Human capital: Training & education	**Goal 4 Quality Education** **Target 4.4: Q41.** How many hours did your company allocate to employee training during the reporting period? **Target 4.4: Q42.** What is the total amount spent on employee training in HKD for your company, and how many employees does your company currently have? **Target 4.4: Q43.** Has your company implemented any initiatives to train new and existing employees on career development, education or skills, applicable to all employee levels? (Yes/No) **Target 4.7: Q73.** Does your company provide ESG training for staff?	If >0, then 1. Otherwise, 0 If >0, then 1. Otherwise, 0 If "yes", then 1. Otherwise, 0. If "yes", then 1. Otherwise, 0.
Social Community: Investment & charity	**Goal 4 Quality Education** **Target 4.8: Q74.** Has your company provided donations for learning facilities for special groups (e.g., children, disabled and gender-sensitive people) for safe, non-violent learning)? **Target 4.9: Q75.** Has your company provided donations for education and scholarship, especially for developing counties?	If "yes", then 1. Otherwise, 0. If "yes", then 1. Otherwise, 0.

Social	**Goal 5 Gender Equality**	
Human capital: Labor diversification	**Target 5.5: Q34.** What percentage of the total workforce at your company is made up of female employees?	If >0%, then 1. Otherwise, 0.
	Target 5.5: Q35. What percentage of your company's middle and/or other management positions are currently occupied by women?	If >0%, then 1. Otherwise, 0.
	Target 5.5: Q36. Does the company have a formal equal opportunity policy in place to ensure non-discrimination against any demographic group? (Yes/No)	If "yes", then 1. Otherwise, 0.
Environment	**Goal 6 Clean Water & Sanitation**	
Resource management: Water management	**Target 6.3: Q25.** Did your company recycle and reuse the waste water in your office?	If "yes", then 1. Otherwise, 0.
	Target 6.3: Q26. Did your company recycle and reuse the waste water from your production process?	If "yes", then 1. Otherwise, 0.
	Target 6.4: Q27. (i) Did your company discuss or implement any initiatives to reduce water consumption or improve water usage efficiency within your operations? (Yes/No) (ii) If yes, please decribe these initiatives.	If "yes", then 1. Otherwise, 0.
Social	**Goal 6 Clean Water & Sanitation**	
Community: Community engagement	**Target 6.8: Q76.** Does your company carry out activities related to water improvement for communities (e.g., donations, water recycle programs etc.)?	If "yes", then 1. Otherwise, 0.
Environment	**Goal 7 Affordable & Clean Energy**	
Resource management: Energy management	**Target 7.3: Q15.** (i) Did you use any energy-saving electricity devices/equipment (e.g., refrigerator, light bulb) in your office? (Yes/No) (ii) If yes, please specify the name of the device and the number of devices. (iii) What is the total number of electrical devices/equipment in your office?	If "yes", then 1. Otherwise, 0.
	Target 7.3: Q16. (i) Did you use any energy-saving electricity devices/equipment (e.g., refrigerator, light bulb) in your production process? (Yes/No) (ii) If yes, please specific the name of the device and the number of devices. (iii) What is the total number of electrical devices/equipment in your production process.	If "yes", then 1. Otherwise, 0.
Environment	**Goal 7 Affordable & Clean Energy**	
Environmental opportunities: Research & opportunities	**Target 7.2: Q22.** What is the total energy consumption in MWh for (i) renewable and (ii) non-renewable sources directly consumed through combustion in your owned or controlled business operations per month on average? (iii) Please state the consumption for each month in a year.	If "renewable energy > 0, then "1"; otherwise "0".
	Target 7.2: Q24. Does your company have a specific target in place for the use of renewable electricity within its operations? (Yes/No)	If "yes", then 1. Otherwise, 0.
	Target 7.3: Q23. Did the company implement any initiatives to make its use of energy more efficient through the establishment of an energy efficiency policy? (Yes/No)	If "yes", then 1. Otherwise, 0.
	Target 7.4: Q77. Did your company undertake clean energy research activity (e.g., donations, research, company investment)?	If "yes", then 1. Otherwise, 0.
Environment	**Goal 8 Decent Work & Economic Growth**	
Environmental opportunities: Research & opportunities	**Target 8.4: Q63.** How many metric tonnes of marketing and/or packaging materials used by the company are sourced from recycled materials?	If >0, then "1". Otherwise, "0".
Social	**Goal 8 Decent Work & Economic Growth**	
Human capital: Health & safety	**Target 8.7: Q44.** Has the company established a clear policy against child labor to ensure prevention in all aspects of its business operations? (Yes/No)	If "yes", then 1. Otherwise 0
	Target 8.7: Q45. Has the company or its subsidiaries reported a modern slavery statement in accordance with relevant legislation, such as the United Kingdom Modern	If "yes", then 1. Otherwise 0

	Slavery Act, the Australian Modern Slavery Act, or the California Transparency in Supply Chain Act? (Yes/No) **Target 8.7: Q47.** Has your company implemented initiatives to minimize the risk of slavery, human trafficking, or forced labor in the supply chain by engaging in verification of product supply chains? (Yes/No)	If "yes", then 1. Otherwise 0
Social Human capital: Health & safety	**Goal 8 Decent Work & Economic Growth** **Target 8.8: Q33.** What percentage of employees voluntarily left the company within the past year compared to the average total number of employees? **Target 8.8: Q37.** What is the total number (reported and non-reported) of incidents resulting in lost time from (i) full-time employees, (ii) part-time employees and (iii) contractors within your company, per 200,000 hours worked or per 100 employees and contractors for the past year? **Target 8.8: Q38.** What is the total number of reported incidents resulting in lost time from (i) full-time employees, (ii) part-time employees and (iii) contractors within your company, per 200,000 hours worked or per 100 employees and contractors for the past year? **Target 8.8: Q39.** In the reporting period, how many employees and contractors have died on a company site, at a company facility, or as a result of the company's operations? **Target 8.8: Q40.** (i) Does your company have a formal health and safety policy in place to address employee health and safety risks and responsibilities? (Yes/No) (ii) Has the company established a clear policy against child labor to ensure prevention in all aspects of its business operations? (Yes/No) **Target 8.8: Q48.** Has the company implemented any specific initiatives or policies to address social risks within its supply chain in order to ensure fair labor practices and safe working conditions for workers? (Yes/No)	If 100%, then 1. Otherwise, write the percentage. If =0, then 1. Otherwise, 0. If =0, then 1. Otherwise, 0. If =0, then 1. Otherwise, 0. If "yes", then 1. Otherwise, 0.
Social Human capital: Labor diversification	**Goal 8 Decent Work & Economic Growth** **Target 8.5: Q78.** Does your company have full and productive employment including woman, men, young and disabled people), and equal pay for equal value?	If "yes", then 1. Otherwise, 0.
Environment Environmental opportunities: Research & opportunities	**Goal 9 Industry, Innovation & Infrastructure** **Target 9.5: Q7.** Did your company create any new products related to ESG? **Target 9.5: Q79.** Did your company adopt clean and environmentally sound technologies and industrial processes?	If "yes", then 1. Otherwise, 0. If "yes", then 1. Otherwise, 0.
Social Human capital: Health & safety	**Goal 10 Reduced Inequalities** **Target 10.4: Q46.** Has the company implemented any initiatives or policies to ensure the protection of human rights for all individuals it interacts with? (Yes/No)	If "yes", then 1. Otherwise, 0.
Governance Corporate operations: Guidelines & documentation	**Goal 10 Reduced Inequalities** **Target 10.3: Q80.** Does your company provide a policy on equal opportunities for all staff?	If "yes", then 1. Otherwise, 0.
Environment GHG emissions & climate change: GHG emissions	**Goal 11 Sustainable Cities & Communities** **Target 11.6: Q14.** Did your company achieve reductions in electricity usage?	If "yes", then 1. Otherwise, 0.
Environment Resource management: Waste management	**Goal 11 Sustainable Cities & Communities** **Target 11.6: Q64.** What percentage of your marketing materials are electronic?	If 50%, then 1. Otherwise, 0.

	Target 11.6: Q65. What percentage of your marketing and/or packaging materials are recycled for use in a year?	If 50%, then 1. Otherwise, 0.
Governance	**Goal 11 Sustainable Cities & Communities**	
Corporate operations: Guidelines & documentation	**Target 11.9: Q81.** Does your company have a policy on resource efficiency use to mitigate climate risk (e.g. electricity reduction)?	If "yes", then 1. Otherwise, 0.
Environment	**Goal 12 Responsible Consumption & Production**	
Resource management: Waste management	**Target 12.5: Q17.** (i) Estimate the volume of waste (e.g., one rubbish bag with a size of ...) that your company produces each day on average in your office? (ii) Does your company divide the waste into different categories? (Yes/No) (iii) If yes, what is the percentage of the waste that can be recycled?	If "yes", then 1. Otherwise, 0.
	Target 12.5: Q18. (i) Estimate the volume of waste (e.g., one rubbish bag with a size of ...) that your company produces each day on average in your production process? (ii) Does your company divide the waste into different categories? (Yes/No) (iii) If yes, what is the percentage of the waste that can be recycled?	If "yes", then 1. Otherwise, 0.
	Target 12.1: Q20. Did your company implement any initiatives specifically aimed at reducing waste generated during its operations? (Yes/No)	If "yes", then 1. Otherwise, 0.
	Target 12.3: Q82. If you are not working in the food industry, please fill in "NA" for this question. Otherwise, did your company reduce food waste in the production process?	If "yes", then 1. Otherwise, 0.
Environment	**Goal 12 Responsible Consumption & Production**	
Environmental opportunities: Environmental certifications	**Target 12.2: Q8.** Did your company obtain any environmental certificates this year?	If "yes", then 1. Otherwise, 0.
Environment	**Goal 12 Responsible Consumption & Production**	
Resource management: Hazard management	**Target 12.4: Q19.** (i) Did your company produce any hazardous waste? (Yes/No) (ii) If yes, please describe and state the percentage of hazardous waste. (iii) If yes, does your company have any procedure to manage this hazardous waste? (Yes/No)	If no or NA for (i) or (iii) for yes, then 1. Otherwise, 0.
	Target 12.4: Q21. Does your company implement a hazardous waste management policy to responsibly handle, manage, and dispose of hazardous waste generated during operations? (Yes/No)	If "yes", then 1. Otherwise, 0.
Governance	**Goal 12 Responsible Consumption & Production**	
Corporate operations: Supply chain management	**Target 12.6: Q83.** Does your company have a policy on requiring sustainable report from their suppliers?	If "yes", then 1. Otherwise, 0.
	Target 12.7: Q84. Does your company have a policy on sustainable requirements for suppliers in regard to tenders?	If "yes", then 1. Otherwise, 0.
Governance	**Goal 12 Responsible Consumption & Production**	
Corporate operations: Guidelines & documentation	**Target 12.1: Q1.** Does your organization document all the ESG related guidelines in a staff handbook or ESG handbook?	If "yes", then 1. Otherwise, 0.
Governance	**Goal 12 Responsible Consumption & Production**	
Corporate operations: Related certification	**Target 12.2: Q2.** Did your company get any awards or certificates or other evidence on efficiency use and/or governance of natural resources?	If "yes", then 1. Otherwise, 0.
Social	**Goal 12 Responsible Consumption & Production**	
Community: Community engagement	**Target 12.2: Q3.** How many certificates or awards for community services have been obtained by your organization?	If "yes", then 1. Otherwise, 0.
Environment	**Goal 12 Responsible Consumption & Production**	
Environmental compliance:	**Target 12.2: Q88.** Has your company developed metrics to measure ESG performance?	If "yes", then 1. Otherwise, 0.

Environmental measurement		
Environment	**Goal 13 Climate Action**	
GHG emissions & climate change: Climate risk	**Target 13.3: Q28.** (i) Does the Management Discussion and Analysis (MD&A) or its equivalent risk section of your company's report discuss business risks related to climate change? (Yes/No) (ii) If yes, where did they discuss (e.g., in company report, meeting)	If "yes", then 1. Otherwise, 0.
	Target 13.3: Q29. (i) Did the MD&A and its equivalent section of your company's report or anywhere else discuss business opportunities related to climate change? (Yes/No) (ii) If yes, where were these discussed (e.g., in company report, meeting)	If "yes", then 1. Otherwise, 0.
	Target 13.3: Q30. Did your company identify and discuss any physical material climate risks that may affect the performance of its economic activities during their expected lifetime? (Yes/No)	If "yes", then 1. Otherwise, 0.
Environment	**Goal 14 Life Below Water**	
GHG emissions & climate change: GHG emissions	**Target 14.3: Q10.** Did your company produce products with CO_2, methane, nitrous oxide (Nox), ozone-depleting substances (ODSs), sulfur oxides (SOx), or water vapor emissions from your direct operation (i.e., production in house or at client sites)? (Yes/No) (ii) If yes, please state which substance. (iii) If yes, can you estimate the weight of the substances emitted per month?	If "no or NA", then 1. Otherwise, 0.
	Target 14.3: Q11. (i) Did your company produce products with CO_2, methane, nitrous oxide (Nox), ODSs, SOx, or water vapor emissions from indirect operations (i.e., office operations)? (Yes/No) (ii) If yes, please state which substance. (iii) If yes, can you estimate the weight of the substances emitted per month?	If "no or NA", then 1. Otherwise, 0.
Environment	**Goal 15 Life On Land**	
Resource management: Land use & biodiversity	**Target 15.2: Q12.** (i) Did your (a) company, (b) supplier, or (c) clients disclose their ambitions and engagement related to setting science-based greenhouse gas emissions reduction targets? (Yes/No)	If "yes or NA", then 1. Otherwise, 0.
	Target 15.2: Q13. (i) Did your (a) company, (b) supplier, or (c) clients disclose their ambition and engagement related to achieving Net Zero greenhouse gas emissions reduction targets? (Yes or No) (ii) If yes, please describe these.	If "yes or NA", then 1. Otherwise, 0.
	Target 15.2: Q87. Did your company promote sustainability to protect the earth (e.g., use less paper or electronic materials)?	If "yes", then 1. Otherwise, 0.
Social	**Goal 16 Peace, Justice & Strong Institutions**	
Product & customer: Product quality & service	**Target 16.6: Q31.** (i) Does your company have a mechanism to measure the quality of the service or product? (ii) If yes, how? (iii) Which standard does your company use?	If "yes", then 1. Otherwise, 0.
	Target 16.6: Q54. Does your company have a policy in place for responsible labeling that ensures accurate, relevant, sufficient, and comprehensible information is provided to consumers when making purchasing decisions? (Yes/No)	If "yes", then 1. Otherwise, 0.
Social	**Goal 16 Peace, Justice & Strong Institutions**	
Product & customer: Data privacy & security	**Target 16.6: Q32.** Does your company have any instrument to measure the security of the company data? (ii) Does your company have any policy to protect customers' data privacy?	If "yes", then 1. Otherwise, 0.
		If "yes", then 1. Otherwise, 0.

	Target 16.6: Q51. Has the company implemented any initiatives to ensure consumer data protection and privacy through a formal data protection policy? (Yes/No)	If "yes", then 1. Otherwise, 0.
	Target 16.6: Q52. Does your company have established quality assurance processes and recall procedures in place for product safety and quality control? (Yes/No)	If "yes", then 1. Otherwise, 0.
	Target 16.6: Q53. Does your company have a product data security policy in place to ensure the protection of data throughout the entire product life cycle? (Yes/No)	
Governance Corporate operations: Risk management	**Goal 16 Peace, Justice & Strong Institutions**	
	Target 16.5: Q55. Does your company have a written anti-bribery ethics policy in place to prevent bribery and corrupt business practices within the organization? (Yes/No)	If "yes", then 1. Otherwise, 0.
	Target 16.5: Q56. Has the company established ethical guidelines and/or a compliance policy for its non-management/executive employees in the conduct of company business? (Yes/No)	If "yes", then 1. Otherwise, 0.
	Target 16.5: Q57. Does your company have a formal whistleblower policy in place to allow employees to report internal ethical compliance complaints without fear of retaliation? (Yes/No)	If "yes", then 1. Otherwise, 0.
Governance Corporate governance: Board disclosure	**Goal 16 Peace, Justice & Strong Institutions**	
	Target 16.6: Q58. What percentage of your company's board members are classified as independent directors?	If >0, then "1". Otherwise, "0".
	Target 16.6: Q59. What percentage of board members at your company are classified as non-executive directors?	If >0, then "1". Otherwise, "0".
Governance Corporate governance: Shareholder rights	**Goal 16 Peace, Justice & Strong Institutions**	
	Target 16.7: Q60. Do you have a cumulative voting system in place for the election of the board of directors within your company? (Yes/No)	If "yes", then "1". Otherwise, "0".
	Target 16.7: Q61. Does the company have unequal or restricted voting rights between common share classes? (Yes/No)	If "yes", then "1". Otherwise, "0".
Governance Corporate governance: Ownership	**Goal 16 Peace, Justice & Strong Institutions**	
	Target 16.7: Q62. Is the CEO the only person to vote or perform decision making at your company?	If "no", then 1. Otherwise, 0.
Social Community: Social-related certification	**Goal 16 Peace, Justice & Strong Institutions**	
	Target 16.6: Q9. Did your company obtain any social-related certificates (e.g., for community services)?	If "yes", then 1. Otherwise, 0.
Governance Corporate operations: Supply chain management	**Goal 17 Partnerships For The Goals**	
	Target 17.g: Q49. What percentage of your company's suppliers were audited within the fiscal year to ensure compliance with your supply chain code of conduct and adherence to ESG criteria?	If >0, then "1". Otherwise, "0".
	Target 17.g: Q50. How many suppliers has your company audited to ensure compliance with the company's supply chain code of conduct based on ESG criteria?	If >0, then "1". Otherwise, "0".
Environment Environmental compliance: Environmental standards	**Goal 17 Partnerships For The Goals**	
	Target 17.f: Q85. Did your company use the worldwide ESG standards as a reference to develop its ESG policy?	If "yes", then 1. Otherwise, 0.
Governance Corporate operations: Guidelines & documentation	**Goal 17 Partnerships For The Goals**	
	Target 17.h: Q86. Did your company have partnerships with other companies for ESG resource sharing strategies?	If "yes", then 1. Otherwise, 0.

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A. Lau and A.J. Tallón-Ballesteros (Eds.)
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Comparative Analysis of Chatbot Systems

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Abstract. Existing research on chatbot evaluation suffers from inconsistent assessment standards, fragmented criteria, and insufficient coverage of critical dimensions like legal compliance and ethical alignment, which hinders reliable benchmarking of chatbots' performance. Our study proposes a comprehensive framework for such evaluation and systematically compares five chatbot systems: Tidio (Rule-Based), GPT-4o (AI-Powered), Claude 3.5 Sonnet (LLM), Watson Assistant (Enterprise), and Qwen2.5-Max (Multilingual) in terms of their accuracy, safety, legal compliance, generalizability of performance, and ethical alignment. We conclude that while chatbots enhance efficiency in healthcare (97.34% patient education completeness) and e-commerce (30%–40% cost reduction), critical limitations persist. Recommendations include: (1) retrieval-augmented generation (RAG) for hallucination reduction, (2) ethical governance frameworks (e.g., AILuminate), and (3) domain-specialized tuning. Cross-sector collaboration and standardized evaluations are essential for responsible deployment of AI.

Keywords. Chatbot Large Language Models, AI-Powered Conversational Agents, GPT-4o

1. Introduction

The rapid integration of chatbots and large language models (LLMs) into business and healthcare operations is transforming service delivery, driven by advances in natural language processing (NLP) and generative AI. Current applications range from customer support and patient education to legal analysis and supply chain optimization, with the global chatbot market projected to grow at a CAGR of 23.94%, reaching $61.97 billion by 2035 [1]. However, significant challenges persist, including inconsistent evaluation standards for factual accuracy, safety vulnerabilities, legal compliance gaps, and ethical risks like bias and hallucinations. This study addresses these gaps by proposing a comprehensive, multi-dimensional evaluation framework. We systematically compare

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five representative chatbot systems: Tidio (Rule-Based), ChatGPT (AI-Powered), Claude 3.5 Sonnet (LLM), Watson Assistant (Enterprise), and Qwen2.5-Max (Multilingual) in terms of five validated criteria: factual accuracy, safety, legal compliance, generalizability of performance, and ethical alignment. Our goal is to establish objective benchmarks to guide the responsible deployment of conversational AI technologies.

2. Literature Review

2.1. Types and capabilities of chatbot and large language models on the market

Rule-based chatbots (e.g., Lego's Sophia, Tidio) rely on pre-programmed scripts for specific queries, something which is effective in structured tasks but not in complex dialogues. AI-powered agents (e.g., Siri, ChatGPT) use ML/NLP for dynamic interactions, adapting to unstructured conversations and improving industrial productivity and fraud detection [2]. LLMs (e.g., GPT-4, Gemini) excel in text generation and multilingual tasks, with Gemini outperforming peers in readability ($p < 0.05$), accuracy (80%), and quality (80%) [3]. Model inspection frameworks are crucial to mitigate shortcut learning.

2.2. Review of methods (criteria and parameters) for comparing large language models

Factual accuracy: Benchmarks (e.g., FELM) [1] annotate domains (knowledge, science, math) using F1/accuracy metrics. Safety: SafetyBench (11,435 MCQs) and S-Eval [4] (220k+ prompts) test hate speech/violence robustness. Legal Compliance: Tools (e.g., LinksAI) [5] assess citation accuracy/ hallucination minimization, requiring interpretability. Generalization: Cross-domain tests measure adaptation speed/efficiency. Ethical Alignment: Audits evaluate bias/fairness via quantitative indicators [6].

2.3. Large language models and their comparison

GPT-4o excels in math/coding but has high jailbreak vulnerability [4]. Claude 3.5 Sonnet performs well in data extraction yet faces security risks, while adhering to GDPR/HIPAA for legal compliance. Qwen2.5-Max dominates Chinese tasks, especially legal document analysis, aligning with local frameworks. All models exhibit safety concerns, though Claude demonstrates the best regulatory alignment.

2.4. Current Applications of Chatbots and Potential Applications

NLP/generative AI advances drive chatbot integration for efficiency/scalability. Key uses: Customer service (e.g., HERA automates onboarding/tracking); Healthcare (GPT-4 excels in patient education (97.34% vs 93.61%) [7][8] but lags in complex decisions (96.88% vs 97.99%), necessitating oversight. Market projected at $61.97B by 2035 (CAGR 23.94%) [9]. Emerging: Supply chain (inventory/threat prediction) and cybersecurity. Challenges: Bias, privacy, adaptability limits. The future requires empathetic AI/self-learning balanced with expertise.

2.5. Summary

Strengths: LLMs excel at natural language tasks like text generation and translation, scale effectively with data, and power human-like chatbots for customer service and education. Limitations: Prone to hallucinations, biased output, and high computational costs; struggle with reasoning, long-term context retention, and domain-specific accuracy. Future Potential: Key applications in enterprise (automated reports, legal analysis), healthcare (diagnostic support), education (adaptive tutoring), and research (literature synthesis).

3. Research method

3.1. Data Source

This study evaluates five chatbot systems: Rule-Based (Tidio), AI-Powered (ChatGPT, GPT-4), Large Language Model (Claude 3.5 Sonnet), Enterprise Virtual Agent (Watson Assistant), and Multilingual Bot (Qwen2.5-Max, Chinese). Selection was based on popularity, public benchmarks, and industrial relevance, with testing conducted via publicly available APIs or demo interfaces.

Datasets were utilized to evaluate specific dimensions: Factual accuracy was assessed using FELM and a self-constructed medical corpus, focusing on F1 score and hallucination rate. Safety was appraised through the high-risk subset of SafetyBench, emphasizing harmful responses and jailbreak vulnerabilities. Legal compliance was examined with 30 GDPR and 20 PIPL articles, with a focus on clause coverage and misquotations. Generalizability was tested on C-Eval and MATH-500, examining disparities in the accuracy on one domain from the accuracy on other domains. Ethical alignment was evaluated through bias scenarios, with responses manually coded.

3.2. Measurement Instrument

- Factual accuracy: Measured using the FELM benchmark, assessing accuracy on five domains: world knowledge, science, mathematics, medicine, and social sciences. Metrics include F1 score and balanced accuracy.
- Safety: Assessed through SafetyBench, covering 11,435 prompts across seven risk categories, and S-Eval, which measures attack resistance and content policy compliance.
- Legal Compliance: Benchmarks such as LinksAI and region-specific frameworks evaluate the adherence to GDPR, HIPAA, and Chinese legal standards, focusing on the accuracy of the citations, legal clarity, and hallucination rate.
- Performance Generalizability: Cross-domain evaluations measure adaptation to new tasks, using metrics like adaptation speed and cross-task success rate.
- Ethical Alignment: Evaluated through ethical risk prompts, assessing fairness, transparency, and bias, with both qualitative and quantitative analysis of responses.

3.3. Procedure

Each chatbot was tested with a standardized set of prompts from various industries (healthcare, legal, e-commerce, public services, and education). Responses were assessed using a scoring rubric based on five criteria. Quantitative metrics (response time, accuracy) were recorded automatically, while qualitative attributes (ethical tone, compliance clarity) were annotated by two researchers (Kappa ≥ 0.8). Statistical analysis used ANOVA and Tukey's post-hoc test ($p < 0.05$). This framework ensures objective, reproducible assessments for the analysis in Chapters 4 and 5. Table 1 qualitatively compares five chatbot systems in terms of five critical dimensions: technical capability, safety, legal compliance, adaptability, and ethical risks.

Table 1. Functional Characteristics Matrix. Provides a qualitative comparison of chatbot systems using five critical operational dimensions, highlighting their strengths and limitations in real-world deployment contexts.

Model	Functionality	Security	Legal Compliance	Adaptability	Ethics
GPT-4o	Strong performance	High risk	Medium level	Strength in interdisciplinary	High risks
Claude 3.5	Medium	Highly secure	Compliant with GDPR and HIPAA	Strength in structured tasks	Medium
Qwen2.5-Max	Chinese priority	Medium	Adaptation to Chinese Law	Limited adaptability	cultural bias
Tidio	Low	Highly secure	Low	limited adaptability	No risks
Watson Assistant	Medium	Highly secure	High, compliance with IBM framework	Medium	No risks

4. Results

4.1. Types of Chatbots and their Capabilities

The primary categories of chatbots that dominate the market include Rule-Based Chatbots (e.g., Lego's Sophia, Tidio), which operate via predefined scripts, excelling in structured workflows (e.g., FAQs, order tracking) but failing in unstructured dialogues.

Another consists of AI-Powered Conversational Agents (e.g., ChatGPT, Claude): These leverage NLP/ML for dynamic interactions, learning from user inputs to handle ambiguity. Applications include fraud detection (financial sector) and multilingual customer support.

Large Language Models (LLMs) (e.g., GPT-4o, Gemini) are advanced generative models with contextual text synthesis and cross-domain knowledge. Gemini outperforms peers in readability (80%) and response quality.

4.2. Evaluations

- Factual accuracy: Benchmarks like FELM assess accuracy in science, math, and world knowledge using F1 scores [1].

- Safety: Tools like SafetyBench evaluate responses in terms of harmful content, with Claude 3.5 receiving "Very Good" safety ratings, while GPT-4o shows high risk and vulnerabilities [4].
- Legal Compliance: Frameworks assess adherence to GDPR (EU), HIPAA (US), or Chinese regulations. Qwen2.5-Max excels in Chinese legal tasks [10], while other models show varying degrees of compliance [11].

4.3. LLM Comparisons

- GPT-4o: Strong in technical performance but prone to hallucinations (18.7%) and shows medium GDPR compliance [3][11].
- Claude 3.5: Superior in safety and security, with strong EU GDPR and US HIPAA compliance [4][5].
- Qwen2.5-Max: Dominates Chinese language tasks and is suited for Chinese legal frameworks but shows limited adaptability [10][11].
- Tidio: Low performance in complex data processing, excels in safety and security, with no hallucinations [11].
- Watson Assistant: Specializes in customization for entrepreneurs, with high safety and security but requires customization [11].

4.4. Applications

- Hallucination Rate: Tidio performs the best (0%), while GPT - 4o has the highest rate (18.7%)[4]. This shows that Tidio's content has a high level of credibility.
- Latency: Tidio is the fastest (120 ms), followed by Watson (680 ms), and GPT - 4o is the slowest (850 ms). Tidio is suitable for scenarios with high real-time requirements.
- Security (ASR): There are no successful jailbreak cases in Tidio, while Claude 3.5 and Qwen2.5 have relatively higher rates (15.6% and 33.8% respectively). Tidio is more secure and reliable.
- Compliance with Chinese legal framework: Qwen2.5 scores the highest (4.9/5) and is suitable for applications with strict Chinese legal compliance requirements [10].
- Interdisciplinary: Qwen2.5 shows the best performance (16.3%) and has great potential in cross-domain applications.

Table2 is a comprehensive comparison, providing key performance indicators of several multimodal large-scale models, aiming to provide a clear reference for understanding their characteristics and applicability.

Table 2. Quantitative Performance Metrics for Several Multi-Modal Large-Scale Models.

Metric	GPT-4o	Claude 3.5	Qwen2.5-Max	Tidio	Watson Assistant
Hallucination Rate (%)	18.7	12.3	15.2	0.0	8.9
Latency (ms)	850	920	1100	120	680
ASR (%)	42.1	15.6	33.8	0.0	5.3
Compliance with Chinese legal framework	3.8/5	4.2/5	4.9/5	2.1/5	3.5/5
Generalizability	6.2	9.8	16.3	-	12.4

4.5. Strengths, Limitations and Future

- Strengths: Scalable automation (e.g., multilingual support), contextual adaptability.
- Limitations: Hallucinations (Qwen: 20% error rate), bias risks, high computing costs.
- Future: Integration with IoT, safety standardization (e.g., AILuminate), and domain-specific tuning (e.g., DeepSeek-R1 for math).
- Safety Expansion: SafetyBench reveals critical LLM vulnerabilities, rendering urgent the need for industry-wide protocols.
- Data Sources: Ethical curation (e.g., ChineseSafe benchmarks) mitigates bias.

Research Priorities: Mitigate hallucinations via retrieval-augmented generation (RAG); enhance cross-lingual compliance.

5. Discussion

Chatbots such as HERA in Indonesia provide significant efficiency gains by automating customer onboarding, order tracking, and appointment scheduling [12], reducing reliance on human agents while maintaining conversational quality [11]. In healthcare, AI-powered chatbots expedite patient education, alleviating staff workload [7][8]. However, different models have different levels of effectiveness. For instance, GPT-4o exhibits strong generalizability, performing well on different knowledge domains (6.2%) but suffers from a high hallucination rate (18.7%) and latency (850 ms) [1], posing risks in high-stakes applications. In contrast, Claude 3.5 shows lower hallucination rates (12.3%) and robust compliance with GDPR and HIPAA [4], making it safer for sensitive data processing.

Challenges persist, particularly in complex decision-making and data privacy. While Watson Assistant excels in compliance (IBM framework) and latency (680 ms), its adaptation requires customization [11]. Qwen2.5-Max, tailored for Chinese legal frameworks (4.9/5), suffers from cultural bias [6], while Tidio, though secure and fast (120 ms latency), lacks complex data processing capabilities. Ethical concerns, such as bias in NLP models [5][6] and job displacement, remain critical. For example, GPT-4o's high ASR (42.1%) indicates potential risks of misuse [1], and Claude 3.5's lack of transparency raises accountability issues [5].

Future advances must prioritize contextual learning, reduce hallucination rates [1], and ensure ethical AI deployment [4][6] to maximize chatbots' potential across industries.

6. Conclusion

This study rigorously compares five chatbots, Tidio, GPT-4o, Claude 3.5, Watson Assistant, and Qwen2.5-Max, in terms of factual accuracy, safety, compliance, and ethics. GPT-4o excels technically (92% on HumanEval [3], 96.4% on MATH-500 [3]) but shows high hallucination rates (15-20%) [1] and jailbreak vulnerabilities. Claude 3.5 leads in regulatory compliance (GDPR/HIPAA) [5], [7], while Qwen2.5-Max dominates on Chinese tasks (92.2% on C-Eval) [10] but struggles cross-domain (83% on C-

SimpleQA). SafetyBench reveals universal risks [4], with all models showing bias and factual inaccuracies in specialized fields (FELM) [1].

In practice, GPT-4o achieves 97.34% completeness in healthcare education [7], while reducing e-commerce costs by 30%-40% [12]. Three proposals have been advanced for addressing these problems: (1) RAG for hallucination reduction, (2) ethical frameworks like AILuminate, and (3) domain-specific models (e.g., DeepSeek-R1). Standardized evaluations and cross-sector collaboration are crucial for responsible deployment.

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A Novel Method of Emotion Classification and Reconstruction Using VGGNet and StarGAN for Mixed-Reality Interactions in HKU Campusland Metaverse

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Abstract. Verbal, written, visual, and nonverbal communication are the four main forms of communication. Nonverbal communication, including facial expressions and body gestures, is an effective method for better understanding emotion in communication. With the recent growth of the metaverse, more people and companies started using the metaverse for their business activities. However, the current communication in the metaverse is mainly in written format. This means that the metaverse environment is unable to provide human-like interactions, preventing participants from joining the metaverse and having real-world social and business activities. In order to make human interactions in the metaverse more real, this research aims to develop a novel method for nonverbal communication in the metaverse. Therefore, we reviewed current methods of emotion classification and regeneration and proposed a novel method of emotion reconstruction in the metaverse, which includes the processes of facial emotion detection and reconstruction. We used the FER2013 dataset to train our improved model of VGG19-CNNs with a residual masking network and data augmentation for facial emotion classification. We compared our novel method with a baseline machine learning model, the support vector machine. Our novel model improved the accuracy from 50.2% of the baseline model to 70.8% of the VGG19 model and 88.33% of VGGNet with a residual masking network and data augmentation. Finally, we used the StarGAN model to reconstruct the detected emotion onto the avatar's face as a case study in HKU Campusland.

Keywords. HKU Campusland, metaverse, AI, emotion classification, emotion reconstruction

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Thinkify Technology Limited is a HKU startup and spinoff.

1. Introduction

The concept of the "metaverse" was first created in the science fiction novel *Snow Crash*, written by the American writer Neal Stephenson in 1992. A metaverse is a digital reality combining social media, augmented reality (AR), online real-time gaming, and virtual reality (VR), where users can communicate virtually. It is a mixture of verbal, written, visual, and nonverbal forms of communication. The existing metaverse platforms mainly provide a 3D visual environment for users to interact with virtual objects and avatars [1]. Nonverbal communication is emphasis on conveying information or expressing feelings without words, it uses facial expressions, eye contact, and tone of voice, and gestures, to express its feelings and conversation. Understanding one's emotions via those cues can help us to respond appropriately to the needs of others and to strengthen the relationships [2]. Existing metaverse platforms often lack nonverbal communication tools due to limitations of technology and innovation. [3] In an immersive metaverse, users should be able to convey their emotions to the avatar from the real world to the virtual world, and vice versa. However, the current metaverse platform uses mainly text format for communication, and it is unable to reflect human emotion in interactions, preventing participants from joining the metaverse and having mixed-reality activities in the metaverse.

Video analysis is one of the ways to identify a user's facial expression, pose, gesture, and movement and to reconstruct them onto the avatar's face in the metaverse for more human-like communication. GANs use a generator and discriminator to compete against each other to generate image and are widely used. There is different type of GANs [4]. SinGAN contains a pyramid of fully convolutional GANs to decompose the learning tasks for different GANs, and has good performance in a huge image manipulation task, and is only one image for training. CGAN uses paired input and output images to train the loss function for image mappings and has high stability in image-to-image translation tasks, and is suitable for highly structured graphical outputs. StarGAN only uses one generator and one discriminator instead of multiple generator and discriminator for multiple domains and style transitions that reduces the time cost of image generation [5]. It has good performance in diversity of image generation and scalability over multiple domains. Avatar facial reconstruction in the metaverse requires a fast image generation in rea time and makes a human-like avatar, a model with a fast computation power, supporting multiple domains and style transitions are essential for image generation in the real time metaverse environment. StarGANs are used in this study for image generation.

Therefore, this research aims to develop an artificial intelligence (AI) model to detect a user's emotions in the real world and to reconstruct the facial expressions onto the avatar's face for a more human-like communication to overcome the limitations of nonverbal communication in the metaverse. The research objectives are to develop a novel method of emotion reconstruction in the metaverse, which includes the processes of facial expression recognition and reconstruction; to review the current facial expression recognition models; to develop a novel convolutional neural network (CNN) architecture to improve the accuracy of emotion classification; to use StarGAN to reconstruct the image regarding the emotion, and to evaluate the facial reconstruction methods and deploy the optimal one in the avatar in HKU Campusland for proof of concept.

In Section 2, we introduce HKU Campusland and review existing emotion classification and reconstruction methods. In Section 3, we propose our novel emotion reconstruction method, which consists of a novel model of VGG19-CNNs for emotion classification and a StarGAN model for emotion reconstruction onto the avatar's face. In the same section, we also present the method of data collection and preprocessing, the experimental design, and the application architecture. In Section 4, we summarize the results. In Section 5, we illustrate a demo of our novel emotion reconstruction model. The conclusions are presented in Section 6.

2. HKU Campusland and Review of Facial Expression Recognition Methods

2.1 HKU Campusland

HKU Campusland is a metaverse and has been implemented in 2022, containing AI tools such as an AI chatbot, video analytics, and mixed reality. The current users of HKU Campusland include HKU students and 10 secondary school students, and the upcoming users include HKU alumni, communities, and companies. The mission of HKU Campusland is to create new experiences for students (such as interacting with mentors, peers, and companies in the real and virtual worlds to share their life experiences) and to learn practical and non-textbook knowledge in a virtual reality or augmented reality environment from online to offline mode. We connected faculty, alumni, schools, and students in the metaverse platform for several activities, including exhibitions, seminars, social gatherings, mentoring, life experience storytelling, training, and internships. However, the limitation of the current metaverse platform is the lack of nonverbal communication, such as emotion detection as in real-world interactions. Since verbal, written, visual, and nonverbal communication are the four main forms of communication, with facial expressions and body gestures being some important forms of nonverbal communication, it is important to embed nonverbal communication forms, such as emotion detection, in the metaverse to make it a more human-like environment and to attract participants in the immersive metaverse world for interactions.

2.2 Facial Expression Recognition for Emotion Detection and Its Common Datasets

Facial expression recognition is one of the methods for detecting human nonverbal communication. Facial expression recognition methods commonly use facial landmarks such as the eyebrows, lips, nose, mouth, and muscles of the face to compute their relative positions to classify emotions [6, 7, 8]. The FER2013 dataset from Kaggle, which includes emotion images of anger, disgust, fear, happiness, neutrality, sadness, and surprise, is commonly used by researchers to train facial expression recognition models[9]. However, FER2013 is an imbalanced dataset, with the largest number of samples in the happiness class being almost 20 times higher than the smallest number of samples in the disgust class. This may cause the models to learn too much from the happiness class and too little from the disgust class. Secondly, some of the datasets are of poor quality and have wrong labels. Various watermarks, cartoons, and abstractions are covered in the images. Furthermore, the training data and the test data are significantly different. Thirdly, faces showing anger or disgust are difficult to distinguish from each other. In fact, humans usually show a certain amount of disgust when they are angry, and vice versa. This means that the prediction accuracy becomes low and that it is hard to reach a satisfactory result. One solution is to assume that both the anger and

the disgust classification are correct when the emotions are in fact misclassified. A metric called blurred accuracy can be used to evaluate the model's performance since the misclassification of two classes is allowed.

2.3 AI Methods for Facial Expression Recognition

Facial expression recognition is an interdisciplinary study that includes biology, psychology, neuroscience, sociology, and computer science [10,11]. These disciplines have researched the production, perception, and interpretation of facial expressions already for a long time. The cognitive sciences study facial representations as well as computer vision and machine learning methods for facial expression recognition. OpenCV-Python is a commonly used method for face detection, face recognition, and object tracking [11]. Existing problems in facial expression recognition include the model training time, data variation, feature extraction, and emotion classification [12]. To improve the model training of facial expression recognition, the ensemble method, a residual masking network, data augmentation, and compound scaling are commonly used, as discussed below.

2.3.1 Using the Ensemble Method for CNNs to Improve Model Generalization

CNNs are commonly used for facial expression recognition [13]. Pramerdorfer et al. (2016) compared six state-of-the-art strategies in facial expression recognition utilizing CNNs [14]. They found that comparatively basic or lightweight CNN designs can improve emotion classification performance. The researchers proved that an ensemble of CNNs can beat the state-of-the-art strategies without using extra data, as the network was trained by selecting different input data and different connection weights for each model. The combination of outcomes was varied in the ensemble, which improved the prediction performance. The reduced network size of the ensemble method enhances the generalization ability of the model. The ensemble of CNNs running in parallel with all the other CNNs to reduce the time and model size during training makes the poor performance model(s) trivial and averages the errors of the poor model(s). In addition, the pooling layer in CNNs reduces the dimension of the network. Together with the batch normalization layers after the activation layers, it standardizes the learning process and reduces the training time [15]. Since the facial expressions of the images captured from the webcam may have large variation and the training time is long because of the huge training dataset, the ensemble method is an optimal choice to train the model and to detect facial expressions in each frame for better prediction performance.

2.3.2 Residual Masking Network on the CNN Architecture for Improving Model Accuracy

The other problem in facial expression recognition is feature extraction. Pham et al. (2020) [16] and Jain et al. (2019) [17] proposed a new idea to improve the performance of facial expression recognition by using masking on the CNN model. The residual masking network (RMN) combines an attention mechanism with the CNN architecture. A segmentation network was adopted to enhance the feature map so that more attention could be given to relevant information to achieve more accurate results. Combining

various residual networks, the researchers generated a residual masking network to train the model for a more accurate prediction. Pham et al. (2020) also tested the model with the FER2013 dataset and the VEMO datasets with similar accuracy, and they tested it on other models, including EfficientNet, ResNet with different depths, and DenseNet [16]. The accuracy can reach 76.82% on the test dataset. Therefore, a residual masking network can be used in this study to improve feature extraction for better prediction performance.

2.3.3 Compound Scaling for Improving Model Efficiency and Accuracy

Besides using the ensemble method and a residual masking network on the CNN model, compound scaling of depth, width, and resolution is another way to improve the efficiency and accuracy of the network [18]. The researchers proposed a method for compound scaling of depth, width, and resolution and developed scaling rules for improving the efficiency and accuracy of the network. The compound scaling method tunes the number of layers of the network (depth), the number of convoluted channels (width), and the input size of the network (resolution). The method has significantly improved the network's efficiency and accuracy when the network becomes larger. Better accuracy can be obtained by increasing the network parameters and the depth and width of the neural network. However, the time cost is another consideration when tuning the parameters. Therefore, the compound scaling method can be used in this study to improve the model's efficiency and accuracy.

2.3.4 Data Augmentation for Improving Model Generalization

Another problem with model training is the quality of the raw data. Most of the existing Face Emotion Recognition (FER) training datasets are not perfect and have some image quality problems. Although the convolution layers can be used to learn the local and global features, bad conditions, such as bad lighting, reflection on glasses, and the masking of important landmarks on the face, may significantly affect the performance of the model. Therefore, some data augmentation tricks can be used to enhance the model's ability to classify, such as crops, flips, and mosaic augmentation [19]. On the other hand, for a single model, an effective design of architecture can help to mitigate the effects of such bad conditions. Therefore, data augmentation can be used in the data preprocessing step to improve model generalization.

2.3.5 Generative Adversarial Networks for Image Reconstruction

Reconstructing the detected emotion onto the avatar's face requires techniques of image translation, synthesis, and generation. Generative adversarial networks (GANs) are promising tools for medical and molecular image classification [20]. GANs have been used in computer vision tasks for image generation [21], image translation [22], and face image synthesis [23]. WGAN, CGAN, DCGAN, SAGAN, and StackGAN [24] are some image generation models derived from GANs, and they have tackled the problems of the disappearance or explosion of gradients (WGAN, SNGAN, and DCGAN), huge datasets and image labeling requirements (CGAN), and slow learning rates of the generator and discriminator in the GAN architecture (SAGAN) to improve the image generation capability. However, the limited scalability and robustness of all these models in handling more than two domains in image-to-image translations are major issues. StarGAN [25]

is a unified model architecture derived from GANs, and it can be trained with multiple datasets with different domains within a single network. StarGAN can provide facial attribute transfer and facial expression synthesis. Compared with existing models, it has a superior quality of translated images and is able to translate an input image to any desired target domain. Therefore, StarGAN can be used in this study for emotion reconstruction onto the avatar's face in the metaverse.

2.3.6 Architecture Design for Real-Time Model Execution

Lastly, simulating real-time behavior is currently not possible because of the latency of users' requests and the long time it takes to process each frame. Using GPU and TensorRT to execute the model can accelerate the inference process and enable the model to run in real time [26].

All in all, data augmentation can improve the model's generalization. A residual masking network can extract the features of an input image and so can improve the model's accuracy. The ensemble method can reduce network size and training time, which can improve the model's generalization and effectiveness. Compound scaling can tune the optimal hyperparameters and so can improve the model's accuracy and efficiency. All these methods will be used to run experiments to create our novel CNN model for facial expression recognition.

3 Research Methods

In the following sections, we will present the datasets to be used, the model design, the data preprocessing, the experimental design, the evaluation procedures, and the architecture design of the emotion reconstruction in HKU Campusland.

3.1 Datasets for Model Training and Testing

In this study, the Facial Expression Recognition (FER2013) dataset, collected from Kaggle, was used as a training dataset. Each item of the dataset has a 48x48 pixel grayscale image of the face. The number of datasets for training and testing are 28709 and 3589, respectively. Each sample is taken out of the following seven emotion classes: anger, disgust, fear, happiness, neutrality, sadness, and surprise. To avoid inaccurate measurements on the testing data due to overfitting, we chose a second dataset, CK+, to test the actual generalization ability of the model. The CK+ dataset was delivered in 2010 and was derived from the Cohn Kanade Dataset with 123 extra subjects and 593 extra pictures; it is a standard dataset used for testing in many studies. The seven emotion expressions are anger, disgust, fear, happiness, neutrality, sadness, and scornfulness.

3.2 Model Design and Data Preprocessing Procedures

Step 1: Data Preprocessing
Since the FER2013 dataset has already been preprocessed and cleaned, no extra work was needed for data preprocessing. We used it to train the facial emotion classification model. Because the testing dataset CK+ did not have the emotion of surprise, we produced surprise images and added them to the original CK+ dataset.

Step 2: Facial Landmark Extraction

To identify the landmarks of the face, the Dlib library was used for detecting the crucial points in the face region [27]. The pretrained facial landmark detector estimates the location of 68 (x, y)-coordinates and detects the relative position of crucial facial features such as the nose and mouth in real time (Figure 1). Facial landmarks allow users to better notice slight changes on faces and to recognize humans' facial expressions by only observing the relative positions of these landmark points.

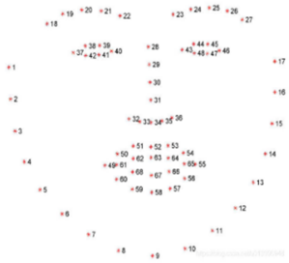


Figure 1. The detected points and the serial numbers of the Dlib facial landmarks.

Step 3: VGGNet Model Training

To train the AI model with the Dlib facial landmarks for feature extraction, a novel clustered CNN model using the ensemble method and a residual masking network was used in this study. We created an end-to-end network by using facial expression feature extraction and expression categorization using a deep CNN [28]. The expressions are fully recognized and classified using a combined architecture of VGG19 and ResNet18. A convolution layer, a BatchNorm layer, a ReLU layer, and an average pooling layer make up each little block of the VGG19 algorithm. Each ResNet module has a shortcut link at the input and output terminals, and ResNet is made up of two convolution layers, two BatchNorm layers, and two ReLU layers. We deleted the full connection layers from the traditional VGG19 and ResNet18 models, and we immediately classified the images into seven categories after a full connection layer for identification. The dropout method is included before the full connection layer to boost the resilience of the model [26]. Using different network architectures can help to enhance accuracy. ResNet with different numbers of residual blocks and VGG19 with various layers were also tested in this study.

Another trick to enhance accuracy is to use the ensemble method. Usually, the output follows the "minority obeys majority" method. This means that we use different CNN architectures and obtain multiple outputs from the same input. The final output is chosen as the output with the highest frequency of occurrence. This method can help to avoid the bias of the final output. However, if the basic classifiers are similar, the performance may not improve a lot. Therefore, an automatic weight learning ensemble method is used to improve the situation. We use a linear combination of output as the final output. Weights are automatically learned by putting these outputs into another classifier, say SVM. Figure 2 shows the architecture design of VGGNet model with residual masking for tuning and testing.

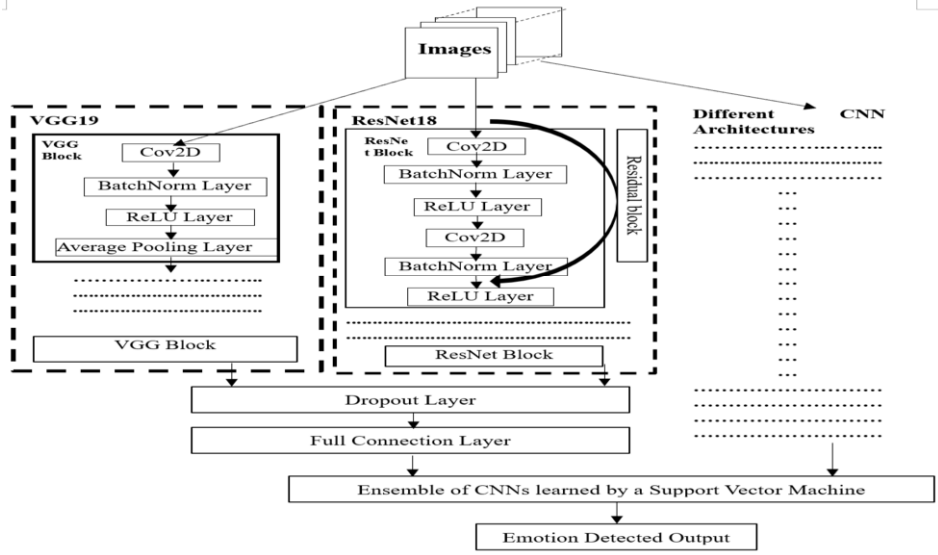


Figure 2. An overview of architecture design of the VGGNet with residual masking.

Design of the Loss Activation Function for Classification

There are two commonly used activation functions for classification problems. The first one is called the cross-entropy loss function. After the full connection layer, the model obtains the output probability of each class, but it is not normalized. Therefore, a softmax layer is added to map the original output, which causes the probabilities to sum up to 1, thereby fulfilling the constraints of a probability density [29]. The cross-entropy loss function is computed as follows. Softmax regression uses normalized probability to solve the multiclassification issue, and the category label y may have k distinct values (instead of 2).

$$J(\theta) = -\frac{1}{m}\sum_{i=1}^{m}[y^i log(h_\theta(x^i)) + (1-y^i)log(1-h_\theta(x^i))]$$

The other commonly used loss function is the linear SVM classification loss function, which is abstracted as the hinge loss function. The class loss expression is listed below. If the classification is accurate, the loss is 0; otherwise, it is 1 - h.

$$J(i) = max(0, 1 - h_\theta(x^i))$$

It generalizes numerous classifications using a logistic classifier. The SVM classifier will output the score for each classification and then choose the class with the highest score. Its overall probability is 1. We will test these two loss functions.

Step 4: HOG Feature Extraction and the SVM Baseline Model of Facial Emotion Recognition for Comparison

HOG feature extraction is used to extract spatial gradient orientation features that describe the local contour, the silhouette, and some texture information of faces [30]. The gradient information focuses on the edge information and can distinguish the human appearance outlined by it. In facial expression recognition, extracting HOG features can help to search and identify the contours of organs such as the nose, eyes, and mouth. They are vital in determining human emotions. HOG features are usually combined with

traditional machine learning algorithms. In this study, we used the baseline machine learning model of the support vector machine (SVM) as the emotion classifier to train on the extracted HOG features for comparison with the CNN model. The flowchart of extracting HOG features is shown in Figure 3.

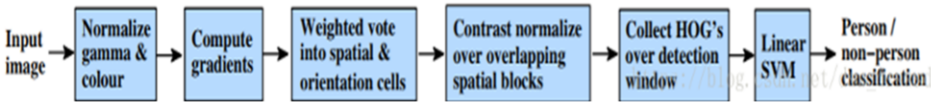


Figure 3. Workflow of extracting HOG features.

Step 5: StarGAN Model for Facial Emotion Reconstruction

StarGAN is a generative adversarial network that can perform image-to-image translations for multiple domains using only a single model. It allows users to train several datasets with different domains at the same time within a single network. In this study, we used the FER2013 dataset to train the facial emotion generation model with StarGAN, which is composed of a generator and a discriminator. The generator has two convolutional layers with a stride size of two for downsampling, six residual blocks, and two transposed convolutional layers with a stride size of two for upsampling. The discriminator has five convolutional layers with a stride size of two for downsampling. For the generator network, instance normalization in all layers was used except for the last output layer. For the discriminator network, leaky ReLU with a negative slope of 0.01 was used.

3.3 App Architecture Design

Figure 4 shows the overall architecture of the emotion reconstruction model for classifying the facial emotions and reconstructing the facial expression onto the avatar's face in the HKU Campusland metaverse. First, a webcam on a user's computer was used to capture the facial expression of the user in the real world. The app in the HKU SAAS Data Science Lab server [31] used the video capture function in the OpenCV package to cut the video into one-second frames. The position of the face was identified by using the Haar cascade algorithm. The main reason for us to use the Haar cascade algorithm rather than some other method such as SSDs or YOLO was that the Haar algorithm runs faster. It enabled us to predict facial expressions in real time without time delay. After identifying the bounding boxes of the faces, we resized them to a size suitable for the model that we had trained. The global and local features of the face (facial landmarks such as the eyebrows, lips, nose, mouth, and muscles of the face) were extracted by using the Dlib library, and they were fed into the trained multilayer CNN model for emotion prediction of every frame. The emotion of the user was finally reconstructed onto the avatar's face by using StarGAN.

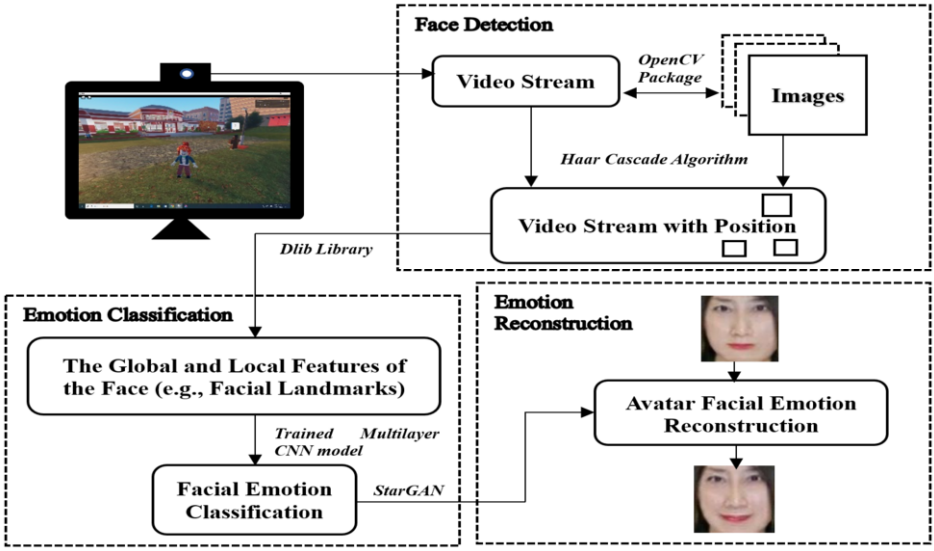


Figure 4. An overview of the emotion reconstruction architecture.

4. Results

4.1 Data Distribution

From the bar plot of the training data distribution, we found that the classes are not balanced. The happiness class has the largest number of occurrences, while the disgust class has the smallest number of occurrences. The ratio between them is around 20, which indicates that the model may be overfitted in the happiness class and underfitted in the disgust class. The frequency of the other five emotions is almost even.

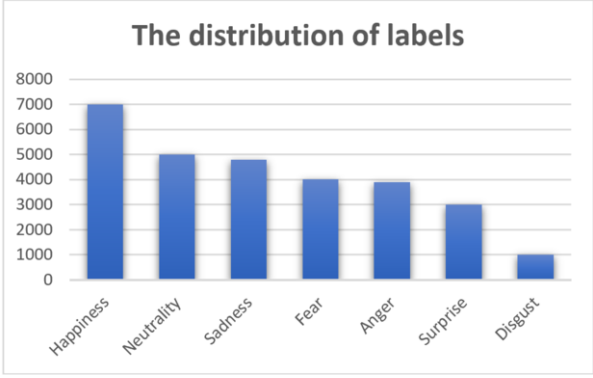


Figure 5. Distribution of the training dataset labels.

4.2 Data Preprocessing and Data Augmentation

After extracting the features using facial landmarks and HOG features [29], we saved the

results in the NumPy array format. Before we trained our deep learning models, some data augmentation tricks were required. We made some image transformations when training with VGGNet and ResNet. Ten crops were used as our main strategy, which was compared with different data augmentation tricks. The original size of the grayscale images was 48 x 48 pixels. First, we used five crops of the original images. The detailed manipulation was cutting five 44 x 44 pixel pictures off the original pictures as the training data. Their positions were upper left, upper right, lower left, lower right, and the corner. Then, the original picture was flipped horizontally and was cut into another five pictures at the same positions. The database was multiplied by 10 in this procedure, and the model then received these 10 images. The largest output class was then determined by averaging the acquired probability and using the resulting equation. Errors in classification were significantly reduced by this technique.

4.2.1 Testing the Results of Different Models With the CK+ Dataset

Since CK+ is a separate dataset, it can better evaluate the real generalization ability of the model. To test the classification results of different facial expressions, we input the test images of the CK+ dataset into the trained models of SVM, VGG19, VGGNet, and VGGNet with data augmentation; VGGNet with residual masking; and VGGNet with data augmentation and residual masking. In the CK+ dataset, there is no surprise class, so we recorded a video and cut out 67 frames of surprise faces. The overall prediction accuracies of the different models are shown in Table 1, and the results are discussed in Experiments 1, 2, and 3.

Table 1. A comparison of machine learning and VGG-CNN methods for emotion classification.

Tested Models	SVM	VGG19	VGGNet	VGGNet with data augmentation (DA)	VGGNet with residual masking (RM)	VGGNet with DA&RM
Accuracy	50.2%	70.8%	76.36%	73%	74%	88.33%

4.2.2 Experiment 1: Using a Support Vector Machine for Facial Emotion Recognition

We used a support vector machine (SVM) as the baseline model for facial emotion recognition. The results revealed that the training time of the 28709 SVM samples was quite long since SVM has low training efficiency on large datasets. The accuracy was 50.2% on the test dataset. Therefore, using the facial feature extraction technique of HOG features and SVM cannot achieve good results. The main reason for this is that such feature extraction is unable to extract abundant features from human expressions because the change in facial features is quite subtle.

4.2.3 Experiment 2: Using VGG19 for Facial Emotion Recognition

For training the VGG19 model, we used an intermediate activation state/characteristic diagram to evaluate the feature selection. An intermediate activation state/characteristic diagram visualizes the intermediate output characteristic map of the convolutional neural network, which is helpful in understanding how the continuous layers of the convolutional neural network expand and change the input data and in understanding the meaning of each filter of the neural network. The intermediate activation state combined with an “attention mechanism” for joint learning can significantly improve the accuracy

of the algorithm. The intermediate activation state/feature map in Figure 6 shows the output result of the learned filters after learning from the input image. Each layer of the convolutional neural network contains *N* learned filters, so the output of each intermediate layer contains *N* channel feature maps. Each channel feature map corresponds to an independent feature, which is exactly given by the corresponding learned filter. By visualizing all channel characteristic maps, we found that each filter can select a unique feature of the input image. The selected features will be input into the CNN model for training the classification model.

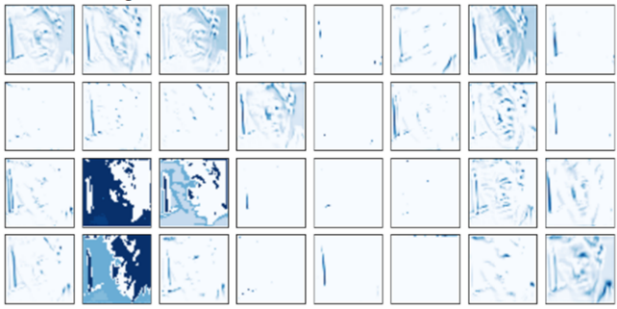


Figure 6. An overview of the extracted patterns from filters.

In order to reduce the overfitting and increase the precision of the model, we used a dropout function to randomly deactivate certain connections during training and replenish them during testing. The 10-time cropping approach can lower the number of identification errors. Random cutting expands the quantity of data during the training phase, thus increasing the dataset and reducing the influence of overfitting. Ten times the amount of data may be forecasted simultaneously in the prediction stage, which is analogous to the situation in which an integrated operation lowers the number of judgment errors of the network. Since softmax can output *k* classification outcomes but SVM can only do binary classification, we used VGG19, dropout, 10crop, and softmax together for training the VGG19 model. Table 2 summarized the hyperparameters of the model for training.

Table 2. Hyperparameters for training.

Hyperparameters	**Value**
Optimizer	optim.SGD(net.parameters(), lr=opt.lr, momentum=0.9, weight_decay=5e-4)
Total_epoch	120
Learning rate decay strategy:	If epoch>learning_rate_decay_start and learning_rate_decay_start >= 0: frac = (epoch - learning_rate_decay_start) decay_factor = learning_rate_decay_rate ** frac current_lr = opt.lr * decay_factor
Learning rate starting config:	learning_rate_decay_start=80 learning_rate_decay_every=5 learning_rate_decay_rate=0.9

After the VGG19 model was trained, the CK+ dataset was used to test the model. The accuracy of the VGG19 model is 70.8%. The VGG19 model can make accurate predictions for each emotion expression. The accuracy is far better than that of the SVM baseline model. This indicates that using deep learning neural networks, specifically convolutional neural networks, is an ideal choice in the field of computer vision and produces better results than using traditional machine learning algorithms. The

convolution layers in a CNN extract local features for training when the sliding window slides across the images. In contrast, machine learning models are unable to obtain related information for direct discrimination through the visualization of intermediate nodes. The representations learned by a convolutional neural network, however, perform well in visualization.

4.2.4 Experiment 3: Comparison of Different Architecture Designs of VGG19-CNNs for Facial Emotion Recognition

The VGGNet was trained with the FER2013 dataset. In this experiment, we tested different VGGNet architectures with data augmentation and residual masking. The optimal results of VGGNet, VGGNet with data augmentation, VGGNet with residual masking, and VGGNet with data augmentation and residual masking are 76.36%, 73%, 74%, and 88.33%, respectively. From the results, we concluded that VGGNet with data augmentation and residual masking has the best performance.

4.2.5 Experiment 4: Comparison Between the Best VGGNet Model and its Base Model for Each Class

Since VGGNet with data augmentation and residual masking had the best performance, we compared the prediction performance of each emotion class for the VGGNet model with data augmentation and residual masking. To better evaluate the model's performance, we defined blurred accuracy as the other measurement metric. Since the anger class and the disgust class have no clear borders, these two emotions are usually mixed up. In fact, humans usually show a certain amount of disgust when they are angry, and vice versa. It is not so important and not necessary to tell exactly which of these two emotions is shown by the user. Therefore, when evaluating the classification performance, we combined these two classes as one class. If anger is classified as disgust, we regard it as acceptable, and conversely, if disgust is classified as anger, it is also acceptable. We test our model with this dataset to calculate the blurred accuracy to see whether combining two classes of angry and disgust with better performance. The prediction accuracy of the different emotion classes is summarized in Table 3.

Table 3. The accuracy and blurred accuracy of VGGNet with data augmentation and residual masking.

Emotion	VGGNet with data augmentation and residual masking	VGGNet with data augmentation and residual masking
	Accuracy	**Blurred Accuracy**
Anger	89.63%	89.63%
Disgust	51.41%	97.74%
Fear	34.67%	34.67%
Happiness	98.55%	98.55%
Neutrality	100%	100%
Sadness	67.86%	67.86%
Surprise	92.37%	92.37%

The results showed that most samples in the anger class are classified into the correct categories. For the anger class, the result was 89.63%. About 10 samples were wrongly classified into the neutrality class. However, when predicting the disgust class, the model achieved a result of 51.41%. The reason for this is that the facial expressions of anger and disgust are difficult to distinguish. Therefore, when we regarded anger and

disgust as the same emotions, the blurred accuracy of disgust significantly improved from 51.41% to 97.74%. It implicates that we should integrate the angry and disgust class together for emotion classification. For the fear class, the result was 34.67%. The distinct expressions are not equally represented in the dataset, and this imbalance may lead to classification errors. Another factor is that the four expressions of anger, disgust, fear, and sadness share some characteristics. The subtle differences between these expressions are sometimes hard to tell. For the happiness class, the result was 98.55%. For the neutrality class, the result was 100%. For the sadness class, the result was 67.86%. For the surprise class, the result was 92.37%.

5. Applying the Meta-Motion Reconstruction Model to HKU Campusland for Mixed Reality

We deployed our novel meta-motion reconstruction model, which includes facial emotion classification and facial emotion reconstruction models, in HKU Campusland to detect the facial expressions of the user in the real world and to reconstruct the emotion onto the avatar's face. In this way, we bring nonverbal communication from the real world to the virtual world, and vice versa, for mixed-reality interactions in the metaverse. The following sections describe how the meta-motion reconstruction model was implemented.

5.1 Real-Time Facial Emotion Recognition App for Emotion Detection

We deployed the trained facial emotion classification model in the HKU SAAS Data Science Lab server. Figure 7 shows the screenshots of the real-time facial expression detection demo [31]. We can directly open our camera and give real-time predictions. The blue bounding box locates the area of the face. The green annotation is the prediction result. To make the picture more vivid, an emoji that changes according to the expression is added above the user's head, which can reflect more effectively and intuitively the user's emotions. The green dots indicate the detected face landmarks. They move when the user's facial expression changes. If no face is detected, a reminder pops up, saying "please adjust the camera."

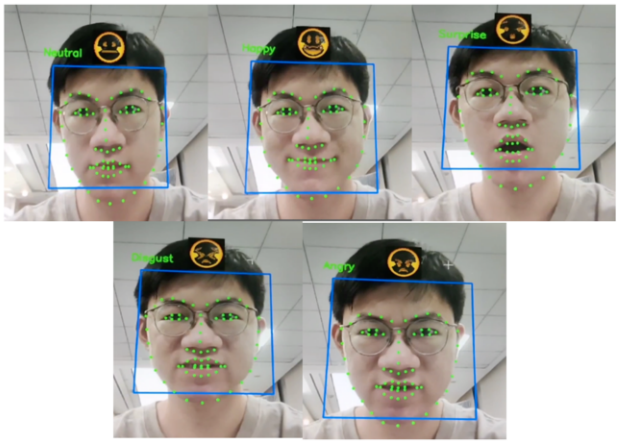


Figure 7. Real-time facial emotion detection demo.

5.2 Real-Time Facial Emotion Reconstruction App for Emotion Detection

StarGAN is a generative adversarial network that can perform image-to-image translations for multiple domains using only a single model (StarGAN Github, 2020). It allows users to simultaneously train several datasets with different domains within a single network. In this study, we used the FER2013 dataset to train the facial emotion generation model. After the emotion was detected, we deployed the facial emotion reconstruction model in the HKU SAAS Data Science Lab server. Figure 8 shows the results of the classified images.

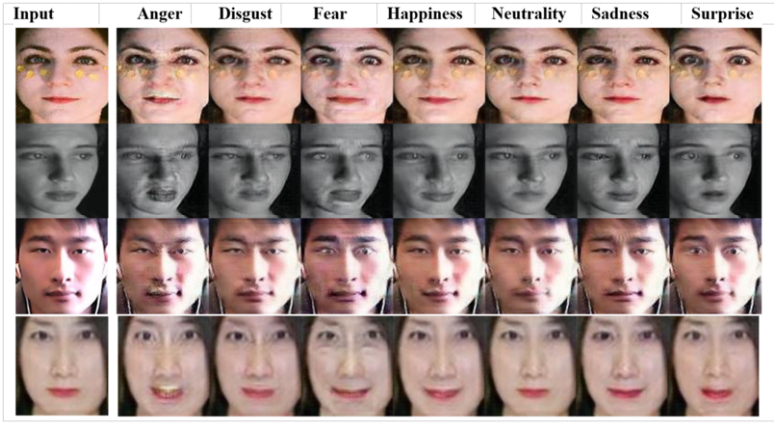


Figure 8. Real-time facial emotion reconstruction demo.

6. Conclusions and Future Work

The existing metaverse can provide only written communication, which prevents users from having an immersive experience in the metaverse. This research developed a new method of emotion reconstruction that includes a facial emotion recognition model and an emotion reconstruction model to reconstruct facial expressions onto the avatar's face, thus making interactions in the metaverse more like real-world interactions. Second, this research developed a new model for facial emotion recognition by combining the traditional VGG19 model and the ResNet model to form the VGGNet model, extended with a residual masking network and data augmentation. Compared with the SVM model and the VGG19 model, the model's accuracy improved by 38.13% and 17.53%, respectively. Different VGGNet architectures were also compared in this study to find the optimal model. Finally, we used StarGAN to reconstruct the detected emotion onto the avatar's face and deployed it in HKU Campusland to demonstrate how our novel emotion reconstruction model can be applied to the metaverse for nonverbal communication so that metaverse interactions become more life-like and users can have a more immersive experience. However, the limitation of StarGAN is that it is lack of capacity to learn mappings among large-scale domains and barely expresses small feature changes. In future work, we will use a SuperstarGAN to solve its scalability problem [32] in larger virtual environments. In addition, we can combine audio signals and images for emotion classification in the metaverse and develop SuperStarGAN for facial emotion reconstruction in the metaverse.

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A Novel DTPB-EM Model for Evaluating GUI and Non-GUI Chatbots for Self-Directed Learning

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Abstract. Traditional learning models such as direct instruction learning, inquiry-based learning, problem-based learning, case-based learning, or self-directed learning are either teacher-centered or student-centered, and limit learners to learning from instruction materials, enquiry, group discussion, or internet searches for problem solving. Self-learning overcomes these limitations and uses a chatbot as a personal tutor for self-learning. The two major types of chatbot are GUI and non-GUI chatbots. The GUI chatbots require programming skills while others require no or minor skills for their creation that make learner difficult to select the appropriate chatbot to use. This research therefore aims to evaluate the strengths and limitations of existing GUI and non-GUI chatbots. We present a novel DTPB-EM model for evaluating the effectiveness of the chatbots for comparison and conducting a face validity pilot test of the effectiveness of the use of GUI and non-GUI chatbots in education. The research methods applied here are review and expert evaluation. Roblox chatbot programmed with a GUI and a Non-GUI chatbots programmed with Python programming language were selected for comparison by five experts. It was found that the GUI chatbot gave positive results in regard to ease of use, compatibility, and self-efficacy, which implies that users will have a positive attitude towards its adoption. The non-GUI chatbot had slightly lower performance for these constructs but gave good performance in resource and technology facilitating conditions in terms of response accuracy, database size, scalability and language support. This implies that a non-GUI chatbot offers good perceived behavior control.

Keywords. GUI and non-GUI chatbot, self-learning, decomposed version theory of planned behavior

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1. Introduction

In traditional teaching methods, only textbooks, online materials and videos are used for learning. The main limitation of this approach is a lack of content filtering based on the learners' needs. Chatbots have become popular tools for learners to use to carry out knowledge enquiries from the internet [1]. This can accelerate the pace of learning and meet the learner's personal needs. There are two main types of chatbot on the market, GUI and non-GUI chatbots. The former type allows the user to customize the chatbot by programming. The challenges of this approach in regard to self-learning depend on the learner's programming capability.

This study therefore aims to evaluate both GUI and non-GUI chatbots, to see which is more appropriate for learners to use based on their personal needs and programming capability. The objectives of this study are to define some criteria for evaluation of chatbots based on a modified, decomposed version of the theory of planned behavior. Both GUI and non-GUI chatbots are assessed using the proposed novel decomposed version theory of planned behavior for effectiveness measurement (DTPB-EM) model, and recommendations are provided to allow learners to select an appropriate chatbot based on the comparison.

The following section reviews the traditional learning model, GUI and non-GUI chatbots, and the use of DTPM to define evaluation criteria for GUI and non-GUI chatbots. Sections 3 and 4 discuss the research methods and present some results respectively. Section 5 gives a discussion of the results, and Section 6 concludes the paper.

2. Literature Review

2.1 Need for Self-Learning Tools

Traditional learning models include direct instruction learning [2], inquiry-based learning [3], problem-based learning [4], case-based learning [5], and self-directed learning [6]. The first of these, direct instruction learning, focuses on transmitting knowledge and skills to the student through in-class instruction and structured materials [2]. It is a teacher-centered teaching method and lacks training in the areas of critical thinking and problem-solving. In an inquiry-based approach, this limitation is overcome, and students are encouraged to ask questions and to explore and investigate issues to develop their skills [3]. However, this is a student-centered teaching method and lacks practical training. Problem-based learning addresses this drawback by assisting students to learn about real-world problems and to develop solutions [7, 8]. Students are encouraged to define a problem, research solutions, and develop critical thinking skills. This requires self-directed learning and the application of knowledge to practical situations [6].

Case-based learning is another approach in which students are encouraged to analyze and discuss problems collaboratively. To solve a case problem, learners break down a problem into sub-problems to better understand the root causes, identify potential solutions, and solve these problems based on step-by-step guidance [9]. In this kind of computational thinking, complex problems are broken down into smaller ones, and an unstructured issue is transformed into a well-structured one, allowing learners to learn and recognize patterns and solutions [10]. However, real-world problems are complex,

and a range of different domain knowledge and skills are required to solve them. Students have limited knowledge and skills, and teachers may not have sufficient practical experience to enable them to learn or to develop their critical thinking and problem-solving skills. Self-directed learning therefore requires collecting, filtering, organizing and analyzing information to create the knowledge needed for problem solving.

2.2 Chatbots for Self-Directed Learning

Chatbots have therefore emerged as powerful tools for enhancing self-directed learning experiences due to their ability to provide personalized, interactive, and on-demand assistance [6]. Recent studies demonstrate that chatbot-mediated learning significantly improves knowledge retention and engagement compared to traditional self-study methods [11]. By simulating one-on-one tutoring interactions, chatbots create adaptive learning pathways that cater to individual needs, making them particularly effective for autonomous learners [12]. Research indicates that the conversational nature of chatbots helps to reduce cognitive load by breaking down complex concepts into manageable exchanges, thereby facilitating deeper understanding [13]. Without the assistance of a chatbot in self-directed learning, learners often struggle with a lack of immediate feedback, which can lead to persistent misconceptions and frustration. In addition, without the interactive elements that chatbots provide, many self-learners experience difficulty in terms of sustaining motivation and tracking progress, resulting in higher dropout rates [12]. Comparative studies show that learners who use chatbots have significantly better performance outcomes than those relying solely on static learning materials, thus highlighting the transformative potential of this technology in education [13,14].

2.3 Comparative Analysis of GUI and Non-GUI Chatbots in a Learning Context

The effectiveness of chatbots varies significantly depending on their functionality, ease of use and interface design. GUI-based chatbots, which incorporate visual elements such as buttons, menus, and multimedia, have been shown to enhance the usability for novice users by reducing input errors and simplifying navigation [13]. GUI-based chatbots are particularly effective in structured learning environments, where clear, guided interactions are beneficial; for instance, in language learning applications, the use of GUI chatbots with interactive exercises and visual progress trackers has been found to increase user engagement and completion rates [13]. By combining GUI elements with sophisticated NLP, the accessibility of visual interfaces can be improved while maintaining the depth of text-based interactions. Their interfaces can be dynamically adjusted based on user proficiency and preferences [13].

In contrast, non-GUI (text-based) chatbots excel in providing flexible, in-depth interactions, making them more suitable for advanced learners and complex problem-solving tasks [13]. These chatbots leverage advanced natural language processing (NLP) capabilities to engage users in open-ended dialogues, closely mimicking human tutoring experiences. Non-GUI chatbots are particularly effective in domains requiring critical thinking and conceptual understanding, as they allow for more natural, unstructured exchanges [13]. This approach uses various artificial intelligence techniques such as NLP, text analysis, text summarization, sentiment analysis, and text generation to empower the interaction between computers and human, and improves the capabilities of chatbots [15]. The non-GUI chatbot can comprehend the user's intent and provide appropriate

responses, using AI techniques for pattern matching, parsing, and comparing the parsed text using pattern matching to understand the meaning. Natural language generation (NLG) techniques are adopted to create coherent, context-based, relevant, and correct grammatical responses. The advanced AI models used for learning conversations to create non-GUI chatbots include recurrent neural networks (RNNs), deep neural networks (DNN), convolutional neural networks (CNNs), long short-term memory (LSTM), and reinforcement learning (RL) [16, 17].

2.4 Critical Factors in Chatbot Evaluation

To measure the adoption of technology, the decomposed version of the theory of planned behavior (DTPB) is the most commonly used model [18,19]. This measures the attitude, subjective norm, and perceived behavioral control of a user. The determinants for attitude measurement include ease of use, perceived usefulness, and compatibility, while peer influence and the influence of superiors are the major determinants for the subjective norm, as they measure how the learner's subjective norm is influenced by peers or superiors. Self-efficacy, resource facility conditions, and technology determine the learner's perceived behavioral control. Ease of use, perceived usefulness, compatibility, self-efficacy, resource facility conditions, and technology facility conditions explain the effectiveness of the technology in terms of influencing adoption. In contrast, the relative advantages and peer influence measure the learner's psychological influence in terms of adoption rather than the effectiveness of a tool influencing this decision.

In this study, we therefore selected and used the effectiveness factors of the DTPB to derive a model for assessment of the effectiveness of a chatbot. This novel model uses ease of use, perceived usefulness, compatibility, self-efficacy, resource facility condition, and technology facility condition as constructs to measure the effectiveness of a chatbot. Ease of use reflects the degree to which a person believes that using the chatbot will be free of effort, while ease of implementation and customization of the chatbot determines the degree of ease of use. Perceived usefulness measures the degree to which a person believes that using a particular system will enhance his or her performance; if the learner's purpose can be achieved via the use of the chatbot, he or she will have a positive attitude towards the perceived usefulness. Compatibility measures the degree to which the tool corresponds to the potential adopter's existing values, previous experiences, and current needs. Ease of learning can be achieved by using existing resources and the learner's internal knowledge. All these constructs can be used to determine the attitude towards the effectiveness of the chatbot.

Self-efficacy measures a person's belief in their ability to succeed in a specific situation or to achieve the desired outcomes. A high level of accuracy of the responses from the chatbot and a faster response time can improve the learner's self-efficacy. The resource facilitating condition reflects the factors related to resources, such as time, money, and other aspects relating to technology compatibility. Since the use of a chatbot requires a great deal of computation and memory resources, cost is the major determinant of this construct. Finally, the technology facilitating condition represents the available technology that is needed to make use of the chatbot, with language support, database size, and scalability being the major considerations for the technology condition.

To evaluate the effectiveness of a chatbot, the major constructs therefore include the purpose of use, database size, ease of learning, ease of implementation, database size, time for response, accuracy rate, scalability, cost, ease of customization, and programming language support. We include all these constructions and determinants

when creating our novel effectiveness measurement model for chatbot adoption behavior.

3. Research Method

3.1 Model Design and Constructs for Chatbot Evaluation

As discussed above, we use the constructs and determinants derived from the DTPB model to assess the effectiveness of GUI and non-GUI chatbots. Figure 1 shows the design of our novel DTPB-EM model, and Table 1 summarizes the constructs and determinants used for chatbot evaluation. The determinants include "purpose of use," "database size," "ease of learning," and "ease of implementation," "database size", "time to response," "accuracy rate," "scalability," "cost," "user customization," and "language support". These determinants provide a comprehensive framework for assessing a chatbot's readiness for deployment and its potential success in real-world applications.

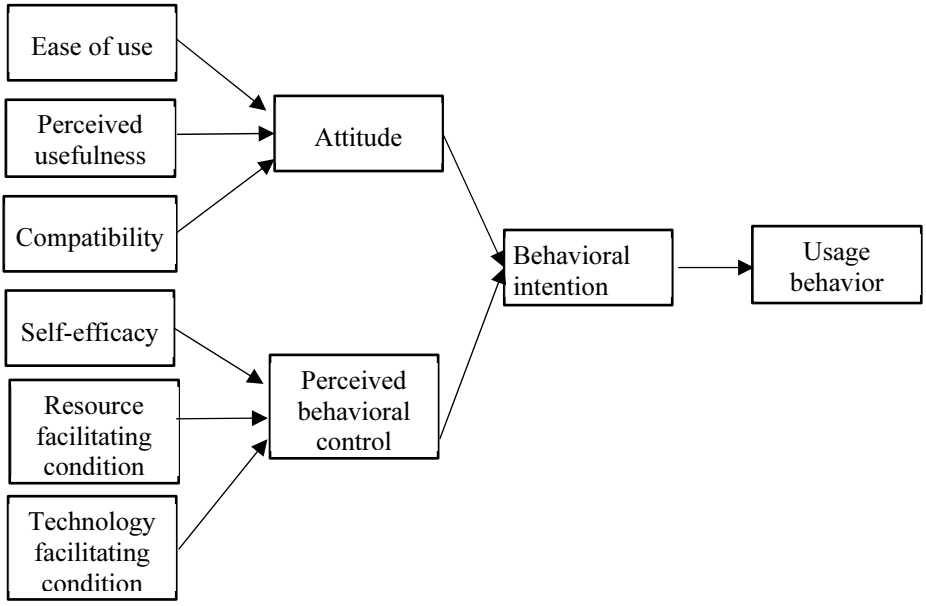


Figure 1. Overview of the framework for DTPB-EM for chatbot effective evaluation.

Table 1. Constructs and measurement metrics for comparison of GUI and non-GUI chatbots

Construct	Description	Determinant(s)
Usage behavior	A person's performance of a specific action or an individual's decision to use the chatbot.	Behavioral intention
Behavioral intention	A measure of the strength of intention to perform a specific action.	Attitude, perceived behavior control
Attitude	Whether a person possesses positive or negative feelings toward the behavior being performed.	Ease of use, perceived usefulness, compatibility

Perceived behavior control	Perceptions of the availability of skills, resources, and opportunities.	Self-efficacy, resource and technology facilitating conditions
Ease of use	The degree to which a person believes that using the chatbot will be free of effort.	Ease of implementation and customization
Perceived usefulness	The degree to which a person believes that using the chatbot will enhance his or her performance.	Purpose of use
Compatibility	The degree to which the chatbot fits with the potential adopter's existing values, previous experiences, and current needs.	Ease of learning
Self-efficacy	A person's belief in their ability to succeed in a specific situation or to achieve the desired outcomes from use of the chatbot.	Accuracy of responses, time to response
Resource facilitating condition	Resource factors such as time, money, and other factors relating to technology compatibility.	Cost of implementation
Technology facilitating condition	Availability of the technology needed to make use of chatbot tool.	Language support, database size, scalability

3.2 Expert Evaluation of the Chatbot

Since this study involves only a pilot test to determine whether the proposed instrument can be used to measure the effectiveness of a chatbot with our novel DTPM-EM model, an expert evaluation was done by the authors. No ethical approval was required. The following describes the evaluation procedures for construct validity of the instrument.

Purpose: The purpose of this expert evaluation was to compare the effectiveness of GUI and non-GUI chatbots for adoption in a learning context. A Roblox GUI chatbot [20] and a non-GUI chatbot created using Python with APIs of ChatGPT, Claude, Meta AI, and Google Gemini [21] and were evaluated by five experts, in order to compare the effectiveness of using GUI and non-GUI chatbots for programming a chatbot application. The components of this assessment of the chatbot's effectiveness included all determinants of the attitude and perceived behavioral control constructs.

Sample Size: For an expert evaluation, the minimal sample size is five experts [22], which was the number adopted here.

Sample Selection: The criterion for inclusion was that the expert had at least two years' experience of using both GUI and non-GUI chatbots. The criteria for exclusion were that the expert without any chatbot programming experience and uses the chatbots in this experiment.

Method: The measurement metric used a rating score from four to one, with a score of four being the highest and one being the lowest. The scores were averaged to give the final score for each type of chatbot. The standard deviations of the scores were also calculated.

4. Results

The following table summarizes the average scores from the experts for GUI and non-GUI chatbots for comparison.

Table 2. Scores for the expert evaluations of the GUI chatbot

	Ease of implementation	**Ease of customization**	**Purpose of use**	**Ease of learning**	**Accuracy of responses**	**Time to response**	**Cost of implementation**	**Language support**	**Database size for training**	**Scalability**
Roblox NPC	3	3.2	2.6	3	2	3.8	3.6	2	1.4	2.6
GUI Chatbot	**3**	**3.2**	2.6	**3**	2	**3.8**	**3.6**	2	1.4	2.6

Table 3. Results for the standard deviation in the experts' evaluations of the GUI chatbot

	Ease of implementation	Ease of customization	Purpose of use	Ease of learning	Accuracy of responses	Time to response	Cost of implementation	Language support	Database size for training	Scalability
Roblox NPC	1.00	1.10	1.52	1.00	0.00	0.45	0.89	0.00	0.89	0.55
GUI Chatbot	**1.00**	**1.10**	1.52	**1.00**	0.00	**0.45**	**0.89**	0.00	0.89	0.55

Table 4. Scores for the expert evaluations of non-GUI chatbots

	Ease of implementation	**Ease of customization**	**Purpose of use**	**Ease of learning**	**Accuracy of responses**	**Time to response**	**Cost of implementation**	**Language support**	**Database size for training**	**Scalability**
ChatGPT APIs	3.6	3.6	4	3.4	3.8	3.2	1.8	3.8	4	3.8
Claude APIs	3.6	3.2	3.8	3.4	3.8	2.8	3	3.8	3.8	3.8
Meta AI APIs	3	3.8	2.6	2.4	3	3	3.2	3	3.8	3.2
Google Gemini APIs	4	3.4	4	3.2	3.6	3.6	2.6	3.6	4	3.6
Non-GUI Chatbot	**3.55**	**3.5**	**3.6**	**3.1**	**3.55**	**3.15**	2.65	**3.55**	**3.9**	**3.6**

Table 5. Results for the standard deviation in the expert evaluations of non-GUI chatbots

	Ease of implementation	Ease of customization	Purpose of use	Ease of learning	Accuracy of responses	Time to response	Cost of implementation	Language support	Database size for training	Scalability
ChatGPT APIs	0.55	0.55	0.00	0.55	0.45	0.45	0.45	0.45	0.00	0.45
Claude APIs	0.55	0.45	0.45	0.55	0.45	0.45	0.00	0.45	0.45	0.45
Meta AI APIs	1.22	0.45	0.55	0.55	0.00	1.00	1.10	0.00	0.45	0.84
Google Gemini APIs	0.00	0.55	0.00	0.45	0.55	0.55	0.55	0.55	0.00	0.55
Non-GUI Chatbot	**0.58**	**0.50**	**0.25**	**0.52**	**0.36**	**0.61**	0.52	**0.36**	**0.22**	**0.57**

5. Discussion

From this comparison of the chatbots, we found that the GUI chatbot was easier to learn, implement and customize, and had a faster response time and a lower cost of implementation. This implies that the GUI chatbot is easy to use, with high levels of compatibility, and self-efficacy, and resource facilitating control, resulting in a positive attitude towards the adoption of this chatbot. The non-GUI chatbot had good results for the database size, time for response, scalability and language support determinants, implying that this type of chatbot has better perceived behavior control for its adoption.

Table 6 summarizes the results and key points of comparison between the GUI and non-GUI chatbots in terms of attitude towards adoption, perceived behavioral control, learning effectiveness and user engagement and retention.

Table 6. Summary of results for the GUI and non-GUI chatbots

Constructs and determinants	GUI chatbot	Non- GUI chatbot
Construct: Attitude towards adoption Determinants: **Ease of use**, perceived usefulness, and **compatibility**	• From the expert evaluation results, GUI chatbot is easy to implement (mean = 3), easy to customize (mean = 3.2), and easy to learn (mean = 3). • This means that the GUI chatbot is easy to use and has high compatibility. • GUI-based chatbots typically demonstrate higher ease of use, particularly for novice users [23].	• From the expert evaluation results, GUI chatbot is easy to implement (mean = 3.55), easy to customize (mean = 3.5), with high results for purpose of use (mean=3.6) and ease of learning (mean = 3.1). • Non-GUI variants necessitate more sophisticated NLP capabilities to ensure seamless interactions [23].
Construct: Perceived behavioral control Determinants: **Self-efficacy**, **resource facilitating conditions**, and technology facilitating conditions	• The results show a good time to response (mean = 3.8) and cost of implementation (mean=3.6). • The GUI chatbot has a lower database size (mean=1.4), scalability (mean=2.6), accuracy of responses (mean =2), and language support (mean = 2) to the user.	• This type has a better accuracy of responses (mean=3.55), time to response (mean=3.15), database size (mean=3.9), scalability (mean=3.6), and language support (mean=3.5) to the user. • The results show that the non-GUI chatbot has a higher cost to implement (mean=2.65).

	• It can be concluded that the GUI chatbot yields good performance in terms of self-efficacy and resource facilitating conditions [24].	
Learning effectiveness in terms of knowledge	• GUI chatbots prove more effective for acquiring procedural knowledge [13].	• The non-GUI type can better support the development of conceptual understanding and critical thinking [13]. • Non-GUI chatbots exhibit greater flexibility across diverse learning contexts, although their implementation often demands more robust technical infrastructure [13].
User engagement and retention	• GUI elements can be used to create progress bars and interactive quizzes that significantly enhance user engagement [23].	• Non-GUI chatbots foster deeper cognitive engagement through sustained conversational depth [23].

In addition to ease of learning, usability, accuracy of responses, and response time, several other criteria such as user interaction and user-friendliness are also determinants that need to be taken into consideration for the attitude and subjective norm for its adoption [23]. The ability to customize a chatbot for personalized use, programming language support, scalability, vocabulary size, and cost are some other important factors that will affect users.

6. Conclusion and Future Work

This study involved a pilot test to evaluate whether GUI and non-GUI chatbots could be measured by the proposed instrument. The results indicated that a chatbot program with a GUI is easier to use, implement and customize, and has a low cost and fast response time. The learner can easily use the GUI of the chatbot to modify the codes to create a personalized chatbot. When deploying the chatbot in the metaverse, students have a higher capability to customize the chatbot for use and interaction. The non-GUI chatbot gave slightly inferior performance to the GUI version in terms of ease of use, implementation and customization, response time and accuracy. It yielded good performance in regard to scalability, database size, and language support, although the implementation cost was higher. This study mainly focused on the development of the instrument and pilot testing by researchers, and a complete study will need to be done to validate the instrument and results. In future work, more GUI and non-GUI chatbots may be compared, and some other research topics will be considered, such as validation and reliability testing of the instrument, and an empirical adoption behavior study of the chatbots will be done with our novel DTBP-EM model, with ethical approval and a sample size of 385 at a confidence level of 0.95.

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Human Non-Speech Vocalization Recognition and Classification Based on Dual Convolutional Neural Networks

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Abstract. Audio signals contain both low-frequency components that represent structural features and high-frequency components that represent detail features. We propose a dual Convolutional Neural Networks for human non-speech vocalizations classification. This algorithm extracts structural features and detail features from the input audio separately, concatenates the two types of features, inputs them into an EfficientNet model, then performs pooling, and finally outputs the classification results. Experimental results demonstrate that using this algorithm can effectively improve human non-speech vocalizations classification performance.

Keywords. human non-speech vocalization, deep learning, Dual Convolutional Neural Networks, recognition and classification.

1. Introduction

Human non-speech vocalizations refer to sound expressions that do not involve specific words or grammatical structures. These vocalizations play an important role in daily communication, conveying information such as emotions, intentions, or physical states. Recognizing and classifying these non-speech vocalizations can help in understanding the multifaceted characteristics of human communication. For example, laughter, crying, sighing, and panting are used for emotional expression; while sneezing, coughing, yawning, and burping are physiological sounds.

FSD50K is a large-scale, open-source audio dataset widely used for audio event detection and classification tasks, particularly suited for Environmental Sound Recognition (ESR) and general Audio Event Detection (AED) research [1]. The audio clips are mostly between a few seconds to 30 seconds in length, with a total of approximately 51,197 audio files. AudioSet is a large-scale audio event dataset released by Google Research, aimed at supporting research in audio event detection and classification [2]. The dataset is built upon YouTube videos and contains millions of 10-second audio clips extracted from these videos. AudioSet provides an extended audio

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label set covering a wide range of everyday sounds, including human non-speech vocalizations, animal sounds, natural environment noises, music, and more. Nonspeech7k is an audio dataset focused on human non-speech vocalizations, comprising approximately 7,000 audio samples [3]. These samples are primarily used for research and classification of voice behaviors that do not involve linguistic content, such as laughter, crying, coughing, sneezing, wheezing, moaning, and more. This type of data holds significant application value in areas including emotion recognition, healthcare monitoring, and voice assistance systems. Gong has developed the VocalSound dataset, which contains six categories, such as sneezes, laughter, sniffs, coughs, sighs, and throat clearing. Each category includes 3,504 recordings, totaling 21,024 speech samples [4]. The number of samples in 6 different categories across the above 4 datasets are shown in Table 1.

Table 1. The number of samples in 6 different categories across the above 4 datasets.

Dataset	FSD50K	AudioSet	Non-Speech7K	VocalSound
Laughter	1186	5696	1273	3504
Sigh	136	301	0	3504
Cough	385	871	702	3504
Throat Clearing	0	355	0	3504
Sneeze	125	1200	266	3504
Sniff	0	205	0	3504

Due to the scarcity of audio datasets, especially non-speech datasets, and the presence of significant label noise, research on human non-speech vocalizations has been severely impacted. This paper proposes a human non-speech vocalization classification algorithm based on Dual Convolutional Neural Networks. The proposed method can handle not only the structures but also the detailed features of audios to improve the performance of recognition and classification.

The rest of this paper is organized as follows: Section 2 discusses Convolutional Neural Networks used in signal processing. Section 3 details the proposed framework. Section 4 presents experimental results. Section 5 concludes with future directions.

2. Related Works

Convolutional Neural Network (CNN) is a type of deep learning model widely used in fields such as image recognition, video processing, and natural language processing. It extracts local features from data by simulating the human visual mechanism and builds more complex feature representations layer by layer. The core structures of a CNN mainly include convolutional layers, activation functions, pooling layers, fully connected layers, and normalization layers. Lecun first proposed using CNN for handling handwriting recognition and achieved excellent results [5]. Simonyan proposed that by increasing the network depth to 16-19 layers and using small 3x3 convolutional filters, recognition accuracy can be significantly improved [6]. The paper introduces a deep residual learning framework that, by introducing the concept of residual functions (or residual blocks), makes training deep networks easier and improves accuracy as network depth increases [7]. Geoffrey Hinton and his team were the first to apply Deep Neural Networks to speech recognition, achieving excellent results [8]. Ossama explained how to use CNNs for speech recognition and proposed a weight-sharing strategy to further improve the algorithm's performance [9]. EfficientNet is an efficient convolutional

neural network architecture proposed by the Google Research team. It aims to achieve a good balance between computational resources and model performance. EfficientNet employs a method called Compound Scaling, which proportionally scales up the depth, width, and resolution dimensions of the network. This approach significantly improves model accuracy while maintaining efficiency [10]. Pan proposes a dual convolutional neural network (DualCNN) for low-level vision problems, which recover the structure and detail components [11], [12]. Given the scarcity of human non-speech vocalizations dataset and the characteristics of audio, we also chose the CNN architecture.

3. Method

3.1. Structure and detail features

In the field of signal processing, audios are essentially time-series data that contain a range of frequency components, from low to high frequencies. These different frequency components are crucial for feature extraction and subsequent speech recognition processing. Low-frequency information typically contains the fundamental frequency and structure feature of audio, which help enhance recognition accuracy. Low-frequency components are also generally more resistant to background noise, meaning that retaining this information can help maintain recognition performance in noisy environments. In contrast, high-frequency information contains rich detail features, such as transient changes and rapid frequency variations, which are vital for accurately recognizing speech content. It can also capture the emotional and prosodic changes in a speaker's voice, which is essential for understanding the emotional state behind the spoken words. For example, laughter, crying, and other non-speech vocalizations typically contain significant high-frequency components.

3.2. Proposed approach

Figure 1 illustrates the flowchart of the proposed human non-speech vocalizations processing and classification method. The specific steps are as follows:

Step1: Input Audio Signal. At the top of the image, a spectrogram of the raw audio signal is displayed. A spectrogram is a visualization tool used to show the energy distribution of an audio signal across different frequencies and time points.

Step2: Feature Extraction. The raw audio signal is decomposed into two parts: structural features and detail features. These features are extracted using different methods, and their distinctions and relationships can be observed in the diagram.

Step3: Feature concatenated. The extracted structural and detail features are concatenated to generate a composite feature map.

Step4: Further Feature Extraction with EfficientNet. The combined feature map is then fed into an EfficientNet for further feature extraction. EfficientNet is an efficient deep learning model capable of extracting higher-level features from the data.

Step5: Pooling Operations. The features extracted by EfficientNet undergo two pooling operations. **Frequency Mean Pooling**: This reduces the amount of information in the frequency dimension by averaging. **Temporal Mean Pooling**: This reduces the amount of information in the time dimension by averaging.

Step6: Event Classification. The pooled features are used to classify segments of audio events. The diagram shows six classification results, each representing a probability distribution for a particular event.

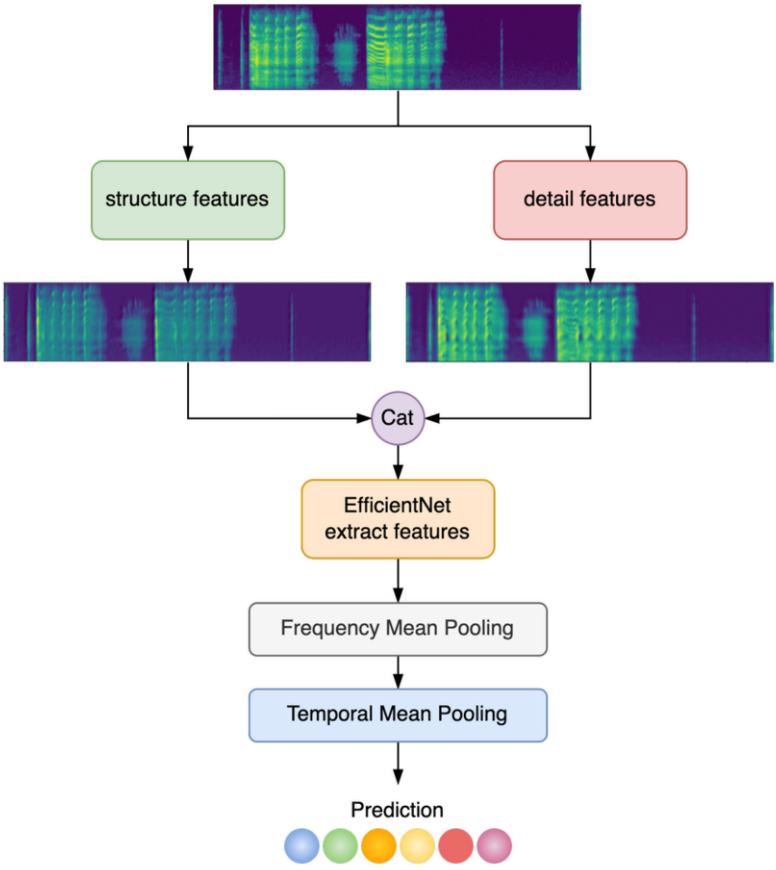


Figure 1. The flowchart of Dual CNN.

The detail feature extractor learns local features through 20 layers of CNNs, making it suitable for tasks that require the retention of spatial details in low-frequency information. In contrast, the structural feature extractor uses three layers of CNNs with varying kernel sizes to learn structural features. This approach enables the construction of a "structure-detail" dual-branch model. The architectures of two CNNs are shown in Table 2.

Table 2. The architectures of two CNNs.

Features	Structure	Detail
Objective	Extract global structure	Capture local details
Layers	3	20
Stride	1	1
Kernel size	9×9/5×5/1×1	3×3
Padding	3/0/3	1

4. Results

To validate the effectiveness of our algorithm, we conducted relevant experiments. The experiments were carried out using an NVIDIA DGX-1 server equipped with 8 V100 GPUs.

The learning rate for structural features is set to 2e-4, and the learning rate for detail features is set to 2e-5. The learning rate for subsequent processes is set to 1.28e-4. The EfficientNet B-7 model is used for feature extraction. The SpecAugment data augmentation technique is employed, with frequency masking set to 48 and temporal masking set to 192. The batch size is set to 50, and the number of training epochs is 300. Additionally, noise is added during the training process.

We first trained a baseline model using EfficientNet B-7 for comparison. The experimental results are shown in Table 3.

Table 3. Experimental results (VocalSound)

Items	VocalSound	Baseline	Proposed
Evaluation Set	90.50	91.92	**92.79**
Age18-25	91.50	93.05	**93.83**
Age26-48	90.10	91.24	**92.22**
Age49-80	90.90	93.68	**93.97**
Male	89.20	90.32	**91.33**
Female	91.90	93.60	**94.31**

We also conducted experiments on Nonspeech7k and AudioSet dataset to further validate the effectiveness of this approach. The experimental results are shown in Table 4.

Table 4. Experimental results (Nonspeech7k and AudioSet)

Dataset	Baseline	Proposed
Nonspeech7k	68.09	**71.08**
AudioSet	93.07	**93.39**

5. Conclusions

The recognition and classification of human non-speech vocalizations are crucial for assessing a person's emotions and health status. However, due to the limited amount of data available, it is challenging to improve the model's performance. Based on the fact that audio signals contain both low-frequency and high-frequency components, this paper proposes a dual CNNs algorithm that can separately extract structural features and detail features and then combine them. Validation on dataset Vocalsound demonstrates that this algorithm can effectively improve the accuracy of human non-speech vocalizations classification. In the future, we plan to apply this method to more datasets and make improvements to enhance its generalization performance.

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Section III

Special Session on “New Ecology of Lifelong Education”

Digitalization and Management Innovation IV
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Assessing AI Literacy in Vocational College Teachers: An Empirical Framework Based on the AI-TPACK Model

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Abstract. Teachers' AI literacy is crucial for achieving the talent cultivation goals in vocational education. Current researches on teachers' AI literacy are focused on the theoretical level, and lacks empirical research targeting vocational college teachers. The author utilized the theoretically mature AI - TPACK Model to evaluate the AI literacy of 795 teachers from 86 vocational colleges in Hunan Province through a questionnaire survey. By using an ANOVA analysis to evaluate the influence of teachers' personal characteristics, such as disciplines, teaching positions, and professional titles, on their AI literacy, and using a MANOVA analysis to evaluate the impact of two external factors, AI skills training and support policies, on teachers' AI literacy. The author found that teaching positions and AI skills training had a significant impact on all four aspects of teachers' AI literacy; disciplines had a significant impact on teachers' AI-EK; professional titles had a significant impact on teachers' AI-EA; and support policies have a significant impact on teachers' AI-EA and AI-ET. Based on the research findings, the author suggests vocational colleges can improve teachers' AI literacy by providing AI skills training, support policies, and personalized training programs in combination with teachers' personal characteristics.

Keywords. AI literacy, AI Educational Knowledge, AI Educational Ability, AI Educational Ethic, AI Educational Thinking

1. Introduction

Nowadays, generative AI has almost penetrated every aspect of education. Vocational colleges serve as crucial bases for cultivating technical and skilled talents. Compared with general higher education, vocational education places more emphasis on practicality and applicability. The AI literacy of higher vocational college teachers is the key to determining whether AI technology can be effectively utilized in vocational education. The level of teachers' AI literacy directly affects the cultivation of students' AI technology capabilities.

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The basic goal of this study is to evaluate the AI literacy of higher vocational college teachers through scientific methods, study the main factors affecting their AI literacy, and put forward targeted suggestions for improving their AI literacy.

Although scholars have different definitions of teachers' AI literacy, through research, the author has found that the definitions of AI literacy by scholars always encompass three core elements. Firstly, it implies the effective integration of AI knowledge and subject knowledge. Secondly, it is mainly reflected in teachers' ability to use AI technology for practical teaching. Thirdly, it as a whole influence the goals, effects, and values of education. The first element represents teachers' basic AI qualities. The second element represents teachers' ability to use AI technology for teaching practice and innovation. The third element represents the comprehensive value of teachers' AI literacy. It not only emphasizes its impact on teachers' duty, but also highlights its effectiveness on educational objects (students). Meanwhile, it also emphasizes its impact on the profound social values. In view of this, this article defines AI literacy as the quality and ability of teachers to use AI technology to promote their teaching practice and innovation, achieve higher education goals, improve teaching effectiveness, and realize educational value on the basis of integrating AI knowledge with their subject knowledge.

There are three typical theories in academia regarding the core elements of teachers' AI literacy: the three elements theory, the four elements theory, and the five elements theory. (see Table 1).

Table 1. Typical theories and representatives of teachers' AI literacy

Theories	Elements	Representatives
three elements theory	understanding basic AI concepts, evaluating things through AI concepts, and solving real-world problems using AI concepts [1].	Kong S-C et al., 2021
	AI teaching capability, AI teaching ethic and AI teaching value [2].	Teresa Hammerschmidt, Oliver Posegga, 2021
	basic cognition, knowledge understanding and AI usage [3].	Duri Long, Brian Magerko, 2020
	AI teaching knowledge, AI core competencies and AI teaching ethic [4].	Liu Bin, 2020
	AI knowledge, AI ability and AI ethic [5].	Zhang Yinrong et al., 2022
four elements theory	AI teaching cognition, AI teaching skills, and AI teaching practice [6].	Guo Yajun, et al., 2025
	AI knowledge, AI ability, AI attitude, and AI ethic [7].	Wang Ming, 2018
	AI awareness, AI knowledge, AI capability, and AI ethic [8].	Huang Xiting, Huang Weirong, 2024
	AI teaching cognition, AI teaching knowledge, AI teaching capability and AI teaching ethic [9].	Zheng Zhiyong, Song Naiqing, 2023
	information literacy, educational ethic, privacy protection awareness, and the combination of adaptability and learning ability [10].	Deng Hanwen et al., 2024
five elements theory	data collection, data organization and dissemination, control over one's thoughts and actions, sensitivity to AI biases, and awareness of AI's potential impacts [11].	Hermann E., 2022
	knowledge, skills, attitudes, values, and ethics [12].	Wilson M. et al., 2015
	technology, function, ethic, collaboration, and self-reflection [13].	Thomas K.F. Chiu, et al., 2024
	AI awareness and concepts, AI knowledge and skills, AI thinking ability, AI teaching application ability, relevant personality traits [14].	Fan Jianli and Zhang Xinping, 2022

The purpose of scholars defining the elements of AI literacy is twofold: one is to conduct further academic analysis, and the other is to construct models for evaluating teachers' AI literacy. The author found 18 articles related to building teachers' AI literacy evaluation models among the 362 relevant literatures searched. Among these articles, although scholars have different names and expressions for the elements of AI literacy, based on their proposed core connotations, the author has renamed and classified these elements from the same or similar dimensions. The reclassified elements are shown in Table 2.

Table 2. The core elements and their frequency of occurrence in the evaluation framework proposed by scholars

Reclassified elements	core connotation	Frequency
AI educational knowledge	Technical knowledge and teaching knowledge related to education	18
AI educational ability	The ability to use AI tools for teaching	13
AI educational ethic	Moral evaluation and value judgment of the impact of AI empowerment on education	13
AI educational thinking	mode of thinking adapted to AI education	8
AI educational attitude	Attitude and self-awareness towards AI empowering higher education	5
AI educational value	Emotional and Value Recognition of AI Empowering Higher Education	5
AI educational awareness	Attitude and cognition towards AI empowering higher education	2
AI application ability	The ability to apply AI technology to teaching and research	2
AI innovation ability	The ability to use AI technology to promote and achieve teaching innovation	3
AI educational reflection	Critical thinking on AI empowering higher education	3

By examining scholars' definitions of "AI application capability" and "AI innovation capability", the author found that these two concepts are actually included in the connotation of "AI educational ability". Similarly, the concepts of "AI educational value" mentioned by scholars is actually included in the scope of "AI educational ethics"; The "AI educational attitude", "AI educational awareness" and "AI educational reflection" are included in the category of "AI educational thinking". Through inductive integration, this article identifies the basic elements that constitute the artificial intelligence literacy of university teachers as: AI educational knowledge (AI-EK), AI educational capability (AI-EC), AI educational ethics (AI-EE), and AI educational thinking (AI-ET).

Scholars' definitions of teachers' AI literacy from different perspectives, as well as the theoretical models proposed to evaluate teachers' AI literacy, provide us with a theoretical basis for in-depth research. But these studies also have certain limitations. Firstly, scholars tend to focus more on constructing theoretical models for evaluating teachers' AI literacy from different perspectives, but overlook empirical research,

especially, lack of empirical studies focusing on vocational teachers ; Secondly, scholars have paid little attention to the impact of personal characteristics such as disciplines, teaching positions, and professional titles, as well as the impact of external factors such as skills training and support policies on teachers' AI literacy. Therefore, it is necessary to use the relatively mature AI-TPACK model to analyze the personal characteristics and external factors that affect the AI literacy of vocational college teachers through empirical analysis, to explore which aspects of teachers' AI literacy these factors will affect and find targeted methods to improve them.

2. Research method

This article adopts an empirical research method to examine the AI literacy of vocational college teachers in Hunan Province. As of 2024, there are approximately 1560 vocational colleges in China, and the faculty of vocational colleges varies depending on factors such as college size, and regional economic development level. The number of teachers in each vocational college is usually between 200 and 500. According to the degree of development, vocational education in China could be roughly divided into three grades: Beijing, Shanghai and Guangdong Province have the highest level of vocational education, followed by Hunan Hubei Shandong, Henan, Sichuan and other central Provinces, and Xinjiang, Xizang, Qinghai and other western Provinces are in the lowest education level. Due to limitations in funding, time, and other resources, this study does not have the conditions for a nationwide evaluation. The survey object chosen by the author is vocational colleges in Hunan Province. One reason is that vocational education in Hunan Province is in a leading position in the central regions and has a certain representativeness; The second reason is that the author's institution is located in Hunan Province, which facilitates our empirical research. Inevitably, this research will have certain limitations as a result.

The author referred to the theories of AI-TPACK framework (Zheng Zhiyong, Song Naiqing, 2023), combined with the goals and characteristics of higher education, to establish an evaluation model which includes 4 fundamental elements and 12 secondary indicators to evaluate college teachers' AI literacy. (see Table 3).

Table 3. The framework of AI literacy for college teachers

Fundamental Elements	Secondary indicators
AI Educational Knowledge (AI-EK)	AI technological pedagogical knowledge (AI-TPK)
	AI technological content knowledge (AI-TCK)
	AI technological pedagogical content knowledge (AI-TPACK)
AI Educational Ability (AI-EA)	AI teaching ability (AI-TA)
	AI educational innovation ability (AI-EIA)
	AI educational evaluation ability (AI-EEA)
AI Educational Ethic (AI-EE)	AI educational ethic safety (AI-EES)
	AI educational ethical obligation(AI-EEO)
	AI educational value orientation (AI-EVO)
AI Educational Thinking (AI-ET)	AI Education Identity Recognition (AI-EIR)
	AI educational subject consciousness (AI-ESC)
	AI educational critical thinking (AI-ECT)

The author designed a survey questionnaire based on above evaluation model of AI literacy for college teachers. The questionnaire was divided into 4 parts, each part with 12 questions, among them, 9 questions are used to examine 3 secondary indicators; 3

questions examine the comprehensive higher-order abilities of each fundamental element. The main body of the questionnaire used a 5-point Likert scale. Taking the assessment of teachers' AI-EK literacy as an example, the questionnaire is shown in Table 4.

Table 4. The list of questions on AI-EK literacy

Survey Objectives	Question lists
AI-TPK	I can choose suitable AI tools to optimize teaching strategies based on students' learning characteristics.
	I am able to use AI technology to design personalized teaching activities to meet the learning needs of different students.
	I am able to evaluate the actual effectiveness of AI tools in teaching and make adjustments based on feedback.
AI-TCK	I am able to combine AI technology with subject content to design more innovative teaching materials.
	I am able to use AI tools to generate teaching resources related to the subject (such as courseware, exercises, etc.).
	I am able to analyze complex problems in subject content through AI technology and help students better understand them.
AI-TPACK	I am able to organically integrate AI technology, teaching methods, and subject content to design efficient teaching plans.
	I am able to use AI tools to solve practical problems in subject teaching, such as students' understanding difficulties and low teaching efficiency.
	I am able to select and integrate suitable AI tools based on the characteristics of the subject to improve teaching effectiveness.
AI-EK (comprehensive evaluation)	I am able to flexibly apply various AI technologies to teaching practice and solve complex teaching problems.
	I am capable of designing innovative teaching models based on AI technology to drive changes in teaching methods.
	I can guide other teachers to integrate AI technology into teaching and share relevant experiences and strategies.

After the questionnaire design was completed, the author invited 5 experts familiar with AI-TPACK and KSAVE (Knowledge-Skills-Attitudes -Values-Ethics) to evaluate the rationality of the corresponding relationships in the questionnaire. Based on their suggestions, some indicators were modified and adjusted. Additionally, 5 teachers engaged in AI-assisted education were invited to participate in the Think Aloud protocol test, and some ambiguous expressions were modified and adjusted according to their suggestions, thus forming the final version of the questionnaire.

In the small-sample test, the author distributed 150 valid questionnaires (including 5% of respondents with AI teaching experience) at the National University of Defense Technology. The author used SPSS V23.0 to conduct Cronbach's alpha test on the questionnaire data that were effectively collected. The results show that the alpha coefficients of the four elements of AI literacy are all greater than 0.7 (CR coefficients of AI-EK, AI-EK, AI-EE, and AI-ET are 0.83, 0.88, 0.79, and 0.86), indicating good internal consistency of the questionnaire. The author also used SPSS V23.0 to conduct comprehensive validity tests on the questionnaire: KMO test and Bartlett test. The results showed that the KMO validity value was 0.921 (the closer the KMO value was to 1, the stronger the correlation between variables), and the Bartlett validity value was 0.001 ($p<0.05$, indicating significant correlation between variables). The results of the validity tests indicate that there are inherent connections between the various elements measured in the questionnaire, and it can effectively capture these connections with good structural validity.

The test of Discriminant validity matrix (correlation coefficient/ √AVE diagonal value) are shown in Table 5. The √AVE is greater than the correlation coefficient of the same row/column which meets the Fornell Larcker criterion. Small sample testing is qualified, and formal investigation can be conducted.

Table 5. The test results of the discriminant validity matrix

Dimension	AI-EK	AI-EA	AI-EE	AI-ET
AI-EK	**0.72**			
AI-EA	0.51	**0.78**		
AI-EE	0.43	0.39	**0.71**	
AI-ET	0.46	0.44	0.34	**0.76**

3. Analysis of teachers' AI literacy in vocational colleges in Hunan Province

3.1 Descriptive Analysis

The author distributed a total of 800 survey questionnaires to teachers in vocational colleges in Hunan Province, and collected 795 valid questionnaires, with a questionnaire collection rate of 99%. The overall status of respondents' AI literacy is shown in Table 6.

Table 6. Respondents' average scores in each element of AI literacy

Element	Average Score	Standard Deviation
AI-EK	3.12	0.82
AI-EA	3.01	0.81
AI-EE	3.67	0.72
AI-ET	4.00	0.58

The performance of the respondents in AI-EK is at a moderate level, and their performance in AI-EA is slightly lower than that in AI education knowledge. The large standard deviation of the above two indicators indicates significant differences between individuals. The reason may be that some teachers may be familiar with the teaching application of AI technology, while others may still be in the learning stage. The respondents scored high in AI-EE with a relatively small standard deviation, indicating that there is not much cognitive difference among teachers. The respondents showed the best performance in AI-ET with the smallest standard deviation, indicating that teachers generally possess strong AI education thinking and can think about the application of AI in education from the perspective of professional needs and the development of the times.

3.2 Influence of Individual Characteristics

In order to further evaluate the impact of relevant factors on the AI literacy of vocational college teachers, the author sorted out the average scores of teachers' AI literacy according to the disciplines, teaching positions, and professional titles of the respondents, as shown in Table 7.

Table 7. Average scores of AI literacy for different types of teachers

	Teachers	AI-EK	AI-EA	AI-EE	AI-ET
Disciplines	Sciences	3.18	3.02	3.72	4.03
	Humanities	3.06	3.00	3.62	3.97

Teaching positions	Teaching-oriented	3.20	3.16	3.74	4.09
	Research-oriented	3.04	2.86	3.60	3.91
Professional titles	Professor	3.12	2.50	3.55	3.90
	Associate Professor	3.15	3.21	3.75	4.02
	Lecturer	3.09	3.32	3.71	4.08

The results show that teachers in the field of sciences have slightly higher levels of AI-EK, AI-EE, and AI-ET than those in the field of humanities. Teaching-oriented teachers have higher levels of AI-EK, AI-EA, AI-EE, and AI-ET than those in research-oriented positions, indicating that teachers in teaching positions generally perform better in AI literacy. Lecturers perform the best in AI-EA and AI-ET; Associate professors perform the best in AI-EK and AI-EE; Professors have the weakest performance in AI-EA, AI-EE, and AI-ET. This implies that there is a certain degree of unsuitability among professors compared to other groups in terms of AI empowerment in higher education.

The author adopted an ANOVA analysis with the data from the questionnaire. Before conducting ANOVA analysis, we conducted normality and homogeneity of variance tests on the data. The Shapiro Wilk test results showed that all dependent variables (AI-EK, AI-EA, AI-EE, AI-ET) met the normality hypothesis (AI-EK: W=0.98, p=0.123; AI-EA: W=0.97, p=0.156; AI-EE: W=0.98, p=0.089; AI-ET: W=0.97, p=0.145). The Levene test results indicate that the hypothesis of homogeneity of variance between groups holds true (AI-EK: F=1.45, p=0.231; AI-EA: F=1.23, p=0.289; AI-EE: F=1.56, p=0.198; AI-ET: F=1.34, p=0.256). Therefore, the results of ANOVA analysis are reliable. ANOVA analysis results (as shown in Table 8) show that Disciplines has a significant impact on AI-EK and AI-EE. Teaching positions has a significant impact on AI-EK、AI-EA、AI-EE and AI-ET. Professional titles has a significant impact on AI-EA.

Table 8. The results of ANOVA analysis on Disciplines, Teaching positions and Professional titles

	Disciplines	**Effect**	**Teaching positions**	**Effect**	**Professional titles**	**Effect**
AI-EK	F = 4.56, p = 0.034	significant (p<0.05)	F = 5.78, p = 0.017	significant (p<0.05)	F = 0.89, p = 0.412	Not significant (p>0.05)
AI-EA	F = 0.12, p = 0.729	Not significant (p>0.05)	F = 6.45, p = 0.012	significant (p<0.05)	F = 5.67, p = 0.004	significant (p<0.05)
AI-EE	F = 3.89, p = 0.05	Not significant (p=0.05)	F = 4.12, p = 0.044	significant (p<0.05)	F = 1.23, p = 0.294	Not significant (p>0.05)
AI-ET	F = 1.23, p = 0.269	Not significant (p>0.05)	F = 7.23, p = 0.008	significant (p<0.05)	F = 2.34, p = 0.099	Not significant (p>0.05)

Although descriptive statistics show that science teachers generally score higher than humanities teachers in all aspects of AI literacy, the results of Cohen's t-test analysis (as shown in Table 9) shows that impact of disciplines on AI-EK are significant, but on AI-EA, AI-EE and AI-ET is not significant, which is consistent with the results of ANOVA. To explain this phenomenon, the author believes that it may be closely related to the knowledge structure and educational goals of different disciplines. Science teachers usually pay more attention to the cultivation of AI technology and scientific

knowledge, so they are more prominent in AI-EK. Humanities teachers may focus more on teaching practices in their fields, which results in their mastery of AI technology and technological knowledge being lower than that of science teachers.

Table 9. The results of Cohen's t-test analysis

	t	p	Cohen's d	Conclusion
AI-EK	2.13	p = 0.034	0.32	significant (p<0.05)
AI-EA	0.33	p = 0.729	0.05	Not significant (p>0.05)
AI-EE	1.96	p = 0.050	0.29	Not significant (p=0.05)
AI-ET	0.72	p = 0.269	0.11	Not significant (p>0.05)

Teaching positions has a significant impact on AI-EK、AI-EA、AI-EE and AI-ET, reflecting the comprehensive shaping effect of job responsibilities on it. Teaching-oriented teachers have to engage in extensive teaching practice, and their AI knowledge, application ability, AI ethics, and AI thinking have also been improved in long-term teaching practice.

Professional titles only have a significant impact on teachers' AI-EA, and have no significant impact on the other three aspects, which may be related to the teaching experience and professional abilities represented by the professional title. Associate professors and lecturers usually work on the front line of teaching and need to directly apply AI technology to classroom teaching, so they perform more outstandingly in AI application ability. In addition, their age advantage may make it easier for them to accept and master AI teaching tools and AI teaching concepts. The difference in professional titles does not have a significant impact on teachers' performance in AI-EK, AI-EE and AI-ET, as these dimensions rely more on teachers' skill training and teaching practices rather than the professional titles themselves.

3.3 Impact of External Factors

The author notes that in addition to factors related to the teacher's disciplines, teaching positions, and professional titles, there are also some external factors that may affect the evaluation results, such as whether the teacher has received AI skills training and whether his/her college has incentive policies.

The author found that among all 795 respondents, 281 teachers received specialized AI skills training, and their average scores in AI-EK, AI-EA, AI-EE, and AI-ET were 3.41, 3.35, 3.90, and 4.25, respectively; There are 514 people who have not received specialized AI skills training. Their average scores in AI-EK, AI-EA, AI-EE, and AI-ET are 2.83, 2.67, 3.44, and 3.75, respectively. On the issue of whether there is technical support or incentive policies, 349 teachers stated that they have received technical support or incentive policies provided by the school, their average scores in AI-EK, AI-EA, AI-EE, and AI-ET were 3.16, 3.23, 3.69, and 4.17; while 446 teachers stated that they have not received technical support and incentive policies, and their average scores in AI-EK, AI-EA, AI-EE, and AI-ET were 3.08, 2.79, 3.65, and 3.83, respectively. The author conducted a MANOVA on the two factors. Before conducting MANOVA analysis, we conducted multivariate normality, homogeneity of variance covariance matrix, and multicollinearity tests on the data. The results of the Mardia skewness and kurtosis tests show that the dependent variables (AI-EK, AI-EA, AI-EE, AI-ET) conform to the multivariate normality hypothesis (skewness statistic=1.23, p=0.287; Kurtosis statistic=2.45, p=0.134). The Box's M test results indicate that the hypothesis of

homogeneity of variance covariance matrix between groups holds (M=15.67, p=0.089). In addition, variance inflation factor (VIF) analysis showed that the VIFs of all dependent variables were less than 5, indicating that there was no serious multicollinearity issue among the dependent variables. Therefore, the results of MANOVA analysis are reliable. The MANOVA analysis result shows that AI skills training has a significant improvement effect on teachers' AI-EK, AI-EA, AI-EE, and AI-ET; Technical support and incentive policies have a significant improvement effect on teachers' AI-EA and AI-ET, but their impact on AI-EK and AI-EE is not significant. The interaction effect between the two is not significant (as shown in Table 10).

Table 10. The results of MANOVA analysis on AI skills training and support policies

Effect	F	P	Conclusion
AI skills training	24.56	0.0001	Significant
Support policies	9.87	0.0002	Significant
AI skills training × Support policies	1.12	0.345	Not significant

As external measures to improve teachers' AI literacy, the comprehensiveness and systematicity of AI skills training enable it to significantly enhance teachers' AI literacy in multiple dimensions; while technical support and incentive policies mainly play a role in application ability and teaching thinking through the supply of resources and motivation. Because technical support can provide teachers with necessary tools and platforms (such as AI teaching software, data analysis tools, etc.), enabling them to apply AI technology more efficiently. This resource support directly enhances the educational ability of teachers. Incentive policies stimulate teachers' exploration and innovation of AI technology through reward mechanisms such as teaching innovation awards, research funding, etc. This external driving force prompts teachers to constantly reflect on and optimize their educational models, thereby enhancing their innovative and forward-looking educational thinking. But the AI-EK of teachers needs to be accumulated through systematic learning and training, and the AI-EE of teachers needs to be achieved through learning, reflection, and practice. The improvement of these qualities cannot be achieved solely through technical support and incentive policies. This difference reveals the complementarity and limitations of different intervention measures in improving teachers' AI literacy, and also provides important references for designing and optimizing relevant policies and training in the future.

4. Conclusion and recommendation

The author conducted an empirical study on the AI literacy of teachers in vocational colleges in Hunan Province using the AI-TPACK model. This study found that personal characteristics of teachers (including disciplines, teaching positions, professional titles, etc.) and external factors (skills training and support policies) have an impact on teachers' AI literacy. In terms of personal characteristics, teaching positions have a significant impact on all four aspects of teachers' AI literacy. The AI literacy of teaching-oriented teachers is generally higher than that of research-oriented teachers. Disciplines have a significant impact on teachers' AI-EK, with Sciences teachers scoring significantly higher than humanities teachers. Professional titles only have a significant impact on teachers' AI-EA. Compared with other groups, professors have a significant gap in AI-EA. The author did not find the reason behind it, and one possible reason is based on age

speculation. As older people, they have more difficulty accepting and using advanced AI knowledge and tools than younger people. But whether this speculation is valid needs further research. In terms of the impact of external factors, this research finds that teachers who have received specialized AI skills training have significantly higher scores in all four aspects of AI literacy than those who have not received such training; Teachers from vocational colleges with technical support and incentive policies generally score higher in AI-EA and AI-ET than teachers from colleges without such support policies.

Based on such findings, the author proposes the following recommendations to enhance the AI literacy of vocational college teachers:

Firstly, strengthening AI skills training is crucial for improving teachers' AI literacy. According to Zhang Qun [15] and Wang Ming [7], vocational colleges should carry out the popularization of ethical norms knowledge in the application of intelligent technology education, and guide teachers to use intelligent technology to exert subjective initiative in the practical teaching process. Vocational colleges should also increase investment in AI skills training and design comprehensive training courses that cover basic theory, practical application, ethical education, and innovative thinking.

Secondly, optimizing technical support and incentive policies plays a significant role in enhancing teachers' AI literacy. As Liu Bin [4] and Zhang Yinrong, et al. [5] pointed out, support policies from universities can stimulate teachers' intrinsic motivation to improve their AI literacy. Vocational colleges should further improve technical infrastructure, providing teachers with convenient AI teaching tools and platforms. At the same time, they should establish special incentive policies, such as teaching innovation awards and research funding, to encourage teachers to actively explore the application of AI technology in education.

Thirdly, paying attention to disciplinary differences and individual characteristics is an important entry point for improving teachers' AI literacy. The ways to improve teachers' AI literacy with different characteristics are not the same, and universities should develop differentiated improvement plans for teachers' AI literacy based on individual characteristics (Huang Xiting, Huang Weirong, 2024). These improvement plans should vary according to the teacher's disciplines, teaching position, and professional title. Teachers in science and engineering can focus more on the cutting-edge development of AI technology, while teachers in humanities and social sciences can focus on the impact of AI technology on society and culture. Considering the differences between teaching-oriented and research-oriented teachers, the training content should be tailored accordingly. Teaching-oriented teachers can focus more on the application of AI technology in teaching, while research-oriented teachers can focus on innovative research in AI technology.

Finally, strengthening AI-EE and AI-ET training is an important supplement to improving teachers' AI literacy. Neglecting these two aspects will lead to a tendency towards educational technology, weaken the humanistic value and ethical orientation of education, ultimately resulting in a deviation from educational goals and a disconnect between talent cultivation and social needs [16]. Vocational colleges should integrate more content on ethical education and educational thinking into training and policies, helping teachers to deeply understand the ethical challenges and social responsibilities of AI technology, and cultivating their innovative thinking and critical thinking abilities, so that they can better cope with the educational changes brought about by AI technology.

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Digitalization and Management Innovation IV
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Comparative Analysis on the Digital Transformation Path of Education in the United States and France: Analysis Based on the Innovation Ecosystem Theory

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Abstract: The digital transformation of education has become the theme of the world's education reform. The United States and France attach great importance to the construction of ecosystems in the digital transformation of education, and the both have made remarkable progress in the digital transformation of education. The article constructs an analysis framework, based on the theory of innovative ecosystems, for analyzing the content digital transformation of education from macro, meso, and micro levels. It extracts the paths for the construction of digital ecosystems in education in both countries, including setting the value orientation of digital transformation in education, improving the technological ecological construction of digital transformation in education, and leveraging the role of the educational ecosystem.

Keywords: Digital transformation of education; Innovation ecosystem theory; Ecological construction

1. Introduction

1.1 Research background

In recent years, the digital transformation of education has gradually become a prominent theme both domestically and internationally. Numerous countries have recognized the importance of digital transformation in education for high-tech talents and national strategies, then successively launched digital strategies and plans. The United States started early in developing digital education. Since 1996, when the U.S. Department of Education (ED) implemented its first National Educational Technology Plan (NETP), it has released five national plans to date. And the latest version of the *National Education Technology Plan* was published in 2024. These national strategies have significantly accelerated its digital technologies and scientific innovation, ensuring America's leading position in the field of digital technology, safeguard economic prosperity and national security in the world. France is one of the early countries in the European Union to

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develop education digitization since the 1970s. In recent years, France's digital transformation of education has shown distinct characteristics among EU countries, especially in the aspect of systematic strategic layout, prioritization of ethical norms, technological integration and innovation, and data security protection. *The Education Digitalization Strategy for 2023-2027* of France released in 2023 proposed four major visions and sixteen actions, covering the full chain transformation from infrastructure to teacher and student capabilities. Analyzing the key content of digital transformation for education and pathway for developing ecosystem in the United States and France can provide useful insights and inspirations for the digital transformation in education for other countries.

1.2 Related works

The international comparative study of digital transformation in education aimed to enhance a global understanding of the development trends of digital transformation in education, reveal the mechanism and best practice, helping policymakers design more scientific, systematic, visionary plan and policies [1]. The related research in this field mainly focuses on two trends: one is to separately sort out the digital education strategies[2], action plans[3], and characteristics of policy in specific country [4], and deeply explore the value orientation of the strategy goals of one country's digital education transformation, the systematic linkage and effectiveness of strategic action plans, policy environment[5], as well as the summary of the achieved results and practical experience. This type of research usually focuses on the specific policy document of a country, such as policy evolution, policy implementation effects, etc. The division of responsibilities and collaborative linkage among different entities during the transformation process [6], how the government promotes the digital transformation of education through financial support, legislative frameworks, and public propaganda, etc. At the same time, the digital competence standards and evaluation methods of teachers, students, and technical personnel are also important research topics [7]. The second trend is the comparative analysis of the policies of two or more countries, focusing on the value orientation, understanding the effectiveness and adaptability [8] of different policies in the global diversified socio-economic environment, and the measures for challenges in the transformation. In terms of research perspective, scholars analyze the mechanism of digital transformation in education from the perspectives of social organization change theory [9], innovation ecosystem theory [10], and field theory, which focused on the content of digital transformation and agents' coordination. The U.S and France started its digitalization education early and both have made rapid progress in many aspects, but there is relatively little research on the comparison of the key content and pathway of the digital education ecosystem.

2. Research Methodology

2.1 Theoretical basis and analysis framework

The innovation ecosystem theory is a theoretical framework developed by synthesizing perspectives of ecology, systems science, and open innovation theory. It specifically elucidates the intricate relationships between innovation entities and their environmental

factors, organizational clusters, and information flows within an ecosystem-centric paradigm [11]. This conceptual framework can be analyzed through two key dimensions: the structural composition and operational mechanisms of innovation ecosystems. In structural composition, an innovation ecosystem comprises macro-, meso-, and micro-structural dimensions. At the macro-level, ecosystem construction emphasizes political, social, and economic developments pertinent to innovation entities, alongside governmental design. The meso-level primarily constitutes sociotechnical network spaces that facilitate innovation-supportive activities, while the micro-level centers on innovation entities' direct acquisition of resource allocation and developmental impetus from their immediate ecological niches [12]. In the operational mechanism, innovation ecosystems are formulated through interdependent dynamics and co-creative synergies among innovation actors, heterogeneous collectives, and informational components within open-system paradigms [13].

Guided by innovation ecosystem theory, the driving forces of educational digital transformation can be analytically deconstructed across three stratified dimensions:

- **Macro-stratum**: Encompasses government-mandated developmental goals and strategic priorities articulated through top-level institutional designs.
- **Meso-stratum**: Involves systemic mechanisms for educational data governance and optimized resource provisioning architectures.
- **Micro-stratum**: Focuses on cultivating teacher-student digital literacy competencies and engineering context-aware digital learning ecosystems.

Critically, educational digital transformation necessitates multidimensional integration of heterogeneous stakeholders, emergent digital technologies, infrastructure, and pedagogical systems, establishing foundational substrates for sustainable innovation ecosystems.

Building upon the principles of the theory, the study develops the framework for analyzing digital transformation of education:

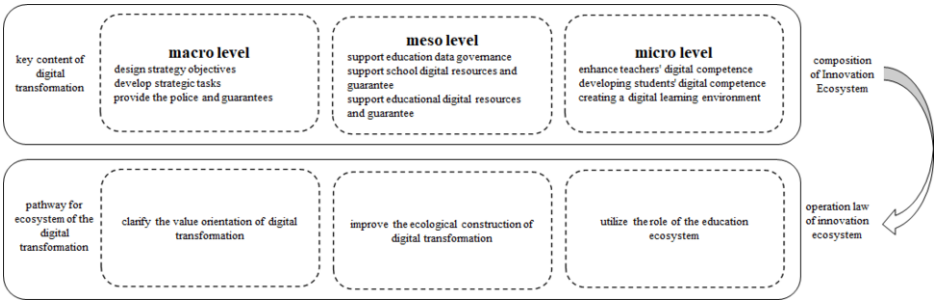


Figure 1. the framework for the digital transformation of education

2.2 Research contents and questions

This research was a comparative analysis of the national strategic plans for digital transformation in education between the United States and France, examining cross-national divergences and convergences through tripartite analytical lenses. The comparison has been made mainly based on the digital strategy or plans of the two countries. The main research content concerns the following three aspects:

(1) Macro-strategic Dimension: Comparative examination the strategy objective of digital education policy and implementation roadmaps; Institutional alignment with

national innovation ecosystems.

(2) Meso-institutional Dimension: cross-country benchmarking of educational data governance frameworks; resource allocation mechanisms and public-private partnership models.

(3) Micro-implementation Dimension**:** learning ecosystem architecture and digital infrastructure deployment patterns; teacher-student capacity building paradigms in digital pedagogy.

Based on the research content, the following two specific questions were explored:

(1) What differences and similarities exist in the key content of digital transformation of education between the U.S and France?

(2) What differences and similarities exist in the pathway for digital education ecosystem development between the U.S and France?

2.3 Document selection

This study employs qualitative content analysis, specifically using thematic analysis method to analyze the similarities and difference in the digital transformation of education in the U.S. and France. The thematic analysis was chosen as the primary method due to the nature of the research materials. Data was collected from a variety of official sources, and the process began with identifying key documents, then expanding the pool of sources based on references within these texts. The data sources include publications and policy documents, official government reports from the website of Federal Government, Ministry of Education in the U.S. and France.

The following criteria was set for the document selection: (1) the latest strategy or plans of educational digital transformation in the U.S and France. (2) all the policy texts were selected from the official websites of the Government, Ministry of Education of the U.S. and France. (3) the selected policy documents centered the theme on the digital transformation in education. (4) the chosen policy documents were the most representative and timely (2020–2025) in the field of digital transformation in the two countries.

The collection of policy documents in the study was primarily searched through keyword searches (“digital transformation of education” “educational ecosystem” etc.) on official government websites including national education ministry and parliamentary portals. A total of 4 policy documents were collected and organized, among which the main document was the national strategy of the two countries, the U.S. *National Education Technology Plan (NETP 2024)* [14] and France’s *Education Digitalization Strategy for 2023-2027* [15]*,* the other two supplementary policy texts were the U.S. *Digital Strategy (2020-2024)* and *France 2030 Strategy.*

2.4 Document coding process

All the document materials in the study were processed and analyzed in the following coding procedures.

(1) Getting familiar with the document: quickly read through the entire text to gain an initial understanding of its general content and subject.

(2) Determining the category: define the coding categories to identify the key content of the digital transformation in education and the pathway of digital ecosystem for transformation based on the framework (Figure 1).

(3) Establishing coding rules: clarify the specific codes and definitions for each

coding level. For example, at the macro level, use "S" to represent strategic goals and "P" to represent the development vision; at the meso level, use "R" to represent policy regulations and "F" to represent financial support; at the micro level, use "T" to represent digital technology resources, "E" to represent educational resources, "TC" to represent the improvement of teachers' digital literacy and capabilities, and "SC" to represent the improvement of students' digital literacy and capabilities.

(4) Pilot coding: select one policy text for initial coding to test and refine the coding rules. During this process, negotiate any issues or ambiguities encountered, such as unclear code definitions or overlapping coding scopes, and revise the coding rules accordingly.

(5) Formal coding: following the finalized coding rules, conduct a comprehensive and systematic coding of all policy texts.

(6) Contextual analysis: the categorized themes were analyzed and synthesized within the historical, political and economic contexts of the U.S and France.

(7) Summarization and interpretation: the final step involved summarizing the essential content from the analyzed documents, and the comparative analysis were made at three levels and further interpreted according to the principles of the Innovative Ecosystem Theory.

This study employed double-blind coding by two coders for pre-coding tests. It also tests the inter-rater reliability of the two pre-coding results to ensure coding consistency. In this study, the Kappa coefficient for the policy tool dimension is 0.86, and for the policy goal dimension, it's 0.91, showing high coding reliability. Then, the two coders formally code all policy analysis units, and the credibility of the policy analysis coding results was reliable.

3. Research Results

3.1 Similarities and Differences in the content of Digital Education Ecosystem Development Between the United States and France

3.1.1 Macro level comparison: the key content of digital transformation

From a macro perspective, the goal of digital transformation in education is centered on better ensuring students' survival and development in the digital age. The government should consider its local development situation and various challenges faced by the education system, thus designing the proper goal of digital transformation for education. The United States and France share significant similarities in key content of digital transformation for education, that is, the two governments have formulated ecosystemic strategic goals based on the development priorities and challenges encountered in their domestic educational digitalization, implementing actions and optimizing the coordination mechanism to advance systemic transformation. The U.S. addressed persistent issues of digital divides hindering educational equity, set the goal of "leveraging technology to realize a national learning vision where ubiquitous, anytime-anywhere learning becomes possible" [14]. France, meanwhile, focuses on "improving the digital education ecosystem, enhancing digital competencies, building a digital education community," and "ensuring success for all students" as its core mission of digital transformation in education [15].

The strategic tasks and goals of digital transformation in education share a mutually reinforcing relationship. Defining these goals requires not only sensitivity to current societal shifts, foresight, and visionary imagination but also a systematic approach to designing the strategic tasks that drive the transformation. The United States has implemented 34 actions to systematically bridge digital divides in access, design, and usage, providing comprehensive solutions for its educational transformation. *France's 2023-2027 digital education strategy* is undertaken within the framework of *France 2030*, a EUR 54 billion cross-sector investment plan. This plan guided the actions in the digitalization of the education system at all levels, outlined 16 key initiatives, including establishing a "digital commons," creating "resource accounts," and scaling digital services, to build an open public policy ecosystem that ensures equal opportunities [15]. The formulation of strategic actions not only aligned with the development goals of digital transformation but also catalyzed cross-sector collaboration and multi-stakeholder coordination, fostering a resilient ecosystem for advancing digital transformation in education [4].

In the aspect of coordination mechanism, the U.S. and France involved governments, schools, and private sectors and other entities. The U.S. clarified institutions' responsibilities, updated funding mechanisms. In 2023, the Office of Education Technology released guidance and future directions for federal funding and support of the educational technology landscape，infrastructure, Intranet servers and digital devices. France, in *the Digital Work Environment* initiative in 2022, a national collaborative platform was proposed to construct to align central and regional governance. While the government of the two countries emphasized multi-tier coordination, the U.S. prioritized equitable decentralization through market-ecosystem synergies, whereas France emphasized centralized ecological integration, balancing digital sovereignty with sustainability. This contrast highlights their divergent focal points—equity-driven solutions in the U.S. versus ecological-systemic coherence in France.

3.1. 2 Meso-Level comparison: Educational Resource Provisioning and Data Governance

At the meso level, it is vital to prioritize establishing collaborative governance ecosystems involving governments, markets, schools, and communities to develop educational resources, promote equitable distribution and sharing. The U.S. federal government enhanced the educational data governance through policies and financial support for ed-tech enterprises, encouraging market entities to serve school digitization through competition and collaboration. France's Digital Education Directorate (DNE) managed information systems coordinated public-private partnerships between government agencies and educational stakeholders, and oversees cybersecurity through a dedicated platform [10].

Regarding the digital resource development and supply, the U.S. created scaling open educational resources (OER), elevating state-level digital textbook into national programs. The states developed OER tailored to local needs, supported by federal funding and quality review systems. The federal "Go Open" initiative employs metadata management technologies to aggregate resources co-developed by schools and enterprises, ensuring quality through user ratings and expert audits. France supports device procurement through programs like "Connected Schools" and fosters institutional innovation to enable personalized student development [14].

In the mechanisms of resource provisioning, the U.S. promoted equity and efficiency by optimizing resource allocation, engaging private stakeholders, and advancing policy-backed research. Developing evaluation standards for digital resources was to ensure the alignment with Universal Design for Learning (UDL) principles and instructional goals. France's DNE coordinated between ministries and schools, managing teacher "resource accounts" and student device distribution. Local governments and schools lead interoperable platforms for cross-regional resource sharing, while private suppliers delivered context-specific digital services.

Despite the similarities mentioned above, some differences existed. the U.S. promoted market-driven innovation, developed cutting-edge technologies, and implements the decentralized governance, which allows states and districts flexibility in implementation at the macro level. Whereas France prioritizes centralized governance and social equity.

3.1.3 Micro Level comparison: the promotion of teachers and students' digital competency

At the micro level, teachers and students need to enhance their digital competence to adapt to the development of digital education. The United States and France prioritized enhancing teachers' and students' digital literacy, constructing the digital learning environments. Three core dimensions of digital competences for teachers were outlined in NETP 2024 of the U.S. [14], which depicted the universal technical standards and provided on-demand teachers' professional development programs, embed generative AI technologies throughout teacher training. France emphasized domain-specific digital pedagogies and responsible digital citizenship, requiring teachers to master innovative teaching methodologies, and critically evaluate educational resources.

For students' digital literacy, the U.S. NETP established comprehensive K-12 students' competence profiles, such as critical thinking, problem-solving, communication, and digital fluency. Teachers promote students' agency by integrating technology to inquiry-based learning, fostering their self-regulation. Feedback mechanisms identify learning gaps, enabling targeted interventions to enhance engagement and collaborative learning roles. France facilitated the use of common standards of students' digital competence, and the use of education data for research in compliance with strict data protection laws. In addition, the Ministry of Education cultivated all stakeholders' digital literary by offering professional development opportunities and establishing specific standards for teachers training and the Age-specific training for students [15].

As a key part of the education ecosystem, the evolution of the micro digital learning environment drives the entire system's co-evolution. The U.S. prioritizes ubiquitous connectivity through infrastructure upgrading to ensure equitable access to devices and cloud-based tools aligned with Universal Design for Learning (UDL) principles. France has implemented series of actions including optimizing infrastructure construction, improving network connectivity, and providing personal digital devices for teachers and students. "Éléa" Plate Form can meet personalized learning pathways with adaptive content, and nationwide initiatives "Connected Schools" will be established for cybersecurity training. And other actions include protecting student data security, strengthening network security education for teachers and students, cultivating their awareness of digital security. These differences in micro digital learning environment between the U.S. and France reflect broader socioeconomic priorities, with the U.S.

aiming for global tech leadership and France balancing inclusivity and sustainability

3.2 The shared Pathway for Digital Education Ecosystem Development

3.2.1 Clarifying the value orientation of digital transformation in education

According to the theory of innovation ecosystem, to achieve the goal of value co-creation, multiple innovation agents are required to share the common value and vison orientation, responsibilities and resources, ensuring the digital transformation of education moves in the right direction. In the process of digital transformation in education, the U.S. and France have taken actions at macro level of nation's political and economic factors. They have innovated training models for digital talent, comprehensively improved students' digital skills, met the social demand for digital talents through national development strategies. In terms of politics, both countries believe that digital sovereignty is a vital element of a country's sovereignty, and strengthening the digital transformation of education is a direct road to preserving its digital sovereignty.

At the meso level, the two countries have attached great importance to equity, digital security, and artificial intelligence in the development of digital education, and has encouraged all the stakeholders to participate in policy formulation, digital resource and experience to form a joint effort to promote the achievement of educational digital transformation.

At the micro level, the inclusiveness of digital education, accessibility, and high-quality of digital resources are all key content for the United States and France. The two countries are concerned about low-income and ethnic minority groups' digital learning needs, to move the digital transformation of education towards fairness and personalization.

3.2.2 Improving the technological ecosystem construction

Based on the principle of Innovation Ecosystem Theory, an innovation ecosystem possesses a hierarchical structure, where different levels of ecosystems collectively provide environmental support for the development of innovation entities. The core dynamic sustaining the operation of the entire system lies in the mutual interdependence and collaborative co-creation between various parties and informational elements. [13] In promoting the digital transformation in education, it has become a consensus among decision-makers to create an ecological chain of government, enterprises, schools, and society that collaborates, co creates, and mutually benefits in the U.S. and France. At the macro level, the two countries have coordinated education governance mechanisms involving multiple stakeholders like the Ministry of Education, local governments, third-party organizations, and school districts. They attach importance to the participation and cooperation of various stakeholders in the digitalization of education, fully leveraging the power of various participating entities and social resources to provide students with diverse and personalized learning experiences. By establishing institutional coordination mechanisms and robust structural frameworks, the two countries have effectively mitigated role ambiguity and implementation misalignment in cross-sector collaboration. And these mechanisms ensure the realization of digital transformation objectives in education and the seamless execution of strategic tasks.

At the meso level, the United States innovated its digital governance approach by building a technological ecosystem to achieve the construction of digital bases, platforms,

and applications. France encouraged diverse entities including enterprises, technology companies, and digital suppliers to collaborate and participate extensively in education data governance, digital education resource supply, and the development of open digital education platforms, enabling multiple stakeholders to achieve easily read and convenient access. France also proposed to establish a specialized governance agent to coordinate the construction of digital infrastructure and strengthen monitoring of relevant administrative departments, to optimize student and teaching management, improve the efficiency of school digital transformation, and gradually implement digital ecological accountability .

At the micro level, both the United States and France have provided abundant resources through various public online platforms, developing a nationwide sharing platform for teachers and peers across the country, to collaborate and promote specific tools and resources. Inclusive education has been supported to enhance the coverage of educational resources, ensuring students with special educational needs can benefit from it.

3.2.3 Leveraging the role of the education ecosystem

Leveraging the dynamic mechanisms of educational ecosystem can effectively advance digital transformation. The U.S. and France have actively constructed a technology ecosystem, encouraging multiple stakeholders to provide the required software/hardware infrastructure, digital resources, and data services. The two countries place great emphasis on effective communication, coordination, and sharing among educational groups and their stakeholders related to individual learner development, optimizing the structure and collaborative mechanisms of the education ecosystem. Through institutional frameworks, they regulate the participation of diverse entities in technology development and application. This multi-stakeholder collaborative engagement surrounding technological systems strikingly aligns with the core principles of the Innovation Ecosystem Theory regarding dynamic interaction and co-creation mechanisms.

At the meso and micro level, digital learning environment and resources supply can achieve the rational allocation and optimization of educational resources, also impact macro-level elements like educational policies and assessment, driving the whole education system towards digitalization and intelligence, and enabling the system's overall transformation and upgrading. The United States and France supported innovation, research, and development through a host of partnerships among government officials and academic research centers, EdTech firms, and educational actors, attached great importance to the use of learning management systems to facilitate teachers' better understanding of students' learning situations, provide learning support, offer personalized learning paths for students, and meet the learning needs and interests of different students, as well as empowering teachers and students with digital technology, to enhance their digital literacy, innovation ability, and critical thinking ability.

4. Conclusion

This study conducts a thorough comparative analysis of the key content and pathway for the formation of the digital education ecosystem. The results show that the U.S and France share more similarities at three levels of digital transformation in education. The

two countries have made national strategy plans and goals for digital transformation, though the value orientations and actions were of little difference. And the two Governments launched a series of policies and provided large amount of funds for infrastructure construction, resources developing and sharing, platform construction and application. Teachers and students' digital competence were the concern of the two countries, and specific training embedded AI technology was provided. The experiences of the US and France in the digital transformation of education offer important references for other nations.

However, there are still deficiencies in the interpretation of operational mechanism and interdependent dynamics among the U.S. and France's innovation actors, and heterogeneous collectives. Future work should focus on the mechanism of different stakeholders' coordination, and the role of educational ecosystem in the integration of digital transformation.

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AI in Math Education: Shifting the Balance Toward Student Empowerment

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Abstract. This study explores the shifting teacher-student dynamics in AI-enhanced mathematics classrooms, focusing on the intersection of student empowerment, instructional clarity, and the evolving role of teacher authority. Utilizing positioning theory and critical pedagogy as analytical frameworks, this paper emphasizes the tension between teacher intentions and student perceptions about autonomy, support, and instructional clarity. While teachers often view GenAI as a means to encourage independent learning, students continue to seek structured guidance and personalized feedback. The findings indicate that effective integration of ChatGPT necessitates intentional scaffolding, clear instructional design, and a redefinition of teacher authority to position AI as a collaborative partner rather than a replacement. The study also highlights challenges related to teacher readiness, digital equity, and ethical AI use, providing recommendations for professional development, inclusive access, and further research into the long-term impacts of GenAI in mathematics education.

Keywords. AI-enhanced learning, Mathematics education, Teacher-student dynamics, Positioning theory, Instructional scaffolding

1. Introduction

Mathematics education is essential for academic achievement and societal advancement in an era increasingly defined by complexity and digital transformation [1]. However, traditional teaching models often feature teacher-dominated structures that limit student participation and engagement [2,3]. This can reduce learner autonomy, stifle creativity, and worsen inequities, especially among historically marginalized groups [4,5].

In many classrooms, students are often passive recipients of knowledge, which hampers critical thinking and reduces their ownership of the learning process [6]. This top-down approach prioritizes compliance over inquiry and standardization over diversity [7]. Recent calls for educational reform emphasize the need for inclusive, participatory learning environments that value student voice, agency, and identity [8,9]. Generative Artificial Intelligence (GAI), such as ChatGPT, offers a unique opportunity to rethink traditional classroom power dynamics. By providing personalized feedback, differentiated content, and collaborative interactions, GAI can redistribute epistemic authority and promote equitable learning environments [10,11, 12]. However, empirical research on the impact of AI on authority relationships in mathematics education remains

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limited [9, 13, 14]. This study investigates the potential of AI to shift teacher-student dynamics and foster participatory, student-centered mathematics instruction [15, 16].

1.1. Statement of the Problem

The hierarchical frameworks of the conventional teacher-centered model in mathematics education hinder student empowerment and perpetuate unequal learning experiences, highlighting the need to explore how GAI can redistribute classroom authority and foster active student engagement. This study examines:

(1) What strategies do teachers use to leverage AI tools to promote student agency in mathematics learning?
(2) How do teachers and students perceive power dynamics in the math classroom when AI technologies are introduced to support student empowerment?

2. Theoretical Framework

2.1. Critical Pedagogy and Artificial Intelligence

Freire's critique of the "banking model" of education frames traditional instruction as a top-down transmission of knowledge that limits learner agency and reinforces asymmetrical power structures [3]. In contemporary classrooms mediated by artificial intelligence (AI), this dynamic re-emerges through algorithmic decision-making that risks reproducing, rather than disrupting, existing educational inequities.

2.2. Risks in AI-Mediated Classrooms

The integration of AI tools in education is far from neutral. Large language models and adaptive learning systems frequently reproduce the biases present in their training data. Studies have shown, for instance, that these systems can reinforce gender stereotypes, such as assigning less challenging math problems to female students based on historical patterns in the data [9]. Beyond bias, the growing reliance on learning analytics promotes a form of "surveillance pedagogy," where behavioral monitoring takes precedence over deep cognitive engagement [14]. These issues highlight the need for critical scrutiny when implementing AI in educational settings.

Within a critical constructivist framework, the reliability of AI—especially in mathematics—becomes a major concern. Mathematical reasoning demands precision, yet generative AI tools like ChatGPT often produce incorrect proofs, misapply logical steps, and generate flawed simplifications [16, 17]. Despite these shortcomings, students frequently display an uncritical trust in AI outputs. For example, a student might say, *"It shows me where I went wrong so I can fix it myself,"* implying self-correction while also assuming the tool's infallibility. This unchecked reliance risks fostering passive learning habits, where students accept algorithmic answers without questioning their validity.

To counter this, educators must cultivate a *pedagogy of skepticism*—one that treats AI as a fallible tool rather than an authoritative source. Teachers play a crucial role in mediating AI interactions by validating outputs against mathematical standards, contextualizing errors within broader concepts, and guiding students to interrogate AI-generated reasoning. Without this structured support, students may mistake technical

efficiency for true understanding, replacing intellectual autonomy with dependency on flawed systems.

Ultimately, AI should not be seen as a definitive problem-solver in mathematics but as a starting point for critical discussion. By teaching students to recognize AI's limitations—and equipping them with strategies to challenge and correct its mistakes—educators can transform generative AI into a tool that strengthens, rather than undermines, mathematical reasoning and independent thought.

2.3. Designing AI for Emancipatory Practice

Despite these risks, AI can also serve as a vehicle for critical pedagogy when designed and implemented thoughtfully. Tools that support dialogic interaction—such as those prompting students with questions like *"Why might this solution fail in a real-world context?"*—mirror Freirean "problem-posing" education and promote reflective reasoning [10]. Recent empirical findings indicate that students engaging with such AI interfaces demonstrate significant increases in critical questioning behavior, suggesting the potential for cognitive empowerment [16].

Moreover, when students are involved in AI development processes, they shift from knowledge consumers to producers. This approach not only contextualizes learning but also supports epistemic justice, enabling students to challenge dominant forms of knowledge production [17].

2.4 Constructivist Foundations and AI Scaffolding

Vygotsky's Zone of Proximal Development (ZPD) provides a constructivist framework in which AI can act as a supportive tool for learning mathematics [18]. Within the ZPD, learners transition from needing assistance to achieving independent performance, and AI systems can provide timely and adaptive support. However, it is essential to manage this support carefully to ensure that it enhances, rather than replaces, students' reasoning abilities. Table 1 presents a taxonomy of AI scaffolding that aligns with the ZPD.

Table 1. A Taxonomy of AI Scaffolding Aligned with ZPD

Scaffold Type	AI Implementation	Teacher's Role	ZPD Connection
Conceptual	AI generates step-by-step explanations for mathematical proofs	Curates counterexamples to induce cognitive conflict	Matches explanation depth to learner's current understanding.
Metacognitive	AI error analysis identifies recuring mistake patterns in student work	Guides reflective journaling ("Why do you think the AI flagged this?")	Develops awareness of thinking processes beyond immediate correction.
Social	AI algorithms optimize heterogeneous group formation	Facilitates collaborative roles such as "AI Validator" or "Real-World Connector"	Extends learning through structured peer interaction.

Table 1 shows that the teacher's role is central in interpreting AI output and guiding students to engage critically with it. Since AI can produce incorrect results, especially in mathematics, explicit instruction in epistemic vigilance is essential. In this way, AI serves not just to provide answers but to facilitate cognitive struggle and conceptual growth.

2.5. Toward a Framework of Critical Constructivism

Synthesizing critical pedagogy with constructivist theory yields a model of *critical constructivism*, wherein AI is positioned not as a neutral tool or instructional authority, but as a participant in dialogic processes of knowledge co-construction. This framework emphasizes two interrelated dimensions. First, power analysis invites students and teachers to critically interrogate the epistemic assumptions embedded in AI systems, posing questions such as: "What assumptions does this model make?" and "Whose perspectives are excluded?" [19]. Second, co-construction of knowledge frames AI outputs as provisional rather than authoritative, subject to critique, debate, and refinement. In practice, this occurs through collaborative discourse in which students compare and evaluate AI and human generated solutions, fostering deeper understanding and cultivating mathematical agency [20].

2.6. Student Empowerment in Mathematics Education

Educational empowerment involves cultivating agency, reflection, and shared epistemic responsibility [14,15]. In mathematics education, it is crucial for learners to achieve procedural fluency while developing confidence in their reasoning and interpretive skills [16,17].

According to Mezirow's model of transformative learning [18], empowerment is fostered through reflective dialogue and interaction with diverse perspectives [14]. Group discussions and peer feedback create a supportive classroom culture, encouraging students to question authority—both algorithmic and otherwise—and build independent mathematical understandings [19, 20].

AI in education should aid these empowerment goals; when students passively accept AI-generated outputs, they undermine constructivist and critical pedagogies. Teacher mediation is vital for fostering critical thinking and meaningful engagement with mathematics in an AI-driven context.

3. Research Methodology

This study employed a qualitative research design to examine power dynamics and student empowerment in mathematics classrooms utilizing by Generative Artificial Intelligence (GAI). The interpretive approach aimed to capture participants' lived experiences and meaning-making processes within AI-integrated educational settings.

3.1. Participants

The study included six secondary mathematics teachers and twelve students (ages 14–18) from three urban public schools, selected to represent diverse socioeconomic and academic backgrounds. Teachers were recruited based on their willingness to integrate AI tools into instruction and their varying years of experience (2–15 years). Students were chosen through purposive sampling to reflect a range of achievement levels (struggling, average, and high-performing) and prior exposure to educational technology.

3.2. Data Collection

To ensure methodological triangulation and data richness, multiple qualitative techniques were utilized:

Teacher interviews, which were semi-structured interviews, explored pedagogical strategies, perceptions of GAI, and its impact on student participation and authority dynamics. A sample question included: *"Can you describe a moment when AI influenced how you responded to a student's mathematical reasoning?"*

Student focus group discussions (FGDs) were used to capture students' perceptions of empowerment, agency, and collaboration in AI-integrated learning environments. Dialogic questioning encouraged collective reflection and debate. A representative question was: *"How do you decide whether to trust the answer that the AI gives you in math tasks?"*

All interviews and FGDs were audio recorded with participant consent, supplemented by field notes to contextualize non-verbal cues and classroom dynamics.

3.3. Data Analysis

Data were analyzed using an inductive-deductive thematic analysis approach [21]. Transcripts were read repeatedly to develop familiarity. Codes were initially generated inductively from participants' language, focusing on expressions related to authority, trust, decision-making, and AI interaction.

To identify the themes, codes were then clustered into conceptual categories. Some categories aligned with the theoretical framework (e.g., *critical agency*, *epistemic authority*), while others (e.g., *overreliance on AI*, *peer correction of AI mistakes*) emerged directly from participant discourse.

After this, categories were refined into themes through iterative analysis. Themes represented shared patterns of meaning across participants and were used to structure the findings tables. The grouping of responses under each theme followed specific criteria: semantic similarity, contextual alignment with the research questions, and recurrence across at least two participant subgroups.

Finally, to ensure trustworthiness, member checking was conducted with four participants (two teachers, two students) to verify the accuracy of thematic interpretations. Additionally, inter-coder reliability was ensured through joint analysis sessions with an independent qualitative researcher, resulting in over 85% agreement on code assignment.

3.4. Ethical Considerations

The study received ethical clearance from the university's institutional review board. Participants were informed about the study's aims, procedures, and their right to withdraw at any stage without penalty. Written informed consent was obtained from all participants and guardians of students under the age of 18. Anonymity and confidentiality were maintained by assigning pseudonyms and securely storing all data in encrypted files.

4. Results and Discussion

Using a framework of critical pedagogy, constructivist learning theory, and student empowerment, the results and findings of the study highlight how AI affects classroom power dynamics and question traditional teaching methods. The analysis examines whether these practices uphold or challenge conventional models of learning.

4.1 Strategies used by teachers leverage AI tools to promote student agency

Teachers in the study used AI as a pedagogical tool to enhance student autonomy, metacognition, and collaboration, resulting in five interconnected strategies outlined in Table 2.

Table 2. Strategies used by teachers to leverage Ai tools to promote student agency

Theme	Description	Teacher Utterance	Student Utterance
Personalized Learning	AI adapts tasks to each student's level, allowing self-paced learning.	"The AI adjusts difficulty, so students stay challenged."	"It gives me different questions than my friend—I like working at my own pace."
Real-Time Feedback	AI gives instant feedback, supporting independent error correction.	"They don't need to wait for me—AI helps them keep going."	"It shows me where I went wrong so I can fix it myself."
AI-Facilitated Inquiry	Students use AI chatbots to explore problems before asking the teacher.	"I tell them to check with the AI first—it builds confidence."	"I use the AI to explain things before asking the teacher."
Data-Driven Reflection	AI dashboards help students track progress and set goals.	"They review their data and decide what to work on."	"I saw I needed help with ratios, so I practiced more."
Collaborative Problem Solving	Groups use AI tools to test ideas and support teamwork.	"AI simulations spark group discussion and decisions."	"We used AI to compare answers and decide what worked best."

The AI-facilitated inquiry strategy revealed a fundamental pedagogical tension. When teachers framed chatbots as catalysts for exploratory reasoning (e.g., "Compare your solution to the AI's"), they aligned with Freirean problem-posing education [20]. However, when reduced to fact-checking tools, they reinforced passive knowledge consumption - what Freire termed the "banking model" [20]. This dichotomy manifested clearly in student statements like "I use AI to explain things first," where agency depended on subsequent teacher mediation through questions like "What limitations might this AI explanation have?"

Similarly, data dashboards created contradictions in agency construction. While theoretically enabling Biesta's "subjectification" [2], in practice they often reduced reflection to metric-chasing unless teachers intervened with critical framing questions. Efficiency-focused implementations exacerbated these issues, using adaptive algorithms for individualized instruction without discursive problematization - what Freire warned against as technocratic depoliticization [20]. Opaque AI systems further compounded digital inequalities through undisclosed biases and access disparities.

These findings necessitate intentional epistemic mediation. Successful implementations positioned AI outputs as hypotheses requiring collective scrutiny (e.g., through "Algorithm Auditor" roles [22], transforming AI from authoritative source to

contested artifact. Without such mediation, AI risks becoming a neoliberal "banking" tool, delivering personalized yet pre-packaged knowledge.

4.2. Perceptions of Power Dynamics in AI-Mediated Classrooms

The integration of GAI has notably altered perceptions of authority and participation in the mathematics classroom (see Table 3).

Table 3. Teachers and Students' Perception of Power Dynamics

Themes	Description	Teachers' Utterances	Students' Utterances
Shifting Power Dynamics	AI redistributes authority, encouraging student autonomy.	"AI lets students take more control of their learning."	"AI gives me a voice in how I learn."
Collaboration and Interaction	AI promotes teamwork and problem-solving among students.	"Group work with AI enhances collaboration."	"Working with peers on AI tasks deepens my understanding."
Enhanced Engagement	Interactive AI tools increase motivation and participation.	"AI simulations grab students' attention."	"AI makes math more fun and less scary."
Equity Concerns	Risks include unequal access and potential bias reinforcement.	"We must ensure fair access to AI tools."	"Not everyone has the same tech access—it's unfair."
Shifting Power Dynamics	AI redistributes authority, encouraging student autonomy.	"AI lets students take more control of their learning."	"AI gives me a voice in how I learn."
Collaboration and Interaction	AI promotes teamwork and problem-solving among students.	"Group work with AI enhances collaboration."	"Working with peers on AI tasks deepens my understanding."

Participants reported noteworthy changes in the redistribution of epistemic authority, with teachers stepping back from their roles as "knowledge holders" and students gaining more control over their learning paths. While this shift aligns with Freire's emphasis on dialogue and shared authority, it raises a critical question: To what extent is authority genuinely shared if students uncritically accept AI-generated answers?

Many students expressed trust in AI outputs, stating comments like, "It shows me where I went wrong so I can fix it myself." While this trust can be empowering, it poses risks, especially in subjects like mathematics, where AI tools can produce incorrect solutions [4]. The lack of teacher guidance in addressing these errors might merely replace one unquestioned authority (the teacher) with another (the AI).

In classrooms that emphasized critical reflection, students not only used AI tools but also evaluated them critically, comparing suggestions and questioning inconsistencies. This approach exemplifies critical constructivism, where learning is collaboratively built through negotiation and critique [22, 23].

Equity concerns were also highlighted, with disparities in access to AI tools outside of school resonating with broader critiques of algorithmic injustice and digital exclusion [10, 11, 12]. Without targeted efforts to address these disparities, AI may worsen existing educational inequalities while being promoted as an innovative solution [24]. Ultimately, how much authority is truly shared if students rely unquestioningly on AI-generated answers?

5. Conclusion

When critically integrated into mathematics classrooms, AI can support student agency and disrupt traditional power dynamics. However, its pedagogical value is not intrinsic but contingent on intentional, reflective mediation by educators. Findings suggest that AI tools—used for personalization, feedback, inquiry, and collaboration—can enhance learning, yet also risk fostering uncritical dependence without appropriate scaffolding.

Methodologically, the study's limited sample size and context constrain generalizability, while conceptually, some student responses reveal overreliance on AI's accuracy, especially in mathematics, highlighting the need for greater emphasis on epistemic vigilance and teacher facilitation.

Future research should pursue three key areas. First, longitudinal studies are needed to examine whether empowerment through AI is sustained over time and across mathematical domains. Second, cross-cultural research would illuminate how contextual factors shape AI integration. Third, participatory models - where teachers and students co-construct AI usage - should be explored to align practice with critical and constructivist pedagogies.

Ultimately, AI must be positioned not as a substitute for pedagogical judgment but as a dialogic partner in learning. As classrooms evolve, so too must our frameworks - ensuring that AI integration remains ethically informed and educationally empowering.

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The Influence of Learning Motivation on Learning Outcomes in Ideological and Political Education: Mediating and Moderating Mechanisms

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Abstract. Aiming to enhance the quality of college students' ideological and political education courses, this study investigates the relationships among learning motivation, learning approaches, teacher-student relationships, and learning outcomes in course engagement. Using the CCSS questionnaire, valid samples were collected from 1670 college students in their study of ideological and political courses, and statistical analysis methods such as hierarchical regression analysis were employed to analyze the sample data.. Results indicated that: (1) Both intrinsic and extrinsic motivation directly improved ideological education outcomes, with intrinsic motivation demonstrating greater explanatory power; (2) Learning approaches mediated the motivation-outcome relationship; (3) Teacher-student relationships positively moderated the motivation-outcome association. The research findings offer practical guidance for enhancing the teaching practices of ideological and political courses in colleges and improving the quality of student learning.

Keywords. Ideological and Political Education in Higher Education; Learning Motivation; Learning Strategies; Teacher-Student Relationships; Learning Outcomes

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1. Introduction

Enhancing ideological-political education quality in higher education is vital to achieving the core mission of moral cultivation and talent development. Learning fundamentally involves two elements: motivation and approaches [1]. Research further confirms that teacher-student rapport critically shapes pedagogical effectiveness and profoundly impacts students' cognitive-psychological development [2]. This study examines how learning motivation, approaches, and teacher-student relationships collectively influence outcomes in university ideological-political education. Through this analysis, we advance domain-specific theory and propose evidence-based strategies to optimize curriculum effectiveness.

2. Literature Review and Research Hypotheses

2.1 Learning Motivation and Learning Outcomes

Learning motivations refer to the psychological tendency to elicit and sustain learning behaviors and satisfy the learning needs of an individual. According to Self-Determination Theory (SDT), human behavioral motivation can be categorized into intrinsic motivation and extrinsic motivation[3]. Cross-cultural studies confirm significant motivation-outcome correlations. Robert and Wendy's meta-analysis linked motivation intensity to academic performance: learners with higher motivation consistently achieve superior outcomes[4]. Thus, we hypothesize: **H1:** Intrinsic/extrinsic motivation in ideological-political education positively correlates with university students' learning outcomes.

2.2 The Mediating Role of Learning Approaches

Learning approaches constitute the aggregate of learning behaviors, methods, and strategies shaped by the interplay of individual psychological characteristics, curricular content, and instructional contexts. The academic inquiry into how motivational drivers shape learning approach selection has established substantive theoretical foundations. Biggs's research indicates that students with surface motivation tend to choose and use mechanical learning strategies, while students with deep motivation tend to opt for and employ meaningful and organizational strategies [5].

Empirical evidence substantiates the critical linkage between learning approaches and educational attainment. Oxford and Nyikos' cognitive engagement model posits that strategic adoption of context-appropriate learning modalities enhances learner autonomy, self-regulation capacity, and metacognitive awareness, thereby generating positive academic outcome trajectories [6]. These theoretical propositions culminate in the following research hypotheses: **H2:** Receptive learning or discovery-based learning modalities positively mediate the association between intrinsic/ extrinsic motivation and academic achievement in collegiate political education contexts.

2.3 The Moderating Role of Teacher-Student Relationships

Teacher-student relationships are conceptualized as a multidimensional construct encompassing pedagogical interactions, ethical alignment, and psychosocial dynamics within educational settings, forming both an institutional mechanism and a developmental catalyst. Empirical investigations have consistently positioned these relationships as critical contextual factors shaping motivational architectures and learning approach selection. Jang et al. found that students who perceive teachers' autonomy support tend to demonstrate greater learning interest and experience more enjoyment in school life[7]. So, we formulate the following research hypotheses: **H3a:** Teacher-student relationships positively moderate the relationship between college students' political education learning motivations and learning outcomes. **H3b:** Teacher-student relationships positively moderate the relationship between learning motivations and learning approaches in political education. **H3c:** Teacher-student relationships positively moderate the relationship between learning approaches and outcomes in political education.

Accordingly, this study proposes a preliminary research model, as illustrated in Figure 1.

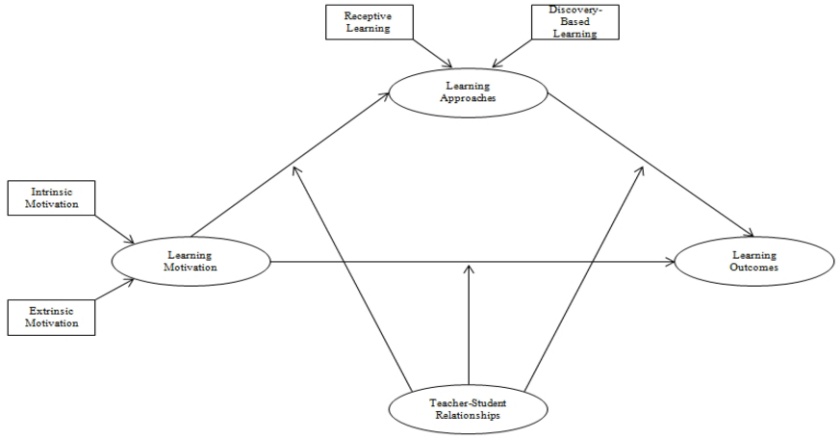


Figure 1. Hypothetical Model Diagram

3. Research Design

3.1 Sampling Procedures

The study implemented a stratified random sampling technique based on academic cohorts, utilizing the Wenjuanxing (Questionnaire Star) platform for data collection. Between June and August 2023, electronic surveys were distributed through institutional WeChat and QQ groups across universities in Guangdong, Hunan, and Jiangxi provinces. From 1,745 initially collected responses, rigorous data screening excluded 75 invalid cases demonstrating insufficient response duration (>2 SD below mean completion time), missing critical variables (>15% item non-response), or

multivariate outliers (Mahalanobis distance < .001). This yielded 1,670 analyzable questionnaires, representing a 95.70% valid response rate.

The final sample comprised 404 male students (24.19%) and 1,266 female students (75.81%). Academic year distribution showed 515 freshmen (30.84%), 1,036 sophomores (62.04%), 105 juniors (6.29%), and 14 seniors (0.84%). Disciplinary composition included 1,267 humanities majors (76.87%) and 403 science disciplines students (24.13%).

3.2 Statistical Tools

This study primarily utilized two questionnaire tools: the Chinese College Student Survey (CCSS) for tracking learning and development, and the Learning Motivation Scale developed by scholar Zhao Linlin. The specific circumstances are detailed below.

3.2.1 Learning Motivation

The psychometrically validated instrument was developed through the integration and adaptation of items from two established scales: the CCSS and Zhao Linlin's Learning Motivation Inventory. This multidimensional measure comprises 16 items (just like “I am interested in the content of the ideological and political courses”) assessing two core dimensions: Intrinsic Motivation: Operationalized through interest-driven motivation and growth-oriented motivation. Extrinsic Motivation: Conceptualized as achievement motivation, obligation motivation, and harm-avoidance motivation. Responses were recorded on a 4-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree), with higher composite scores indicating stronger motivational tendencies in respective dimensions.

3.2.2. Learning Outcomes

The learning outcomes measurement instrument was psychometrically refined from the "Self-Reported Educational Gains" subscale of the CCSS. This validated scale comprises 11 items (just like “I've learned a lot from my political education classes”) operationalized through a 4-point Likert-type response framework (1 = no improvement, 4 = significant improvement), with composite scores reflecting progressive levels of academic development.

3.2.3 Learning Approaches

The psychometrically validated instrument was adapted from established CCSS metrics encompassing active collaborative learning, "reflective-integrative processing", and "higher-order cognitive engagement". This multidimensional scale comprises 10 items (just like “I paid full attention to the teacher in class”) operationalized through two theoretically distinct dimensions: Receptive Learning: Characterized by systematic knowledge acquisition through structured instructional modalities. Discovery-Based Learning: Manifested through self-directed inquiry and experiential knowledge construction. Responses were captured using a 4-point frequency scale (1 = never, 4 = very often), with higher composite scores indicating more frequent utilization of specific learning modalities.

3.2.4 Teacher-Student Relationships

The teacher-student relationships dimension was composed of selected items from the "student-teacher interaction" metric in the CCSS questionnaire, totaling 4 items, just like “Would you discuss values and outlook on life with your political education teacher”. These items used a 4-point scoring method, where 1 represents "Never" or "Very poor," and 4 represents "Very often" or "Very good." Higher scores indicate better teacher-student relationships.

Table 1. Cronbach's Alpha Coefficient Table

Variable	Learning Motivation (LM)	Learning Outcomes (LO)	Learning Approaches (LA)	Teacher-Student Relationships (TSR)
Cronbach's α	0.922	0.942	0.894	0.865

4. Empirical Analysis

4.1 Descriptive Statistical Analysis

College students' political learning motivations are moderately high (intrinsic: M=3.00, SD=0.53; extrinsic: M=2.84, SD=0.48), with intrinsic motivation significantly higher. This reflects substantive engagement beyond instrumental goals. Receptive learning strategies (M=2.63, SD=0.60) dominate discovery-based approaches. Positive teacher-student relationships (M=2.36, SD=0.66) correlate with higher perceived outcomes. Independent t-tests and ANOVA showed no significant differences in political course learning outcomes by gender or major (arts/science), but freshmen had significantly higher outcomes than upperclassmen.

4.2 Mediation Analysis of Learning Approaches

PROCESS Model 4 tested receptive learning's mediation between motivations and outcomes. Intrinsic ($\beta = 0.526$, $p < .001$) and extrinsic motivation ($\beta = 0.079$, $p < .01$) significantly predicted receptive learning, which strongly impacted outcomes ($\beta = 0.323/0.525$, $p < .001$). Bias-corrected bootstrap confirmed: 1) significant direct motivation effects (95% CIs $\neq$ 0), and 2) receptive learning's significant partial mediation (95% CIs $\neq$ 0). Discovery-based learning also partially mediated, underscoring learning approaches' complementary bridging role.

4.3 Moderating Role of Teacher-Student Relationships

Using PROCESS Model 59, this study examined teacher-student relationships' moderation of motivation-strategy-outcome linkages (Tables 2 & 3). Teacher relationships × intrinsic motivation significantly enhanced receptive learning ($\beta = 0.134$, $p < .001$), discovery learning ($\beta = 0.108$, $p < .001$), and directly boosted outcomes ($\beta = 0.100/0.092$, $p < .001$). Teacher relationships × extrinsic motivation also improved outcomes ($\beta = 0.050$, $p < .01$; $\beta = 0.039$, $p < .05$). These results confirm that relational dynamics amplify motivation→strategy→outcome pathways in political

learning through moderated mediation. The simple slope results also support these findings.

Table 2 Test of Moderated Mediation Effect via Receptive Learning

Predictor variable	M1：RL		M2：LO		M3：RL		M4：LO	
	β	t	β	t	β	t	β	t
IM	0.196	0.764***	0.297	5.473***				
EM					-0.057	-1.066	-0.077	−1. 716
RL			0.345	6.251**			0.468	8. 373***
TSR	-0.321	-3.697***	-0.236	-3.174**	0.205	3.049**	-0.044	−0. 566
IM x TSR	0.134	5.045***	0.100	4.005***				
EM x TSR					0.012	0.525	0.050	2. 611**
RL x TSR			-0.018	-0.768			0.006	0. 277
R^2	0.245		0.527		0.093		0.330	
F	180.564***		192.175***		56.740***		164.200***	

Note : "***"indicates p<0.001, "**"indicates p<0.01, "*"indicates p<0.05 ; the same applies hereafter.

Table 3. Test of Moderated Mediation Effect via Discovery-Based Learning

Predictor variable	M5：DL		M6：LO		M7：DL		M8：LO	
	β	t	β	t	β	t	β	t
IM	0.210	4.124***	0.277	4.937***				
EM					-0.086	-1.858	-0.049	-1.133
DL			0.440	7.203***			0.588	10.079***
TSR	-0.137	-1.823	-0.289	-4.127***	0.264	4.496***	-0.116	-1.633
IM x TSR	0.108	4.721***	0.092	3.544***				
EM x TSR					0.024	1.222	0.039	2.131*
DL x TSR			-0.009	-0.380			0.012	0.512
R^2	0.354		0.505		0.209		0.383	
F	304.067***		339.697***		146.896***		206.803***	

5. Research Conclusions and Implications

5.1 Research Conclusions

5.1.1 Intrinsic vs. Extrinsic Motivation in Ideological Education: Differential Effects on Learning Outcomes.

Data analysis reveals that both intrinsic and extrinsic motivation correlate with learning outcomes in university ideological and political education, though intrinsic motivation has a stronger effect. It drives deep cognitive engagement, whereas extrinsic motivation

primarily influences superficial learning behaviors, failing to foster emotional resonance or cognitive internalization. Students driven extrinsically often fail to recognize the discipline's significance for self-actualization and national service, engaging only for external rewards (e.g., exam success). Consequently, intrinsic motivation—rooted in genuine interest and growth—demonstrates greater explanatory power for learning outcomes than extrinsic motivation (achievement orientation, obligation compliance, loss aversion). This differential impact confirms intrinsic motivation's superior predictive validity for learning gains.

5.1.2 Learning Approaches Mediate Motivation-Outcome Links in Ideological Education

This study confirms that intrinsic/extrinsic motivations in ideological-political education affect learning outcomes via discovery-based or receptive learning approaches. Pathway analysis reveals: (a) The intrinsic motivation → learning approach → outcome pathway demonstrates stronger efficacy than extrinsic pathways; (b) The motivation → discovery-based learning → outcome path holds greater predictive power than motivation → receptive learning → outcome paths. Thus, the intrinsic motivation → discovery-based learning → outcome trajectory proves most potent. These findings align with pedagogical theories: intrinsically motivated learners inherently prefer exploratory strategies, best predicting substantive outcomes.

5.1.3 Teacher-Student Rapport Moderates Motivation-Outcome Links in Ideological Education

This study empirically confirms that positive student-instructor relationships in ideological and political education significantly moderate: links between intrinsic/extrinsic motivation and learning gains, and connections of intrinsic motivation to discovery-based or receptive learning modalities. Research shows these relationships indirectly affect outcomes by mediating students' affective domain. Specifically, instructors' supportive teaching approaches enhance students' behavioral engagement and emotional investment, creating synergistic knowledge internalization. Consequently, strong teacher-student rapport amplifies motivation's beneficial impact on learning. For intrinsically motivated learners, this relational capital further enables strategic application of learning modalities, optimizing competence development through self-regulated cognitive scaffolding.

5.2 Research Implications

5.2.1 Strengthen College Students' Motivation for Political Education, Particularly Their Intrinsic Drive.

Firstly, elevate faculty quality through exemplary conduct, strengthened ideological commitment, and improved pedagogical skills to inspire engagement. Secondly, guide students to recognize intrinsic value—developing critical thinking, ideological awareness, and theoretical foundations—avoiding extrinsic motivators like exam utility. Thirdly, Innovate pedagogy using preferred technologies (e.g., short videos, VR) to foster active participation and critical analysis

5.2.2 Advance the Diversification of Learning modalities in Ideological and Political Education.

At the first, leverage receptive learning through optimized lectures: guide focused attention on key theories and structured note-taking for core concepts. Secondly, promote discovery-based learning via pedagogical reform: employ interactive methods (e.g., heuristic questioning, case studies, debates, simulations) to activate intellectual curiosity and self-driven engagement..

5.2.3 Foster Equal Interaction and Harmonious Teacher-Student Relationships.

We should adopt a student-centered approach. Educators should deepen their commitment to understanding students, building familiarity, mutual respect, and rapport. Secondly, strengthen institutional frameworks for engagement. Universities should establish mentorship programs, regular teacher-student forums, and structured interaction systems to expand communication opportunities. Furthermore, broaden collaborative platforms. Organize competitions and events where teachers guide and students lead, creating shared spaces to encourage proactive participation from both parties.

6. Limitations

This study has methodological limitations. First, the sample was limited to Guangdong Province, China, reducing ecological validity. Future research should include more diverse regions. Second, convenience sampling focused solely on college students, limiting generalizability. Future studies could strengthen external validity by using probability sampling and broadening the participant demographic.

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Research on the Impact of Virtual Reality (VR) Physical Education Courses on the Willingness for Lifelong Learning

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Abstract: This paper aims to explore the influence of virtual reality (VR) physical education courses on individuals' willingness for lifelong learning. Through literature research to sort out relevant theories, combined with research methods such as questionnaire surveys, the mechanism of VR physical education courses in enhancing learning motivation and creating a learning environment is analyzed. Research has found that in terms of the learning experience of VR physical education courses, students' overall satisfaction with the course content and sense of immersion are relatively good, but there is still room for improvement in terms of smoothness. Students' intrinsic learning motivation is relatively strong. The learning experience of VR physical education courses is significantly positively correlated with learning motivation, self-efficacy, learning attitude and lifelong learning willingness. This indicates that VR physical education courses, with their unique immersion and interactivity, can significantly enhance individuals' learning interest and self-efficacy, and thereby increase the willingness for lifelong learning. Meanwhile, strategies such as optimizing the curriculum design and enhancing the application level of technology are proposed for the existing problems, providing theoretical and practical references for promoting the deep integration of VR technology in the fields of physical education and lifelong learning.

Keywords: Virtual Reality VR; physical education course; Willingness for lifelong learning; Learning motivation Self-efficacy

1. Introduction

VR technology has revolutionized the field of education with its immersive and interactive features. In physical education courses, its intuitive, vivid and highly participatory characteristics effectively make up for the deficiencies of traditional continuing education [1], break through the limitations of venues, equipment and weather, provide learners with a brand-new sports experience, solve problems such as scarce teaching resources and single means [2], and significantly improve the quality of education. With the popularization of the concept of lifelong learning, how to utilize VR technology to

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enhance the appeal and effectiveness of physical education courses and stimulate individuals' willingness for lifelong learning has become an important research direction in the field of education.

2. Related works

2.1 Relevant Theoretical Basis

(1) The theoretical connection between VR physical education courses and the willingness for lifelong learning

Constructivist theory points out that the immersive environment constructed by VR technology supports students' active exploration. Its characteristics of breaking through the limitations of time and space and providing immediate feedback can stimulate students' lasting interest in physical education learning[3]. Social learning theory emphasizes the influence of the environment on behavior. The diverse scenarios of VR physical education courses can strengthen learning motivation and enhance the willingness for lifelong learning.

(2) Explanation of the Mediating Role of Learning Motivation

According to the self-determination theory, the interactivity of VR physical education courses meets students' autonomous needs, the virtual scenes and feedback mechanisms meet the competency needs, and the social functions meet the belonging needs, thereby stimulating the intrinsic learning motivation. Learning motivation, as the core driving force of learning behavior, directly affects learning engagement and persistence [4].

(3) The mediating mechanism support of self-efficacy

Bandura's theory of self-efficacy indicates that the low-risk virtual environment of VR physical education courses helps students accumulate successful experiences and enhance their self-efficacy. When students perceive their learning ability, they will increase their investment in learning and promote the formation of the willingness for lifelong learning.

(4) Analysis of the mediating path of Learning attitude

According to the theory of planned behavior, VR physical education courses change students' cognition of traditional physical education courses with novel technological forms and form a positive learning attitude. A positive attitude promotes students' active learning, cultivates long-term learning habits, and enhances their willingness for lifelong learning.

2.2 Literature Review

2.2.1 Advantages of VR Physical Education Courses.

VR technology enhances the appeal of physical education courses and stimulates students' interest in learning by creating immersive virtual environments [5]; Its simulation function provides diverse sports scenarios and training modes to help students master and repeatedly practice sports skills [6]; Meanwhile; Meanwhile, VR technology can

customize learning content based on students' abilities and needs, provide real-time feedback, and optimize the learning effect [7]; In addition, it can also help students intuitively recognize the value of sports, set personalized exercise goals, and strengthen their intrinsic learning motivation [8].

2.2.2 The Long-term Impact of VR Physical Education Courses

The long-term aim of VR physical education courses is to cultivate students' positive attitude towards physical exercise, encourage them to integrate sports into their lives, and develop the habit of lifelong learning [9]. The courses should be interesting, interactive and challenging, suitable for students of different ages and interests [10], and rely on stable VR devices and technology to ensure a smooth learning experience ([11]) and assist in guiding physical exercise [12]. However, VR physical education teaching also has its limitations. The high cost of the equipment restricts its popularization in economically underdeveloped areas. Long-term use is prone to cause visual fatigue, dizziness and other discomforts.

Overall, VR physical education teaching can stimulate learning motivation, promote mental health, and cultivate lifelong learning ability, opening a new path for fostering students' willingness to learn throughout their lives. With the help of virtual reality technology, students gain high-quality exercise experiences, cultivate a positive attitude towards sports and the willingness for lifelong learning, laying the foundation for a healthy life.

3. Methods

3.1 Background introduction of research subject

This study selects three schools, namely Chenzhou No.1 High School, Xiangnan High School and Xiangnan University, which have rich practical experience in smart education. Under the background of "Healthy China 2030" and the digital transformation of education, the three schools have taken the lead in integrating VR technology into the reform of physical education teaching.

When designing VR physical education courses, the school aims to cultivate students' lifelong learning willingness. A team composed of physical education teachers; educational technology experts and course designers is formed. Based on constructivism and social learning theories, the courses are planned around "stimulating interest, enhancing ability and cultivating habits". The course objectives not only focus on sports skills but also emphasize cultivating students' interest in independently exploring sports learning and their long-term participation awareness.

The course content is developed based on the differences in educational stages to create diverse virtual projects: in primary schools, fun game courses are used to stimulate interest; Middle schools and universities enhance skills and tactics through simulation competitive projects, while setting up personalized learning paths to support students in independently choosing the difficulty level and strengthening their learning motivation.

In terms of implementation, the school is equipped with professional VR devices, conducts specialized training for teachers, and adopts a hybrid model of "online virtual learning + offline practice", with one class hour per week. It also encourages students to practice independently through the VR platform after class, facilitating the formation of lifelong learning habits.

3.2 Research object

This study selected students from three schools in Chenzhou City, namely Chenzhou No.1 High School, Xiangnan High School and Xiangnan University, as research subjects. In each school, 150 students from the second year of junior high school, 150 from the first year of senior high school and 150 from the first year of university were randomly selected, totaling 450 students to participate in this study. The students of these three grades were chosen because they are in a critical period of physical and mental development, have a strong ability to accept new things, and physical education courses are important basic courses in all three stages, which can well reflect the influence of VR physical education courses on the lifelong learning willingness of students at different stages.

3.3 Research methods

(1) Literature research method: Systematically review the application achievements of VR technology in education and physical education courses at home and abroad, as well as theoretical and empirical research related to the willingness for lifelong learning.
(2) Questionnaire survey method: The content of the questionnaire includes students' basic information, cognition and experience of VR physical education courses, learning motivation, self-efficacy, learning attitude and willingness for lifelong learning, etc. Questionnaires were distributed through a combination of online and offline methods. A total of 450 questionnaires were distributed, and 420 valid questionnaires were retrieved, with an effective recovery rate of 93.33%.
(3) Classroom observation method: Researchers delve into VR physical education classes to observe students' class participation, interaction, learning performance, etc., record typical behaviors and events, and provide rich qualitative data for the research.
(4) Mathematical statistics method：Conduct data statistical analysis on the collected questionnaires to enhance data support for this research.

4. Results

4.1 Basic Information for Students

Table 1 Student Basic Information Form

	Male	Female	Grade Two of Junior High School	Grade One of senior high school	Freshman
Number	225	195	140	140	140
Percentage	53.57%	46.43%	33.33%	333.33%	33.33%

Descriptive statistical analysis is used to gain a preliminary understanding of the basic characteristics and data distribution of the samples. The basic information of the students was statistically analyzed. The results in Table 1 show that among the 420 valid samples,

225 were male, accounting for 53.57%. There are 195 female students, accounting for 46.43%. There are 140 students in the second grade of junior high school, accounting for 33.33%. There are 140 first-year high school students, accounting for 33.33%. There are 140 first-year university students, accounting for 33.33%.

4.2 Satisfaction Survey and Analysis on the Learning Experience of VR Physical Education Courses

Table 2 Survey Form on Students' Satisfaction with VA Courses

	Course content	Evaluation of teaching methods	Immersion	Interactivity	Fluency
Satisfaction (5)	3.85	3.78	3.48	3.55	3.48

Table 2 shows that in terms of the learning experience of VR physical education courses, the average satisfaction score of students with the course content is 3.85 (out of a full score of 5), indicating that students are relatively satisfied with the course content. The average score of the evaluation of the teaching method is 3.78, indicating that the teaching method has been recognized by the students. In terms of VR technology experience, the average score for immersion is 3.60, for interactivity it is 3.55, and for smoothness it is 3.48. The overall experience is good, but there is still room for improvement in smoothness.

4.3 Investigation and Analysis of Lifelong Learning Willingness

Table 3 Survey Form on Students' Willingness and Satisfaction with Lifelong Learning

	Intrinsic motivation	Extrinsic motivation	Self-efficacy	Learning attitude	Lifelong learning
Satisfaction (5)	3.52	3.78	3.45	3.62	3.58

Table 3 shows that in terms of learning motivation, the average score of intrinsic motivation is 3.52 and that of extrinsic motivation is 3.25, indicating that students' intrinsic learning motivation is relatively strong. The average score of self-efficacy was 3.45, the average score of learning attitude was 3.62, and the average score of lifelong learning willingness was 3.58. This indicates that students have a relatively high satisfaction with lifelong learning, but satisfaction with self-efficacy needs to be improved.

4.4 Correlation Analysis between VR Physical Education Course Experience and Lifelong Learning Willingness

To deeply explore the relationship between VR physical education course experience and the willingness for lifelong learning, this study conducted a correlation analysis. The specific results are shown in the following table:

Table 4 Statistical Table of the Relationship between VR Physical Education Course Experience and Lifelong Learning Willingness

Variable	Lifelong learning willingness
Satisfaction with course content	0.562**
Satisfaction with teaching methods	0.538**
Satisfaction with the equipment usage experience	0.485**
Frequency of course participation	0.426**
Duration of course participation	0.408**

Note: ** indicates a significant correlation at the 0.01 level (bilateral).

Table 4 shows that each dimension of the VR physical education course experience is significantly positively correlated with the willingness for lifelong learning. The correlation coefficient between course content satisfaction and lifelong learning willingness is 0.562, indicating that the more satisfied students are with the VR physical education course content, the stronger their lifelong learning willingness will be. When the course content is rich and diverse, covering a variety of sports events, and the teaching depth and breadth are appropriate, it can meet students' learning needs and interests, stimulate their enthusiasm for sports learning, and thereby enhance their willingness to continuously participate in sports learning in the future. The correlation coefficient between the satisfaction of teaching methods and the willingness for lifelong learning is 0.538, indicating that effective teaching methods, such as the precise guidance of virtual coaches and the reasonable design of interactive links, can improve students' learning experience and learning effect, make students participate in physical education learning more actively, and thereby enhance their willingness for lifelong learning. The correlation coefficient between the satisfaction of equipment usage experience and the willingness for lifelong learning is 0.485, which means that factors such as the comfort level, ease of operation and picture clarity of VR devices have significant influences on students' learning experience and willingness to learn. Comfortable, convenient and clear VR devices can enable students to focus more on their course studies, reduce the discomfort and interference caused by device problems, enhance their favorable impression of VR physical education courses, and thereby promote their willingness to learn throughout their lives. The frequency and duration of course participation were also significantly positively correlated with the willingness for lifelong learning, with correlation coefficients of 0.426 and 0.408 respectively. This indicates that the more times and the longer the duration of students' participation in VR physical education courses, the higher their commitment to physical education learning, the more they can feel the joy and value of physical education learning and thus are more likely to develop a willingness to keep learning.

4.5 Analysis of the Mediating Roles of Learning Motivation, Self-efficacy and Learning Attitude among Them

Table 5 Data Table for the Analysis of the Impact and Mediating Effect of VR Physical Education Course Learning Experience on Lifelong Learning Willingness

Analysis type	Variable relationship	Effect type	Effect value	Statistics	Proportion of mediating effect	Hypothesis verification result
Regression analysis	VR learning Experience → Lifelong learning Willingness	Total effect	β=0.35	t=5.68, p<0.01	—	H1 support
Analysis of mediating effect	VR learning experience → Learning motivation → Lifelong learning willingness	Mediating effect	0.12	—	34.29%	H2 Hsupport
	VR learning experience → Self-efficacy → Willingness for lifelong learning	Mediating effect	0.10	—	28.57%	H3 support
	VR learning experience → Learning attitude → Lifelong learning willingness	Mediating effect	0.14	—	40.00%	H4 support

In order to further verify the influence of VR physical education courses on the willingness for lifelong learning, as well as the mediating roles of learning motivation, self-efficacy and learning attitude therein, a regression analysis was conducted. Taking the learning experience of VR physical education courses as the independent variable and the willingness for lifelong learning as the dependent variable, a regression analysis was conducted. The results in Table 5 show that the learning experience of VR physical education courses has a significant positive impact on the willingness for lifelong learning ($\beta = 0.35$, $t = 5.68$, $p < 0.01$), and hypothesis H1 was verified. Then, taking the learning experience of VR physical education courses as the independent variable, learning motivation, self-efficacy and learning attitude as the mediating variables, and the willingness for lifelong learning as the dependent variable respectively, the mediating effect analysis was conducted. The results show that learning motivation plays a partial mediating role between the learning experience of VR physical education courses and the willingness for lifelong learning (the mediating effect value is 0.12, accounting for 34.29% of the total effect), and Hypothesis H2 is verified. Self-efficacy plays a partial mediating role between the learning experience of VR physical education courses and the willingness for lifelong learning (the mediating effect value is 0.10, accounting for 28.57% of the total effect), and Hypothesis H3 is verified. Learning attitude plays a partial mediating role between the learning experience of VR physical education courses and the willingness for lifelong learning (the mediating effect value is 0.14, accounting for 40.00% of the total effect), and Hypothesis H4 is verified.

5. Discussion

This study confirmed that VR physical education courses significantly enhance students' willingness for lifelong learning, with learning motivation, self-efficacy and learning attitude playing a mediating role. This result is closely related to the existing literature and theories and also points out the direction for subsequent research.

Based on the constructivist theory, the virtual environment of VR physical education courses supports students' independent exploration, breaks through the temporal and spatial limitations of traditional teaching, and its immediate feedback mechanism effectively stimulates students' interest in learning, thereby enhancing their willingness for lifelong learning. However, compared with the initial application obstacles of VR technology mentioned in some literatures, the school in this study avoided this problem better through early training and guidance.

In terms of mediating effect, the mediating effect of learning motivation validates the self-determination theory. VR physical education courses stimulate students' intrinsic learning motivation by meeting their needs for autonomy, competence and belonging, and thereby influence their willingness for lifelong learning.

The mediating role of self-efficacy further expands Bandura's theory of self-efficacy. The low-risk virtual environment of VR physical education courses helps students accumulate successful experiences, enhance their sense of self-efficacy, and promote the formation of a lifelong learning willingness. However, the issue of maintaining and transferring self-efficacy in the virtual environment still requires subsequent research and exploration.

The mediating role of learning attitude is in line with Ajzen's theory of planned behavior. VR physical education courses change students' perception of traditional sports in a novel form, foster a positive learning attitude, and promote enhancement of lifelong learning willingness. This study fills the research gap on the role of learning attitudes in the formation of the willingness to learn throughout life, but the influence of cross-cultural differences on it awaits in-depth exploration.

In conclusion, this study provides theoretical and practical references for VR physical education, but there are sample limitations. Future research can expand the sample, explore group differences and improve relevant theories.

6. Conclusions

This study adopts a mixed method combining quantitative and qualitative approaches. The theoretical framework is constructed through literature research, and quantitative analysis is conducted through questionnaires to provide methodological references for subsequent research. The research focuses on the influence mechanism of VR physical education courses on the willingness for lifelong learning and reveals the intrinsic correlation through empirical evidence. Theoretically, fill the gap in the intersection of VR technology and lifelong learning; In practice, it provides a basis for educational institutions to develop courses and formulate strategies, and promotes the construction of a lifelong learning system.

Aiming at the existing problems, an optimization strategy is proposed: optimize the curriculum design, develop diverse contents and focus on gradient advancement; Strengthen the VR technology training for teachers; Increase investment in equipment research and development to enhance the user experience; Strengthen home-school cooperation and enhance society's support for lifelong learning through publicity.

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Rural Teachers' Information-Based Teaching Ability in AI-Supported: A Survey Study

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Abstract. Artificial intelligence (AI) technology is rapidly transforming the educational landscape. In this context, enhancing rural teachers' pedagogical competence in intelligent environments has become pivotal for the effective integration of AI into rural education. Drawing on the TPACK framework, this study conducted a questionnaire survey among rural teachers in China, aiming to systematically investigate the current status and structural differences in their AI-integrated instructional competence. The findings reveal that rural teachers possess a strong foundation in traditional disciplinary content understanding and pedagogical application, but their competence in effectively integrating AI technology into instruction remains relatively underdeveloped. Analysis of group differences indicates no significant disparities across dimensions based on gender. Teaching experience exhibited non-linear characteristics, with early-career teachers demonstrating higher scores in AI-related technological dimensions, while mid-career teachers performed relatively weaker. Professional title significantly influenced AI-related technological knowledge and pedagogical integration competence, showing a certain advantage for junior teachers. Educational background mainly affected technological knowledge, with minimal impact on other dimensions. Consequently, the findings highlight that significant group disparities exist in rural teachers' pedagogical competence development within the AI context. Therefore, future teacher training initiatives should adopt a tiered and differentiated approach, focusing on the specific application of AI technologies in teaching scenarios, and precisely enhancing the AI instructional competence of teachers across different seniority and professional title groups, to facilitate the effective application and deep integration of AI technology in rural educational settings.

Keywords. Rural teachers, western China, information-based teaching ability, artificial intelligence

1. Introduction

The rapid development of artificial intelligence (AI) technology is profoundly transforming education and teaching. In this context, teachers' instructional competence has evolved from traditional Information Technology (IT) application to a complex ability integrating intelligent technologies with disciplinary content [1]. Consequently, fostering teachers' adaptive and innovative capacities in AI-enhanced learning

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environments and effectively leveraging emerging technologies for pedagogical innovation has become a pressing issue demanding in-depth exploration within contemporary education [2].

Against the backdrop of digital transformation, rural teachers face even greater challenges in enhancing their digital competence. Currently, rural schools often suffer from limited technological resources, including weak hardware infrastructure and unreliable internet connectivity, which leads to a suboptimal professional development environment for teachers [3]. Furthermore, compared to urban counterparts, rural teachers often have fewer opportunities to participate in emerging technology training, making it challenging for them to keep pace with the advancements of new technologies in educational practice [4]. Moreover, teachers from diverse backgrounds exhibit notable differences in their capabilities and needs when engaging with AI technology. Despite a recent increase in rural teachers' participation in professional development and training activities [5], most programs still adopt standardized and homogenous formats, failing to adequately address the unique context of rural education and teachers' individualized needs [6], thereby resulting in suboptimal training outcomes. Therefore, precisely identifying the current capabilities and developmental needs of rural teachers is a prerequisite for designing effective and personalized teacher training programs.

Existing studies predominantly focus on teachers' ICT competence in traditional information technological environments [7]. Conversely, studies investigating teachers' competence in AI-driven environments are relatively scarce and primarily centered on urban primary and secondary school teachers or higher education faculty [8]. While some international efforts have begun to explore this domain, for example, revealing the effectiveness of TPACK-based professional development programs in improving K-12 CS teachers' AI teaching competency and expanding the design of effective professional development [9] the rapid emergence of Generative Artificial Intelligence (GAI) is providing new insights into enhancing teaching practices. A recent study focusing on GAI's role in improving instructional design capability among university teacher-training students, demonstrated that participants significantly enhanced the quality of their instructional designs [10]. Despite these valuable contributions and emerging insights into AI's impact on learning processes and the potential of GAI, there remains a notable lack of in-depth investigation and systematic analysis specifically targeting rural teachers' AI-integrated instructional competence.

Building on these identified gaps, this study aims to systematically investigate the levels and structural disparities in rural teachers' AI-integrated instructional competence through a questionnaire survey. This research seeks to provide empirical evidence for rural teachers' professional development and to further promote the effective application and deep integration of AI technology within rural educational settings.

2. Method

2.1. Questionnaire design

The TPACK (Technological Pedagogical Content Knowledge) framework, as a core model integrating content, pedagogy, and technology, possesses inherent versatility that allows it to continually evolve with technological advancements. Artificial Intelligence (AI) technology is conceptualized as an extension and deepening of Technological Knowledge (TK). Its integration with Content Knowledge (CK) and Pedagogical

Knowledge (PK) further enriches and expands the conceptual scope of TPACK's cross-cutting dimensions (PCK, TCK, TPK, and TPACK). Consequently, this study adopts the seven dimensions of the TPACK framework. By measuring teachers' mastery and application of these core knowledge domains within an AI context, we aim to systematically assess their AI-integrated instructional competence and delve into the specific applications and developmental needs of intelligent technologies in rural educational settings.

This study developed the *Survey on Rural Teachers' AI-Integrated Instructional Competence in AI Environments* based on the TPACK theoretical framework. The questionnaire items were adapted and localized from well-established instruments [11-12] to ensure contextual relevance to rural education in China. The final version consists of 33 items across seven dimensions: Technological Knowledge (TK, 4 items), Content Knowledge (CK, 4 items), Pedagogical Knowledge (PK, 6 items), Pedagogical Content Knowledge (PCK, 5 items), Technological Pedagogical Knowledge (TPK, 5 items), Technological Content Knowledge (TCK, 5 items), and Technological Pedagogical Content Knowledge (TPACK, 4 items). Specifically, Technological Knowledge (TK) refers to teachers' fundamental understanding and operational proficiency of AI tools and technologies. Content Knowledge (CK) pertains to teachers' comprehension of the disciplinary content they teach. Pedagogical Knowledge (PK) encompasses teachers' understanding of classroom teaching strategies, methods, and student learning processes. Pedagogical Content Knowledge (PCK) denotes teachers' understanding of how to effectively transmit disciplinary content to students through appropriate teaching methods and strategies. Technological Pedagogical Knowledge (TPK) describes teachers' ability to apply AI technologies in pedagogical activities. Technological Content Knowledge (TCK) indicates teachers' skill in utilizing AI technologies to represent, transform, and understand disciplinary content. Lastly, Technological Pedagogical Content Knowledge (TPACK) represents teachers' comprehensive understanding and practical application of the seamless integration of AI technology, pedagogy, and content.

Each item is rated on a five-point Likert scale ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree"), reflecting the extent to which participants perceive each statement as representative of their actual teaching practices. To better reflect the specific connotations of teachers' AI-integrated instructional competence in an AI environment, the questionnaire items incorporated various AI technology application scenarios. Below are representative examples of items from each dimension:

- **TK:** I am familiar with common AI teaching tools (e.g., AI grading, intelligent voice assistants).
- **CK:** I am familiar with the basic principles, core concepts, and knowledge system of my subject discipline.
- **PK:** I know various teaching methods and can flexibly adjust teaching strategies based on student feedback.
- **TPK:** I am capable of utilizing AI technology to optimize teaching methods and processes.
- **TCK:** I am able to use AI tools to help students better understand disciplinary content.
- **PCK:** I can select teaching methods and design tasks based on content to promote students' deep thinking.
- **TPACK:** I can organically integrate AI technology with teaching content and methods to improve teaching efficiency.

2.2. Participants

The participants in this study were rural primary and junior high school teachers from western China. A convenience sampling method was adopted, acknowledging its potential limitations regarding the generalizability of the findings due to possible sampling bias. Data were collected through an online questionnaire titled *Survey on Rural Teachers' AI-Integrated Instructional Competence in AI Environments,* distributed via the Wenjuanxing platform, a widely used online survey tool in China. A total of 883 responses were received. After excluding incomplete or inconsistent responses based on a pre-designed consistency check item, 642 valid questionnaires were retained, resulting in a response rate of 73%.

Among the valid respondents, 26.6% were male and 73.4% were female. Demographic information including years of teaching experience, educational attainment, and professional titles were also collected for subsequent subgroup analyses.

Table 1. Demographic information of the teachers (N=642)

Variables	Category	Frequency (n)	Percentage (%)
Gender	Male	171	26.6%
	Female	471	73.4%
School type	Primary school	229	35.7%
	Junior high school	413	64.3%
Educational background	Master's Degree or Higher	10	1.6%
	Bachelor's Degree	613	95.5%
	Associate's Degree	16	2.5%
	Secondary Vocational Education	2	0.3%
	Others	1	0.2%
Professional title	Senior teacher	2	0.3%
	Associate senior teacher	73	11.4%
	Intermediate teacher	222	34.6%
	Junior teacher	226	35.2%
	Unranked	119	18.5%
Subjects	Chinese	187	29.1%
	Mathematics	159	24.8%
	English	141	22%
	Science	90	14%
	Social Studies	81	12.6%
	Arts and PE	64	10%
	Others	6	0.9%
Years of teaching experience	<5	234	36.4%
	6—10	111	17.3%
	11—15	80	12.5%
	16—20	74	11.5%
	>20	143	22.3%

2.3. Reliability and validity of the questionnaire

To evaluate the reliability of the measurement scales, internal consistency analysis was conducted. The results showed a high level of overall reliability, with a Cronbach's α coefficient of 0.972 for the entire questionnaire. The Cronbach's α values for each dimension—Technological Knowledge (TK), Content Knowledge (CK), Pedagogical Knowledge (PK), Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and Technological Pedagogical Content Knowledge (TPACK)—were respectively 0.894, 0.915, 0.928, 0.915, 0.937, 0.943, and 0.910. All values exceeded the commonly accepted threshold

of 0.8, indicating high internal consistency and confirming that the questionnaire meets the reliability requirements for subsequent data analysis.

To validate the construct validity of the questionnaire, exploratory factor analysis was conducted on the data from 173 pilot test questionnaires using SPSS 24.0. The Kaiser-Meyer-Olkin (KMO) values for each dimension were above 0.80, and Bartlett's test of Sphericity was statistically significant ($p < 0.001$) (see Table 2), which suggests that the questionnaire has good structural validity.

Table 2. Results of KMO and Bartlett's test of sphericity

Dimension Tested		TK	CK	PK	PCK	TPK	TCK	TPACK
KMO Value		0.825	0.827	0.836	0.834	0.802	0.847	0.805
	Chi-Square	484.269	611.591	674.966	792.289	788.452	802.179	665.706
Bartlett's Test of Sphericity	df	6	6	6	10	6	6	6
	Sig.	.000	.000	.000	.000	.000	.000	.000

2.4. Data Analysis

This study primarily employed descriptive statistics and non-parametric inferential statistical methods for data analysis. Initially, descriptive statistics were used to delineate the overall and dimensional levels of rural teachers' AI-integrated instructional competence.

Prior to conducting comparative analyses, the normality of data for each dimension of teachers' AI-integrated instructional competence was examined using the Kolmogorov-Smirnov and Shapiro-Wilk tests. As the results indicated that data for all dimensions did not meet the assumption of normal distribution ($p < 0.05$), non-parametric tests were chosen for analyzing differences between various groups. Specifically, the Mann-Whitney U test was applied for gender, a binary variable. For categorical variables with multiple levels such as years of teaching experience, professional title, and educational attainment, the Kruskal-Wallis H test was utilized. When the Kruskal-Wallis H test yielded significant differences, post-hoc pairwise comparisons were further conducted using the Dunn-Bonferroni method to pinpoint the specific sources of these disparities. All statistical analyses were performed using SPSS 24.0 software.

3. Results

3.1. Descriptive analysis of teachers' AI-Integrated Instructional Competence

This study conducted a descriptive statistical analysis of the overall and seven-dimensional levels of rural primary and junior high school teachers' AI-integrated instructional competence in an AI environment (see Table 1 for specific data). The results indicate that the teachers' overall AI-integrated instructional competence had a mean score of 3.83.

As shown in Table 3, CK, PK, and PCK all demonstrated mean scores above 4.0, suggesting that rural teachers possess a relatively high foundational competence in traditional disciplinary content understanding and pedagogical application. In contrast, dimensions related to technology integration (TK, TCK, TPK, and TPACK) consistently showed mean scores below 4.0. Among these, TCK had the lowest mean score.

Table 3. Descriptive statistics on teachers' information-based teaching ability in the context of artificial intelligence

Item	N	Max	Min	M	SD
TK	642	5.00	1.00	3.6367	0.85258
CK	642	5.00	1.00	4.0366	0.70754
PK	642	5.00	2.25	4.0958	0.65795
PCK	642	5.00	2.4	4.0894	0.64905
TCK	642	5.00	1.00	3.7056	0.87028
TPK	642	5.00	1.00	3.5853	0.89353
TPACK	642	5.00	1.00	3.6269	0.88045
Total	642	5.00	2.04	3.8252	0.67969

3.2. Analysis of differences in AI-integrated instructional competence among different teacher groups

To gain a deeper understanding of the variation in AI-integrated instructional competence among different groups of rural teachers, this study examined differences across gender, teaching experience, professional title, and educational background.

- **Gender differences in AI-integrated instructional competence among rural teachers.** Gender difference analysis revealed no significant disparities between male and female teachers across all seven dimensions of AI-integrated instructional competence ($p > 0.05$). Despite the absence of statistically significant differences, a comparison of medians and interquartile ranges (P25, P75) showed that male teachers had slightly higher medians in the TK, CK, PK, and PCK, whereas female teachers exhibited slightly lower medians in the TPK, and TCK.

- **Differences in AI-integrated instructional competence by years of teaching experience.** Analysis of teaching experience differences revealed no significant disparities among teachers with different years of experience in CK, PK, and PCK ($p > 0.05$). However, significant differences were observed in TK, TPK, TCK, and TPACK. Post-hoc comparisons revealed that teachers with 0–5 years of teaching experience demonstrated significantly higher competence in TK, TPK, TCK, and TPACK compared to those with 11–15 years, 16–20 years, and more than 21 years of teaching experience ($p < 0.05$).Specifically, the medians for teachers with 0-5 years of experience in these four dimensions were 16 (12, 19), 16 (13, 18.25), 16 (12, 18), and 16 (12, 18), respectively. Furthermore, teachers with 6–10 years of experience scored significantly higher in the TPK and TCK dimensions than those with 16–20 years and over 21 years of experience. In the TPACK dimension, teachers with 6–10 years of experience also scored significantly higher than those with over 21 years of experience. Across the CK, PK, and PCK dimensions, the medians for all five teaching experience groups were relatively close.
- **Differences in AI-integrated instructional competence across professional title.** Analysis of professional title differences revealed significant differences among teachers with different professional titles in TK, TPK, TCK, and TPACK (H values were 42.205, 26.289, 39.691, and 38.733, respectively, with $P < 0.001$). However, no significant differences were found in CK, PK, and PCK ($p > 0.05$). Post -hoc comparisons indicated that significant

differences existed TK, TPK, TCK, and TPACK between uncategorized/junior teachers and intermediate/senior teachers. Notably, the medians for highly-ranked (senior) teachers across all dimensions of AI-integrated instructional competence demonstrated a noticeable advantage.

- **Differences in AI-integrated instructional competence by educational background.** Analysis of educational background differences indicated that significant disparities existed only in the dimension of TK. No statistically significant differences were observed across the other six dimensions ($p > 0.05$). Post-hoc comparisons revealed that teachers with a bachelor's degree demonstrated significantly higher competence in the TK compared to those with an associate degree or below ($p < 0.05$). Specifically, the median for bachelor's degree holders in the TK dimension was 14 (12, 17), which was significantly higher than for teachers with junior college degrees or below.

4. Discussion and Conclusion

4.1. Absence of significant gender differences in rural teachers' AI-integrated instructional competence

The analysis revealed no statistically significant differences between rural male and female teachers across all seven dimensions of the TPACK framework ($p > 0.05$). This finding suggests that, within the context of AI, gender is not a critical variable influencing the development of rural teachers' AI-integrated instructional competence. This is consistent with [1], who found that differences between male and female teachers in both conventional and intelligent technology teaching competence were not significant. Although not statistically significant, descriptive data indicated that male teachers had marginally higher medians in the TK, CK, PK, and PCK, while female teachers showed slightly higher scores in TPK and TCK. These subtle differences suggest that in the nascent stages of AI application in education, male teachers may exhibit a relative advantage in the use of AI technologies, possibly because males significantly outperform females in technology use [13], while female teachers may excel at integrating AI technology with pedagogy and content. This observation is broadly consistent with conclusions drawn from some previous studies [14], who found that male teachers generally exhibited stronger overall informational teaching ability than female teachers.

Consequently, in the process of cultivating rural teachers' AI-integrated instructional competence, it is crucial to move beyond prescriptive gender-based assumptions and instead prioritize teachers' individual differences and their specific needs. Furthermore, while descriptive statistics indicate subtle differences between male and female teachers, future teacher professional development programs should foster collaborative exchange between genders to leverage these complementary strengths, collectively enhancing their AI-integrated instructional competence.

4.2. The nonlinear development characteristics of AI-integrated instructional competence by years of teaching experience

This study revealed a nonlinear pattern in the development of rural teachers' AI-integrated instructional competence concerning their years of teaching experience. While

no significant differences were found in the CK, PK, and PCK across different experience groups, suggesting these competencies are primarily shaped by pre-service professional training or long-term classroom practice and are less correlated with technological iterations.

In contrast, significant differences emerged in the four technology-related dimensions: TK, TCK, TPK, and TPACK, teachers with 0–5 years of experience significantly outperformed other groups. This advantage likely stems from their exposure to more systematic modern teacher education, coupled with a stronger receptiveness and adaptability to emerging AI technologies, enabling them to better integrate AI into their teaching practices.

Notably, some senior teachers with over 20 years of experience showed no significant differences in scores across multiple dimensions compared to early-career teachers (0-5 years). This could be attributed to their participation in advanced professional development programs and their extensive teaching experience [15], which may compensate for their initial challenges in AI technology operation. In contrast, mid-career teachers (those with 6–20 years of experience) often exhibit a plateau or even a decline in AI-integrated instructional competence. This may stem from a degree of professional inertia or complacency [16]. Beyond these internal considerations, these educators frequently face increased work overload and a lack of access to professional development programs specifically tailored to their evolving needs and career stage.

In summary, rural teachers' AI-integrated instructional competence exhibits a 'high at both ends, low in the middle' non-linear pattern. This finding suggests that while the accumulation of teaching experience contributes to enhancing teachers' disciplinary pedagogical competence, AI technology integration skills do not naturally improve with increasing seniority; instead, they may encounter bottlenecks at specific career stages. Therefore, it is recommended to establish a tiered and differentiated training mechanism for rural teachers. This should focus on enhancing the AI application competence of teachers with 6–20 years of experience, providing them with more systematic and continuous AI pedagogical practice guidance. In addition, there should be a strong advocacy for establishing collaborative learning communities, collaborative teacher communities can be developed to encourage experience-sharing and mutual learning across different experience levels [17]. Finally, it is essential to improve the professional development support system in rural areas to provide teachers with sustained and effective guidance in information-based teaching.

4.3. Differentiation of rural teachers' AI-Integrated Instructional Competence by professional title

The findings indicate differentiation in AI-integrated instructional competence among rural teachers at different professional title. Significant disparities were found in the technology-related dimensions—TK, TPK, TCK, and TPACK. Uncategorized and junior teacher performed significantly better than those with intermediate or senior titles. This may be partially explained by the fact that lower-title teachers are often younger and more likely to have received systematic modern educational technology training during their pre-service education. Additionally, in pursuit of career advancement, junior teachers may be more proactive in participating in various professional development and AI technology application competence-building activities [18].

While descriptive data showed that senior teachers generally presented higher medians across all dimensions of AI-integrated instructional competence, potentially

suggesting their stronger ability to integrate AI technology with pedagogy and content for more effective teaching, it is crucial to acknowledge a limitation: the sample size for highly-ranked teachers in this study was very small (only 2 individuals). This imbalance in the professional title structure of rural teachers might have limited the statistical significance and generalizability of our findings, leading to post-hoc test results not indicating significant differences between highly-ranked teachers and other groups. Overall, these findings suggest that professional title advancement does not guarantee improved AI technology integration capabilities, instead, a unique 'junior teacher advantage' structure may exist. Therefore, it is recommended that future efforts provide more targeted AI technical training and ongoing support for intermediate and senior teachers. Concurrently, establishing collaborative professional learning communities among teachers of various professional ranks could facilitate experience sharing and mutual support, maximizing the complementary strengths across different career stages. Such initiatives may help bridge the gap between teaching experience and AI technological innovation, ultimately promoting the quality of rural education.

4.4. Limited impact of educational background on rural teachers' information-based teaching ability

This study reveals no statistically significant correlation between rural teachers' educational qualifications and their AI-integrated instructional competence, as measured by the TPACK framework, suggesting that educational background has a limited influence on their overall abilities. Analysis of educational differences revealed that within the seven dimensions of TPACK, only TK shows a significant variation, teachers holding a bachelor's degree outperform their counterparts with an associate degree or below. However, no substantial differences are observed in the remaining six dimensions. This observation aligns with existing research suggesting that formal educational background is not the sole or primary determinant of teachers' overall digital competence or AI-integrated instructional ability [19].

These findings suggest that while higher academic qualifications may enhance teachers' foundational understanding of technology, this advantage does not necessarily translate into their ability to integrate technology with pedagogy. In other words, while formal education plays a role in enhancing teachers' basic AI technological knowledge, its overall facilitative effect on comprehensive AI-integrated instructional competence is limited. Several factors may contribute to this phenomenon. Firstly, the lack of technological infrastructure and instructional support in rural schools may restrict the practical application of AI technologies in daily teaching. Second, the enhancement of AI-integrated instructional competence is often developed through practical experience accumulated in specific teaching contexts rather than formal education alone [20]. Finally, rural teachers frequently rely on in-service training and self-directed learning opportunities, which are often more directly aligned with their instructional realities than traditional degree programs. Therefore, future training initiatives for AI-integrated instructional competence in rural settings should prioritize providing teachers with ample opportunities for hands-on AI practice and personalized professional support tailored to authentic teaching contexts.

This approach aims to help teachers effectively transform AI theoretical knowledge into practical instructional abilities, thereby further enhancing their AI technology integration proficiency in actual classrooms.

5. Limitations and Future Research

Before discussing its limitations, it is important to summarize the main contributions of this research. This study adopted a quantitative approach to objectively assess current status of rural teachers' AI-integrated instructional competence in western China. By systematically analyzing large-scale data, this research provides empirical evidence for understanding the competence structure and disparities within this specific group in the intelligent era. It further offers insights for developing more targeted and feasible professional development strategies for rural teachers within an AI-empowered educational context.

However, the study has certain limitations concerning its methodology and sample selection. Firstly, regarding the research methodology, while quantitative data reveal general trends and group differences in rural teachers' AI-integrated instructional competence, it struggles to delve into the underlying profound issues and causes of observed phenomena, as well as teachers' specific perceptions, attitudes, and concerns regarding the application of AI technology. Secondly, in terms of sample selection, the study adopted a convenience sampling method, and its participants were primarily concentrated among rural primary and junior high school teachers in western China. This approach limits the representativeness of the sample, which may consequently impact the generalizability of the research findings. Building on these identified limitations, future work can be deepened and expanded in the following areas:

First, expand research methods and incorporate qualitative approaches. Building upon quantitative research, future studies should consider combining quantitative analysis with qualitative methods from the teachers' perspective. This will allow for a deeper insight into their practical needs and challenges in integrating AI technology into their instruction, thereby providing a more comprehensive and multidimensional understanding of the development mechanisms of AI-integrated instructional competence in rural educational settings. Second, enlarge and optimize the sample. Future research could consider expanding the scope of the sample coverage, employing more rigorous sampling methods such as stratified random sampling. This would involve encompassing a wider range of rural areas across different regions and economic development levels, thereby enhancing the generalizability of the research conclusions.

Third, deepen theoretical construction and explore practical models. As this study primarily focused on a status quo investigation, future research can further explore the expansion and deepening of the TPACK model within the AI context. Concurrently, a focus on specific innovative application scenarios of AI technology in rural educational practices is needed to explore and build human-AI collaborative teaching models that are more aligned with rural characteristics, ultimately providing more operational theoretical support and practical guidance for the effective application and deep integration of AI technology in rural educational settings.

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A Case-Control Study on Maternal Pregnancy and Perinatal Conditions and Childhood Attention-Deficit/Hyperactivity Disorder

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Abstract. Objective: To investigate the associations between childhood attention deficit hyperactivity disorder (ADHD) risk and key perinatal factors: maternal tobacco and alcohol exposure during pregnancy, parity, gestational age/preterm status, and delivery mode, to provide evidence for ADHD prevention. Methods: A total of 75 children with ADHD from The First People's Hospital of Chenzhou City between October 2024 and April 2025 were enrolled as the case group, while 125 children without ADHD from the same hospital served as controls. General demographic characteristics and maternal pregnancy/perinatal conditions were assessed through parent-reported questionnaires. Logistic regression was used to analyze the data. Results: The case group exhibited a 4.6-fold higher rate of prenatal tobacco exposure compared to controls (*OR*=4.626, 95%*CI*:1.439-14.874). Conversely, the proportion of full-term infants in the case group was significantly lower than in the control group (*OR*=0.260, 95% *CI*:0.084-0.809). Conclusion: Maternal prenatal tobacco exposure may be a risk factor for childhood ADHD, whereas full-term birth is a protective factor. Targeted preventive measures, including reducing prenatal tobacco exposure and preventing preterm birth, may help mitigate ADHD incidence.

Keywords. Attention-Deficit/Hyperactivity Disorder (ADHD); Pregnancy; Perinatal period; Case-control study

1. Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder characterized by inattention, hyperactivity, and impulsivity in children [1]. According to a meta-analysis, the global pooled prevalence of ADHD is 5.29% [2], with China showing a prevalence of 5-6% among children and adolescents and approximately 2.5% in adults [3]. Accumulating studies have confirmed that ADHD pathogenesis involves genetic susceptibility, adverse perinatal events, neurobiological abnormalities, and

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environmental factors, among which maternal health status during the pregnancy and perinatal periods is considered an important modifiable risk factor [4,5,6]. Growing evidence from domestic and international studies has demonstrated that Maternal Pregnancy and Perinatal Conditions constitute a significant factor influencing ADHD development [7–8], evidence indicates prenatal nicotine/alcohol exposure may disrupt fetal neurodevelopment and correlate with preterm delivery[9–10]. Separately, research suggests birth order and delivery mode may be associated with childhood ADHD risk[11]; however, existing studies on the impact of maternal pregnancy on ADHD remain inconsistent. This case-control study aimed to investigate the association of specific maternal factors−antenatal tobacco exposure, alcohol consumption, preterm delivery, birth order, and delivery mode−with offspring ADHD to inform evidence for reducing ADHD risk.

2. Methods and Materials

2.1. Study Participants

In this case-control study, 75 children aged 6–12 years with newly clinician-diagnosed ADHD were recruited from Chenzhou Children's Hospital between October 2024 and May 2025 for the ADHD group. The control group was non-ADHD children aged 6-12 years matched based on age at the same hospital during the same period. Inclusion criteria: (1) age 6–12 years; (2)first-time ADHD diagnosis according to DSM-5 criteria. Exclusion criteria: (1) Comorbid neurological deficits, intellectual disabilities, or other conditions interfering with ADHD assessment; (2) Major physical illness such as severe cardiac, hepatic, or renal dysfunction or substance dependence history. Based on previous studies reporting 28% maternal tobacco exposure prevalence in control groups, and an odds ratio (OR) of 2.705, set at $\alpha = 0.05$ (bilateral) and $\beta = 0.10$, using *PASS* software to obtain the sample size of the case group and the control group, $N1=N2=69$, and 69 cases were needed for each of the case group and the control group[12–13].

Ethical approval was obtained from Xiangnan University and The First People's Hospital of Chenzhou (Approval No.2024104), with informed consent from participants.

2.2. Study Instruments

Self-administered questionnaires were employed to gather demographic data on maternal pregnancy/perinatal conditions. The collected data encompassed the child's gender, age, birth weight, permanent household size, number of children in the household, primary caregiver, age of parents at birth, parents' education level, parents' occupation, family history of ADHD, mother's smoking during pregnancy (including passive exposure), mother's alcohol consumption during pregnancy [14-15], whether the child was full-term [16], mode of delivery, and child's birth order. [17-18].

2.3. Quality Control

During the pilot phase, a preliminary survey was conducted at the pediatric inpatient department of the Fourth People's Hospital in Chenzhou City. During formal data

collection, the questionnaires were uniformly distributed and collected on the spot; with all respondents being the children's primary legal guardians. During data processing, the questionnaires were verified promptly, incomplete questionnaires were supplemented, and unqualified questionnaires were eliminated.

2.4. Statistical Analysis

All statistical analyses were performed using *SPSS* 25.0. Normally distributed continuous variables are presented as mean ± standard deviation (SD), while non-normally distributed variables are summarized as median and interquartile range [*IQR; M (Q1–Q3)*]. Group comparisons for non-normal variables were conducted using the Wilcoxon rank-sum test. Categorical variables were expressed as frequencies and percentages (%), and between-group differences were assessed with the chi-square test. Binary logistic regression was utilized to identify factors associated with ADHD, with statistical significance defined at α=0.05.

3. Results

3.1. Demographic Characteristics

Among 220 questionnaires distributed, 200 were returned (response rate =95.65%), comprising 75 ADHD cases and 125 controls. Significant intergroup differences were observed in gender, number of siblings, primary caregiver types, paternal age at childhood, and paternal occupational category. No significant differences were observed in other demographic variables (p>0.05). See Table 1.

Table 1. Univariate Analysis of Demographic Characteristics

Factor	ADHD group(n=75)	Control group(n=125)	Z/χ^2	P
Sex（*n*,%）				
Male	65(86.7)	59(47.2)	30.990	<0.001*
Female	10(13.3)	66(52.8)		
Age[*M(P25,P75)*]，y	[9(8,10)]	[9(8,10)]	-0.572	0.567
Birth weight（*n*,%）				
<2.5kg	3(4.0)	1(0.8)		
2.5kg-4kg	65(86.7)	112(89.6)	2.449	0.294
>4kg	7(9.3)	12(9.6)		
Household Size（*n*,%）				
2 People	5(6.7)	3(2.4)		
3 People	11(14.7)	24(19.2)	2.844	0.416
4 people	33(44.0)	58(46.4)		
5 or more People	26(34.7)	40(32.0)		
Children in Family（*n*,%）				
One children	8(10.7)	33(26.4)		
Two children	51(68.0)	72(57.6)	7.225	0.027*
Three or more children	16(21.3)	20(16.0)		
Primary caregiver（*n*,%）				
Parents	38(50.7)	87(69.0)	9.622	0.022*

Father	3(4.0)	1(0.8)		
Mother	26(34.7)	32(25.6)		
Other (Grandparents)	8(10.7)	5(4.0)		
Father's Age at Child's Birth[*M(P25,P75)*], y	[31(28,36)]	[29(26.5,32)]	-2.018	0.044*
Mother's Age at Child's Birth [*M(P25,P75)*], y	[28(25,33)]	[27(25,30)]	-1.198	0.231
Father's educational level（*n*,%）				
Junior high school or below	16(21.3)	15(12.0)		
High school or below	22(29.3)	36(28.8)	3.461	0.177
College or above	37(49.3)	74(59.2)		
Mother's educational level（*n*,%）				
Junior high school or below	15(20.0)	20(16.0)		
High school or below	24(32.0)	34(27.2)	1.479	0.477
College or above	36(48.0)	71(56.8)		
Father's occupation（*n*,%）				
Worker	9(12.0)	14(11.2)		
Farmers	6(8.0)	2(1.6)		
Teachers	1(1.3)	3(2.4)		
Medical workers	3(4.0)	4(3.2)		
Self-employed	9(12.0)	37(29.6)	16.657	0.020*
Public officials	20(26.7)	22(17.6)		
Corporate Employee	18(24.0)	19(15.2)		
Retired, unemployed	1(1.3)	2(1.6)		
Service Industry Employee	3(4.0)	2(1.6)		
Others	5(6.7)	20(16.0)		
Mother's occupation（*n*,%）				
Worker	3(4.0)	5(4.0)		
Farmers	4(5.3)	3(2.4)		
Teachers	7(9.3)	7(5.6)		
Medical workers	6(8.0)	16(12.8)		
Self-employed	7(9.3)	22(17.6)	8.894	0.447
Public officials	10(13.3)	12(9.6)		
Corporate Employee	12(16.0)	13(10.4)		
Retired, unemployed	10(13.3)	17(13.6)		
Service Industry Employee	2(2.7)	9(7.2)		
Others	14(18.7)	21(16.8)		

**P<0.05*

3.2. Maternal Perinatal Characteristics

The prevalence of maternal smoking was higher in the ADHD group than in the control group (χ^2=7.273, P=0.007); Term births were less common among ADHD cases compared to controls (χ^2=6.306, *P*=0.012); The cesarean - delivery rates was higher in the ADHD group relative to the control group (χ^2=6.935, *P*=0.008). No significant inter-group differences were found for maternal alcohol consumption during pregnancy or parity. (*P*>0.05). See Table 2.

Table 2. Prenatal/Postnatal Variable Distribution Between Groups

Item	ADHD group (*n*=75)	Control group (*n*=125)	Z/χ^2	*P*
Maternal Tobacco Exposure During Pregnancy (*n*,%)				
yes	15(20.0)	9(7.2)	7.273	0.007*
no	65(80.0)	116(92.8)		
Maternal alcohol consumption during pregnancy (*n*,%)				
yes	3(4.0)	1(0.8)	1.088	0.297
no	72(96.0)	124(99.2)		
Term birth (*n*,%)				
yes	59(78.3)	114(91.2)	6.306	0.012*
no	16(21.3)	11(8.8)		
Mode of delivery (*n*,%)				
Cesarean delivery	32(42.7)	31(24.8)	6.935	0.008*
Vaginal delivery	43(57.3)	94(75.2)		
Birth order (*n*,%)				
Firstborn	36(48.0)	75(60.0)		
Second-born	33(44.0)	38(30.4)	4.401	0.221
Third-or-higher-order birth	6(8.0)	12(9.6)		

**P<0.05*

3.3. Risk Factors for ADHD

In the binary logistic regression model, using the ENTER method, ADHD diagnosis (yes=1, no=0) served as the dependent variable. Maternal smoking during pregnancy (including second-hand exposure), term birth status, and delivery mode were used as primary predictors. The model was adjusted for covariates, including the child's sex, paternal occupation, number of siblings, primary caregiver type, and paternal age at birth. The analysis indicated that maternal smoking during pregnancy (including second-hand exposure) (OR=4.376, *95% CI: 1.408~13.601*) increased the risk of ADHD, while term birth (OR=0.260, *95% CI: 0.084~0.809)* had a protective effect against ADHD. See Table 3.

Table 3. Multivariable Logistic Regression Analysis of Maternal Perinatal Characteristics

Factor	*B*	*SE*	*Wald* χ^2	*P*	*OR*	*95% CI*
Sex	1.919	0.463	17.147	0.001*	6.811	2.747-16.888
Children in Family						
One children	-	-	-	-	1.000	-
Two children	-1.185	0.569	4.347	0.037*	0.306	0.100-0.931
Three or more children	-1.620	0.688	5.552	0.018*	0.198	0.051-0.761
Primary caregiver						
Parents	-	-	-	-	1.000	-
Father	-2.786	1.562	3.180	0.075	0.062	0.003-1.318
Mother	-0.775	0.425	3.328	0.068	0.461	0.200-1.059
Other (Grandparents)	-1.830	0.789	5.384	0.020*	0.160	0.034-0.753
Father's occupation	-	-	-	-	1.000	-

Farmers	-0.351	1.102	0.102	0.750	0.704	0.081-6.097
Teacher	0.112	1.407	0.006	0.936	1.119	0.071-17.635
Medical workers	-0.433	1.243	0.121	0.728	0.648	0.057-7.415
Self-employed	0.664	0.724	0.841	0.359	1.942	0.470-8.024
Public officials	-1.090	0.695	2.462	0.117	0.336	0.086-1.312
Corporate Employee	-0.918	0.699	1.725	0.189	0.399	0.101-1.571
Retired, unemployed	-0.767	1.562	0.241	0.623	0.464	0.022-9.924
Service Industry Employee	-1.253	1.189	1.112	0.292	0.286	0.028-2.934
Others	0.561	0.810	0.479	0.489	1.752	0.358-8.566
Father's Age at Child's Birth	-0.038	0.034	1.258	0.262	0.963	0.900-1.029
Maternal alcohol consumption during pregnancy	1.476	0.579	6.511	0.011*	4.376	1.408-13.601
Term birth	-1.346	0.578	5.415	0.020*	0.260	0.084-0.809
Cesarean delivery	0.348	0.416	0.700	0.403	1.416	0.627-3.198

*$P<0.05$

4. Discussion

This study, based on survey data from a local sample, examined the influence of maternal pregnancy and perinatal factors (tobacco exposure, alcohol consumption, premature birth, parity, and delivery mode) on childhood ADHD, found that maternal tobacco exposure during pregnancy as a potential risk factor for ADHD development in offspring, full-term birth might be a protective factor. Emerging evidence suggests that ADHD should be prevented by reducing prenatal tobacco smoke exposure, avoiding preterm birth, and addressing neurodevelopmental issues of preterm infants.

The findings of this study regarding the elevated risk of ADHD in offspring associated with prenatal tobacco exposure align with previous studies. Dong T et al. [19] conducted a meta-analysis that the critical window of foetal neural development occurs during the early perinatal period, during which smoking exposure may increase ADHD risk, with a potential dose-response relationship between smoking during pregnancy and ADHD risk in progeny. A China-based cohort study further demonstrated that maternal smoking before and during pregnancy was a risk factor for ADHD in offspring [20]. Consistent with Zhao et al., who revealed robust statistical links between physiological signals and behavioral events, our findings emphasize that early biological exposures such as tobacco smoking during pregnancy can have lasting neurodevelopmental effects detectable in postnatal behavior [21]. Wickström R [22] confirmed that nicotine readily crosses the placental barrier, resulting in foetal circulatory concentrations 15% higher than maternal plasma levels, Tobacco contains high levels of nicotine, tar, and its components have neurotoxic effects on foetal development. Both of which exert neurotoxic effects on foetal brain development, particularly disrupting neural circuits associated with attention and impulse control, and this disruption can lead to the development of ADHD. Notably, our study found no association between prenatal alcohol exposure and elevated ADHD risk in offspring, which is consistent with the findings of Ren Hongling et al. [13]. However, Zheng Yuxia et al. [23] found that prenatal alcohol exposure was a risk factor for childhood ADHD through a case-control study. This limitation may be attributed to selection bias and limited sample size, as the study exclusively recruited participants from a single-center study, potentially compromising the generalisability of the findings. Future research with expanded multi-

center samples is required to validate this association. To mitigate the risk of ADHD, public health initiatives should strengthen parental education programs emphasizing avoidance of smoking, alcohol consumption, and second-hand smoke exposure during pregnancy.

Consistent with existing evidence, term birth demonstrates ADHD-protective effects. Zhao et al. [24] conducted a meta-analysis showing that preterm infants had a significantly increased risk of ADHD compared to full-term infants. This risk was particularly evident in infants born before 32 weeks of gestation and exhibited a dose-dependent relationship with preterm severity. A Spanish cohort study further revealed an inverse correlation between ADHD prevalence and gestational age, reporting a 12.7% prevalence among infants born at ≤28 gestational weeks compared to 3.2% in those born after 37 weeks. Even within the term range (≥37 weeks), the risk of ADHD increased as gestational weeks decreased [25]. Ask et al. [26] also found that preterm birth was associated with ADHD symptoms in preschool children and attentional deficits in school-aged children. Studies on the mechanisms linking preterm birth and ADHD risk have focused on the following: i. Repeated hypoxic-ischemic events associated with preterm birth may disrupt striatal pathophysiology, thereby increasing susceptibility to ADHD [27]. ii. Postnatal infections in preterm neonates contribute to ADHD pathogenesis. Preterm infants exhibit underdeveloped respiratory and immune systems, heightening their susceptibility to postnatal infections and inflammatory responses. These physiological vulnerabilities are strongly linked to adverse neurodevelopmental outcomes [28]. Studies have pointed out that active/passive smoking, alcohol consumption, and an unbalanced diet during pregnancy are risk factors for the development of preterm labor. The number of pregnancies, adverse obstetric history, and antenatal comorbidities are associated with the development of preterm labor[29] Therefore, mothers should undergo regular obstetric checkups during pregnancy for early detection of hidden dangers, adopt good living habits, maintain healthy diet, avoid exposure to harmful substances in the environment, and avoid preterm delivery to reduce the risk of ADHD.

This study observed a higher prevalence of cesarean delivery among mothers of children with ADHD (whose mode of delivery was cesarean section) compared to mothers of children without ADHD. Prior studies have shown that cesarean delivery elevates the risk of ADHD [30]. Zhang et al. [31] found a 17% increased risk of attention deficit/hyperactivity disorder (ADHD) in offspring delivered via cesarean section compared to those born by vaginal delivery through a meta-analysis. Similarly, in a cohort study, Lin et al.[32] demonstrated that after controlling for confounding factors, children delivered by cesarean had significantly higher risks of ADHD, ASD, and intellectual disability than those delivered vaginally.

The study has several limitations. Firstly, the case group demonstrated a higher proportion of male participants, with notably imbalanced baseline characteristics between groups that may limit the generalisability of findings. This gender disparity may be explained by two primary factors: firstly, Male children are more likely to manifest hyperactive symptoms, which tend to elicit greater parental recognition and subsequent clinical referral [9]; ADHD subtypes in girls predominantly manifest as inattention, disorganisation, motivational deficits, and internalising symptoms, including low mood and anxiety. These presentations feature fewer externalising behaviours than observed in boys, contributing to underdetection [33]. Again, relevant studies suggest that genetic, social psychological, and endocrine factors may contribute to boys' pronounced negative reactions to early-life stressors, lead to an increase in the rate of visits and

morbidity[34]; in addition, the study subjects were all from a single tertiary hospital's outpatient department, the limited sample size and source may have restricted the detection of potential differences. Future investigations should expand the sample size and enhance sample diversity to strengthen methodological rigor.

In conclusion, the findings establishes that gestational tobacco exposure constitutes an independent risk factor for childhood ADHD development; while full-term birth exhibits a modifiable protective effect associated with attenuated neurodevelopmental risk trajectories. These findings provide critical empirical support for the primary prevention strategies of childhood ADHD, indicating that reducing perinatal tobacco smoke exposure, avoiding preterm birth and paying attention to the neurodevelopment of preterm infants, may be clinically actionable pathway for ADHD risk reduction.

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A Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage Based on an Adapter-Tuned Large Language Model

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Abstract. Currently, there is not much research on digital preservation systems that utilize Large Language Models and have strong pertinence and timeliness for Lingnan intangible cultural heritage. This study designed a three-module collaborative digital preservation system for Lingnan intangible cultural heritage based on an adapter-tuned Large Language Model. The system consists of three major modules: data processing and analysis, display and dissemination, and user interaction. It can process and analyze data of Lingnan intangible cultural heritage, diversely display and disseminate high-quality content, and interact well with users. The content created through this system outperforms traditional cultural heritage promotional materials in multiple engagement metrics, including reading traffic, likes, comments, and shares.

Keywords. Large Language Model; Lingnan Intangible Cultural Heritage; Digital Preservation; VR; AR

1. Introduction

With the acceleration of the globalization process and the impact of modernization, many intangible cultural heritage projects, including those in the Lingnan region, are facing inheritance difficulties. Lots of valuable skills and cultures are disappearing. There is an urgent need for effective preservation and innovative dissemination methods.

In recent years, researchers and practitioners have increasingly sought innovative methodologies to modernize intangible cultural heritage preservation approaches. Jin Hui et al. combined Xiangyunsha cultural and creative products with modern daily necessities when designing and developing Xiangyunsha cultural and creative products [1]. Deqingquzhen et al. pointed out that there have been many studies and practices in the design of intangible cultural heritage display systems [2]. Du Wenxiao and others developed PC-end and mobile-end display systems for immovable cultural relics based on SuperMap and Vue, respectively. They conducted tours and displays of different types

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of cultural relic information on a digital image map with unified geographical space and scale standards. It has become an advanced means for cultural relic publicity, promotion, and preservation. [3] Li Xiaolong et al. designed and developed four aspects: a database, an intangible cultural heritage cultural portal website, an intangible cultural heritage product trade platform, and a back-end transaction management system [4]. This platform can play a good role in inheriting and developing intangible cultural heritage. Zhou Chuanting explored the design and implementation methods of a digital museum website based on HTML5 around key links such as requirement analysis, architecture design, digital resource library establishment, Web static page design, interactive design, and virtual display [5]. Then it promotes the development of intangible cultural heritage and provides certain practical references for the construction and improvement of digital museums. Hoshang Kolivand et al. used technologies such as augmented reality (AR) and 3D modeling to reconstruct historical buildings into virtual heritage buildings. These technologies are frequently applied in architectural and art-related contexts [6]. Yang, R. et al. explored the application strategy of the meta-universe [7]. Through digital reconstruction, digital twin, VR, AR, regional chain, and other technologies, intangible cultural transmission is not limited by time and space for effective communication.

This study aims to design a three-module collaborative digital preservation system for Lingnan intangible cultural heritage based on an adapter-tuned Large Language Model. Through the construction of the system framework, it improves the effect and efficiency of the preservation and dissemination of Lingnan intangible cultural heritage and helps its inheritance and development.

2. Related Technologies of the Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage

The Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage designed in this study mainly relies on Large Language Model technology and data collection and processing technology.

2.1. Large Language Model Technology

A Large Language Model is a computer model based on the deep learning technology framework. It has a huge parameter scale and can simulate human intelligence. Examples include ChatGPT and DeepSeek. These Large Language Models are trained with massive data and have strong capabilities in language understanding, generation, data processing, and knowledge reasoning.

This study's Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage uses LLaMA-2-13B-chat as the base model. Its 40-layer Decoder-Only Transformer architecture is suitable for generation tasks. The system uses the Lingnan intangible cultural heritage text dataset (containing 20,000 corpus entries) for adapter tuning. In terms of cultural adaptation strategies, the system has corrected cultural biases in the corpus. For example, the corpus integrates authoritative classics and characteristic resources from the Lingnan region. Special terms in Lingnan culture, such as "Lion Dance" (a festive dance, not an animal), "Herbal Tea" (a beverage with therapeutic effects, often not cold), "Red Boat" (referring to opera troupes), etc., have been given semantic annotations to avoid model confusion. In the system, the Large Language Model performs multi-dimensional semantic analysis through natural

language processing techniques, including sentiment analysis, topic modeling, and entity recognition, Large Language Model and explores its potential value. It provides data support for formulating and optimizing innovative dissemination strategies driven by the Large Language Model. For example, by learning a large amount of text data on intangible cultural heritage projects, the Large Language Model can automatically extract key information, summarize dissemination hotspots, and predict audience interest points.

2.2. Data Collection and Processing Technology

Data collection technology includes multiple methods such as web crawlers, API interfaces, and sensor collection. For Lingnan intangible cultural heritage, web crawlers can be used to obtain information, pictures, and videos related to Lingnan intangible cultural heritage on the Internet. Through API interfaces on smart devices, data related to users and Lingnan intangible cultural heritage can be obtained. Data from other websites and systems can also be collected into this system through API interfaces. With the help of sensors such as high-definition cameras, recording equipment, and temperature and humidity sensors, the performance process, production process, and surrounding environment of various intangible cultural heritages can be recorded. The collected data has diverse formats and uneven quality. Data cleaning, conversion, annotation, and other processing technologies are needed to transform it into structured data suitable for Large Language Model processing. It improves data quality and availability and provides a basis for in-depth research on Lingnan intangible cultural heritage.

3. Construction of the Three-Module Collaborative Digital Preservation System Based on an Adapter-tuned Large Language Model

Nowadays, there are not many studies on digital preservation systems using Large Language Models. There are also not many digital preservation systems with strong pertinence and timeliness for Lingnan intangible cultural heritage. Therefore, the digital preservation system designed in this study will focus on researching and trying to solve these problems. This study designs the user structure diagram as shown in Figure 1.

The users are intangible cultural heritage inheritors, technicians, and the public. They influence each other. Intangible cultural heritage inheritors are the information sources of Lingnan intangible cultural heritage-related information. All the information and data required and presented by the system come from them. They can also point out the deficiencies of the Digital Preservation System. Technicians manage the platform and are responsible for the whole process of collection, processing, and presentation. They ensure the normal operation of the system. The public is the audience for disseminating Lingnan intangible cultural heritage and the communicator of re-dissemination. They will also provide valuable opinions and suggestions for the system.

On the basis of this user structure diagram, this study will refine the system framework, database, and carry out a modular design of the system. During the process, this study will enhance the stability, practicability, and innovation of the system by combining Large Language Model technology with the system.

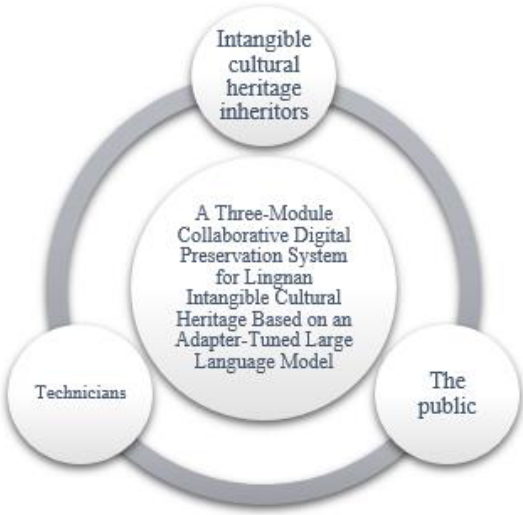


Figure 1. User Structure Diagram

3.1. System Framework Design

According to the Figure 1 User Structure Diagram, the modules required by each user are planned as a whole. The basic framework of the system is constructed as shown in Figure 2.

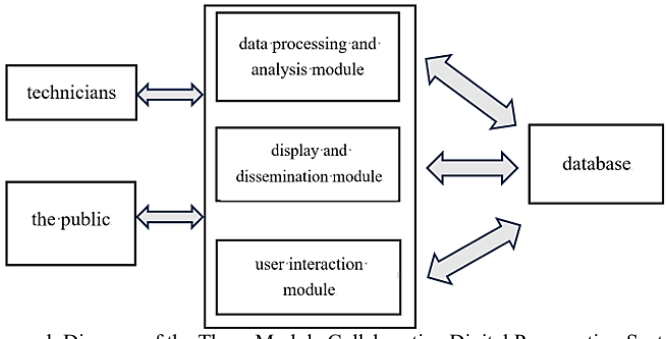


Figure 2. Framework Diagram of the Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage

As shown in Figure 2 Framework Diagram of the Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage, the framework consists of four parts: technicians, the public, modules, and the database. Among them, the modules consist of a data processing and analysis module, a display and dissemination module, and a user interaction module. Each part cooperates to realize the functions of the system.

3.2. Modular Design of the System

The Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage consists of three modules: a data processing and analysis module, a display and dissemination module, and a user interaction module, Framework Diagram

of the Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage, as shown in Figure 3.

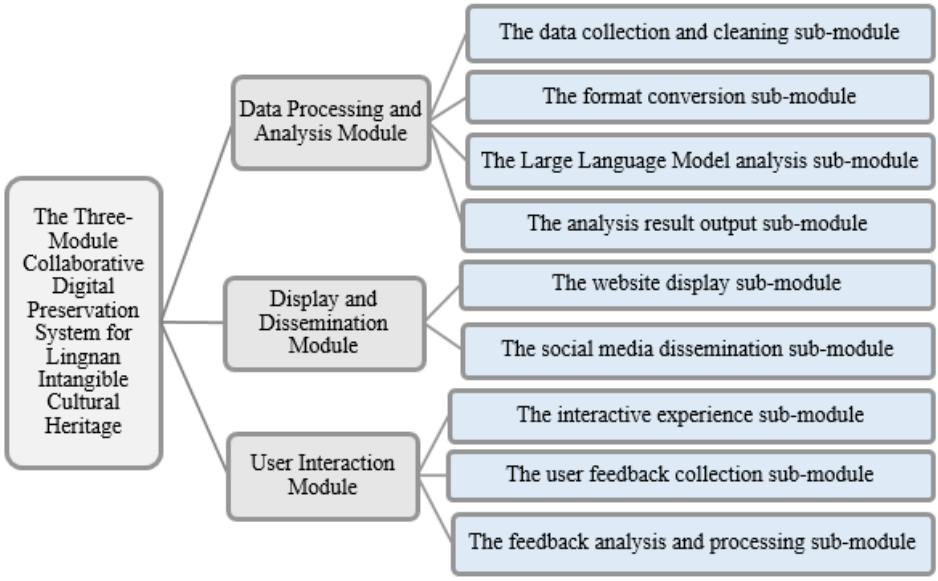


Figure 3. Framework Diagram of the Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage

3.2.1. Data Processing and Analysis Module

- The data collection and cleaning sub-module is responsible for obtaining Lingnan intangible cultural heritage data from multiple channels, such as field research, the Internet, and cooperative institutions. Then it performs operations such as deduplication and error correction on the collected data to improve data quality.
- The format conversion sub-module converts the cleaned data into a format acceptable to the Large Language Model. For example, it converts text data into a vector representation.
- The Large Language Model analysis sub-module calls the trained Large Language Model to perform operations such as semantic understanding, sentiment analysis, and topic mining on the data. For example, through semantic understanding, it analyzes the text of intangible cultural heritage project introductions and extracts key information. It uses sentiment analysis to understand the public's attitude towards different intangible cultural heritages. Through topic mining, it discovers potential communication hotspots.
- The analysis result output sub-module organizes the analysis results of the Large Language Model into structured data and outputs them to the display and dissemination module and the user interaction module. It provides a basis for subsequent display and interaction.

3.2.2. Display and Dissemination Module

The website display sub-module is responsible for building a Lingnan intangible cultural heritage display website. It sets up a homepage carousel, an intangible cultural heritage

project classification navigation bar, and a detail page for each intangible cultural heritage project. It displays various aspects of each intangible cultural heritage project, such as basic information, pictures, videos, and introductions of the inheritors.

3.2.3. User Interaction Module

- The interactive experience sub-module designs various interactive activities such as intangible cultural heritage knowledge quizzes and online manual production experiences. It encourages users to participate. Through gamification methods, it improves users' interest and understanding of Lingnan intangible cultural heritage.
- The user feedback collection sub-module sets up special feedback channels, such as online forms and comment areas, to collect users' opinions and suggestions on the display content and dissemination methods of various intangible cultural heritages.
- The feedback analysis and processing sub-module analyzes user feedback data and extracts valuable information such as users' hot topics and improvement needs for system functions. It feeds the analysis results back to the data processing and analysis module and the display and dissemination module to optimize the system content and functions and dissemination strategies. It forms a good interaction cycle.

4. Further Experiments

4.1. Experimental Purpose

The purpose of this experiment is to test the performance and effect of each module of the Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage based on an Adapter-tuned Large Language Model in actual operation.

4.2. Experimental Verification

4.2.1. Experimental Environment

In this verification, the experimental environment is first built. The construction of the experimental environment is shown in Table 1 Experimental Environment.

Table 1. Experimental Environment

Server	Database	Front-end	Back-end	Simulated User Access
Multi-CPU, memory above 16GB, hard disk above 512GB, operating system is Windows Server system	MySQL 8.0	HTML, CSS, JavaScript	Python, Flask framework	Automated testing tools (such as JMeter)

4.2.2. Experimental Scheme Design and Analysis

This study selects a certain number of Lingnan intangible cultural heritage projects as samples, covering different types of intangible cultural heritage projects. For each module of the system, corresponding experiments are designed. In the data processing and analysis module, the integrity of data collection and the accuracy of Large Language

Model processing are tested. In the display and dissemination module, the display effect of social media dissemination content is tested. In the user interaction module, the smoothness of interaction and feedback is tested.

The author collected 500 pieces of intangible cultural heritage data, such as Lingnan music and traditional handicrafts, from 10 data sources, such as public intangible cultural heritage databases (such as the Guangdong Intangible Cultural Heritage Museum), local archives, and folk documents. It compares the coverage of the data collected by this system and the traditional system with the original data. Then, 100 pieces of intangible cultural heritage data are manually annotated with cultural characteristics. The data is input into the Large Language Model of this system. It compares the accuracy of the output results of the Large Language Model of this system and the traditional system with the manual annotation. Thanks to the fluent user interaction and feedback processing, this system can further improve itself and better preserve and innovatively disseminate Lingnan intangible cultural heritage.

5. Conclusion

There are not many studies on digital preservation systems using Large Language Models. There are also not many digital preservation systems with strong pertinence and timeliness for Lingnan intangible cultural heritage. The Three-Module Collaborative Digital Preservation System for Lingnan Intangible Cultural Heritage based on an Adapter-tuned Large Language Model proposed in this study provides a new solution for the preservation and dissemination of Lingnan intangible cultural heritage. The system deeply explores the value of intangible cultural heritage through its data processing and analysis module, presents the charm of Lingnan intangible cultural heritage diversely through its display and communication module, and enhances audience participation through its user interaction module while continuously improving the system. It can effectively address some issues existing in the traditional preservation and dissemination of intangible cultural heritage. This system shows enormous growth potential.

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Towards an Intelligent and Adaptive Evaluation Framework for E-Commerce Talents in Vocational Colleges: Integrating AHP with AI-Driven Design Concepts

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Abstract. This study proposes an intelligent and adaptive evaluation framework for assessing e-commerce talents in higher vocational colleges under the "New Business" paradigm. Drawing on the Analytic Hierarchy Process (AHP), the framework integrates expert-driven judgments with competency-based evaluation indicators across six dimensions: professional knowledge, technical application, innovation, market analysis, communication, and ethics. Based on 192 valid survey responses and 10 expert consultations, an empirical AHP-based model was constructed, with indicator weights validated through consistency testing.To address the inherent subjectivity and static nature of traditional AHP, this research introduces a forward-looking design that incorporates AI-driven concepts. A three-layer intelligent evaluation architecture is proposed, consisting of data input, evaluation logic, and feedback layers. While actual AI modeling is reserved for future work, the conceptual integration outlines how machine learning, fuzzy logic, and behavioral data from LMS and internship platforms can enable dynamic weight adjustments, personalized feedback, and real-time competency profiling.This hybrid approach not only enhances the flexibility and scalability of the evaluation process but also aligns with the digital transformation of vocational education. The study provides a theoretical and methodological foundation for the development of smart evaluation platforms and future AI-powered educational decision-support systems tailored to evolving vocational demands in the digital economy.

Keywords. E-commerce education, AHP, intelligent evaluation, AI-driven framework, vocational colleges, competency assessment, adaptive learning, New Business model

1. Introduction

The global online retail market is rapidly growing, with projections indicating a rise from US$4.4 trillion in 2023 to US$6.8 trillion by 2028, driven largely by China's leadership in the digital economy [1]. This expansion is reshaping industries, introducing new business models such as live commerce, online healthcare, and remote work, and transforming consumer behaviors [2]. In response, business education, especially in fields like e-commerce, is evolving to meet these dynamic shifts. The

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concept of "New Business" is central to this change, emphasizing interdisciplinary integration, emerging technologies like big data and AI, and innovative pedagogies to equip students with a forward-looking, transdisciplinary education [3].

Despite the growing demand for e-commerce professionals, many graduates struggle to find employment due to gaps in their skill sets [4,5]. This study addresses this issue by developing a comprehensive evaluation index for "New Business" e-commerce professionals, using the Analytic Hierarchy Process (AHP) to create a quantitative model that supports both academic curricula and industry talent needs. The integration of artificial intelligence (AI) into evaluation systems is also explored to enhance adaptability and scalability, ensuring alignment with the fast-paced technological transformation of the industry.

This research also addresses the challenges in cultivating e-commerce professionals within higher vocational colleges, including outdated pedagogical approaches, lack of practical experience, and unclear program positioning [6, 7]. These challenges highlight the need for a robust evaluation system to guide curriculum development and better prepare students for the demands of modern industries [8-9]. The proposed AHP-based framework, enhanced by AI-driven design, offers a dynamic and data-informed solution to talent assessment, aligning traditional methods with the future-oriented needs of the e-commerce sector[10] .Through this hybrid approach, the study aims to bridge gaps in current evaluation frameworks and provide a scalable model for vocational education in the digital age [11-12]. AI-driven methods such as neural networks, decision trees, and fuzzy logic have been used to analyze student performance data, personalize learning pathways, and enhance decision-making accuracy in talent assessment systems [13-14].

Prior research has advanced competency-based evaluation for e-commerce from several angles. ONET-informed KSA taxonomies provide a generalizable basis for job analysis [15–17] and digital competence in the workplace [18], while AHP and its variants have been used to structure multi-criteria judgments in e-commerce talent assessment—e.g., AHP-PSO models for cross-border e-commerce talent [7] and fuzzy comprehensive schemes tailored to e-commerce training quality [8]. However, these frameworks are largely static, rely heavily on expert judgment, and seldom reflect the interdisciplinary demands of the “New Business” paradigm in higher vocational contexts [3,5]. Recent studies highlight the promise of AI to reduce subjectivity and enable adaptive, data-informed assessment, including fuzzy-AHP applications in customer/FinTech settings [10], hybrid deep-learning and ontology-driven evaluation [13], and generative-AI-enabled learning analytics [14]. Building on these strands, this study proposes an AHP-based index specifically tailored to higher vocational e-commerce programs and outlines an AI-enhanced architecture to support dynamic weight updating, real-time feedback, and scalable implementation

2. E-Commerce Professionals Evaluation Index System Design

2.1. Expert Consultation and Weight Determination

This study utilized a dual-sampling approach to gather a comprehensive dataset. The first phase involved a quantitative survey, where a Likert-scale questionnaire was distributed to e-commerce professionals working in higher vocational colleges and e-commerce-related businesses in Xuzhou. The survey aimed to assess the importance of

various skills and competencies under the "New Business" framework. A total of 200 questionnaires were distributed, resulting in 192 valid responses, which represents a 96% response rate.

The second phase involved a qualitative survey targeting a panel of 13 industry experts and educators with extensive experience in fields such as e-commerce education, curriculum design, talent management, and business administration. Of the 13 experts, 10 completed the survey, yielding a 77% response rate. This panel was instrumental in validating the evaluation index framework. The combination of responses from e-commerce professionals and experts allowed for a robust assessment of the proposed evaluation index system, ensuring its practical applicability and theoretical soundness. The feedback from both groups was used to determine the weights of the indicators in the final evaluation index.

While the steps of AHP follow the classical model proposed by Saaty (1980), this study extends its application by integrating the weight outputs into a broader AI-enhanced framework (see Section 3.3). In particular, the AHP weights serve as the initial structure for future dynamic adjustments using machine learning models, which allows the framework to evolve over time with the accumulation of educational and behavioral data.

2.2. Selection of evaluation indicators

The evaluation index system for e-commerce professionals in higher vocational colleges adopts a competency-based approach, drawing on the O*NET framework [15]. It identifies the key knowledge, skills, and abilities (KSAs) necessary for success in the e-commerce industry, with a balanced emphasis on both hard and soft skills. The system is organized into six key dimensions [16-18], which will be summarized in the table below in table 1 for clarity and ease of understanding.

Table 1. Evaluation index system of talent literacy of electronics professionals

	Primary indicators	Secondary indicators	Reference
Evaluation index system of electronic professional talent quality in higher vocational colleges and universities	E-commerce Professional Knowledge (A)	E-commercebPlatform Operation（A1）	[18-19]
		Digital Marketing Strategy（A2）	
		Data Analysis and Application（A3）	
		Logistics-related Knowledge（A4）	
		E-commerce-related Legal Knowledge（A5）	
	Technical Application Skills（B）	Website Development and Management（B1）	[20-23]
		Database Management（B2）	
		Information Security Management（B3）	
		E-commerce System Application（B4）	
		Search Engine Optimisation（B5）	
		Application of AI Technologies（B6）	
	Innovation（C）	Innovative Thinking and Practice（C1）	[24-25]
		Entrepreneurial Spirit and Business Model Innovation（C2）	
		Product Development and Management（C3）	
	Market Analysis and Planning（D）	Consumer Behavior Analysis（D1）	[26-27]
		Market Research and Forecasting（D2）	
		Brand Management and Promotion（D3）	
	Communication and Collaboration Skills（E）	Cross-departmental Communication Skills（E1）	[28-29]
		Project Management and Execution（E2）	
		Teamwork and Coordination（E3）	
		Cross-cultural Communication Skills with a	

	Global Perspective（E4）	
Social Responsibility and Professional Ethics （F）	User Data Privacy Protection（F1）	[30-34]
	Sustainable Development Awareness（F2）	
	Business Integrity（F3）	
	Ability to Manage Work Pressure（F4）	
	Professional Dedication（F5）	
	Customer Service Orientation（F6）	

2.2.1 Hierarchical analysis method

Hierarchical analysis is a multi-criteria decision making method.The Analytical Hierarchy Process (AHP) proposed by Saaty (1980) has been widely used in the evaluation of complex multi-criteria scenarios in a number of fields. The method has advantages in terms of simplicity, systematic construction of problems, and calculation of criterion weights and alternative priorities. In AHP, the problem is first decomposed into a hierarchical structure that consists of objectives (final goals), criteria (direct influences), and sub-criteria (indirect influences), in a hierarchical progression; subsequently, a decision matrix is computed; and finally, the optimal solution is selected. The specific steps are as follows.

- Construct a judgement matrix:

$$A=\begin{bmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2n} \\ \cdots & \cdots & a_{ij} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & \cdots & a_{nn} \end{bmatrix}$$

In the pairwise comparison matrix, each element a_{ij} represents the relative importance of criterion A compared to criterion B. A value of $a_{ij} > 1$ indicates that A_i is more important than A_j ; $a_{ij} = 1$ signifies that A_i and A_j are equally important.

- Matrix element importance judgement

The Analytic Hierarchy Process (AHP) begins with the construction of a pairwise comparison matrix using a standardized judgment scale, as shown in Table 2.

Table 2. Pairwise Comparison Scale for Relative Importance

Scale	Meaning
1	Two factors are equally important.
3	One factor is slightly more important.
5	One factor is moderately more important.
7	One factor is strongly more important.
9	One factor is extremely more important.

2、4、6、8	Intermediate values between adjacent judgments
1/x	The reciprocal of the original comparison

- Calculate the weight vector of the indicators

First: the matrix is normalised using the following equation:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (i, j = 1, 2, \cdots n) \tag{1}$$

where is the data in the ith row and jth column of the judgement matrix A and is the data in the ith row and jth column of the normalisation matrix.

Second: add the elements of the matrix.

$$\overline{w_i} = \sum_{j=1}^{n} b_{ij} \quad (i, j = 1, 2, \cdots n) \tag{2}$$

Third: For w_i in the above equation, normalisation is performed:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}} \quad (i = 1, 2, \cdots n) \tag{3}$$

where w_i is the weight of the ith indicator

Fourth: Compute the largest eigenvalue of the judgement matrix A

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(Aw)_i}{w_i} \tag{4}$$

Where n is the order of the matrix, A is the judgement matrix and w_i is the weight of the ith indicator.

$\lambda_{\max}$ is the largest eigenvalue of the judgement matrix A.

- Consistency test, for the vector obtained earlier, as well as the eigenvalues, consistency test, if you can pass the test, it means that the judgement matrix is reasonable, that is, there is the value of interpretation.

To assess the consistency of the judgment matrix, the Random Index (RI) is used, as presented in Table 3. Assuming that CI stands for Consistency Indicator, the following arithmetic.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{5}$$

Table 3. Randomised consistency indicator RI（）

N	RI
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45

10	1.49
11	1.51

With the value of n, it is possible to obtain the value of RI and so obtain the consistency ratio : $$CR = \frac{CI}{RI} \quad (6)$$

When CR<0.1, then the test meets the requirement.

2.2.2 Determination of evaluation indicator weights

Based on the established index system, a panel of domain experts independently assessed the relative importance of each indicator using a scoring system. Following individual scoring, the results underwent internal discussion and refinement, yielding the pairwise comparison matrix below(table 4):

Table 4. Discriminant matrix of Primary Indicators

Column1	A	B	C	D	E	F
A	1	3.0157	4.429	2.9242	3.637	1.9175
B	0.3316	1	3.3539	1.4182	2.0939	0.3671
C	0.2258	0.2982	1	0.2747	0.5	0.328
D	0.342	0.7051	3.6399	1	2.9926	0.4409
E	0.275	0.4776	2	0.3342	1	0.3429
F	0.5215	2.7241	3.049	2.2679	2.9159	1

- Calculating the Maximum Eigenvalue: The maximum eigenvalue (λmax = 6.2465) of the pairwise comparison matrix was calculated.
- Consistency Ratio Check: A consistency check was performed to validate the reliability of the pairwise comparison matrix. The consistency index (CI) was calculated using the following formula:

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{6.2465-6}{6-1} = 0.0493 \quad (7)$$

where λmax represents the maximum eigenvalue and n denotes the matrix order (number of indicators).

- The average random consistency index (RI) was then determined based on the matrix order. The consistency ratio (CR) was calculated as:

$$CR = \frac{CI}{RI} = \frac{0.0493}{1.24} = 0.0398 < 0.10 \quad (8)$$

Given that the CR value was below 0.1, the pairwise comparison matrix was deemed acceptable. Therefore, the weights for each indicator were calculated, as shown in the table below.

Utilizing the aforementioned methodology, the weights for each indicator at each hierarchical level, as well as the overall global weights, were calculated (see Table 5).

Table 5. Summary of Weights for the E-commerce Professional Competency Evaluation Index System

Primary Indicators	Weighting value	Secondary indicators	Weighting value	Combined Weighting value
A	0.3433	A1	0.1609	0.055237
		A2	0.2518	0.086443
		A3	0.0998	0.034261
		A4	0.0499	0.017131
		A5	0.4376	0.150228
B	0.142	B1	0.0488	0.00693
		B2	0.1269	0.01802
		B3	0.0659	0.009358
		B4	0.1264	0.017949
		B5	0.3827	0.054343
		B6	0.2491	0.035372
C	0.0539	C1	0.3106	0.016741
		C2	0.1266	0.006824
		C3	0.5628	0.030335
D	0.1451	D1	0.1675	0.024304
		D2	0.5306	0.07699
		D3	0.3018	0.043791
E	0.0782	E1	0.1354	0.010588
		E2	0.5533	0.043268
		E3	0.2445	0.01912
		E4	0.0668	0.005224
F	0.2374	F1	0.0682	0.016191
		F2	0.0416	0.009876
		F3	0.0909	0.02158
		F4	0.2626	0.062341
		F5	0.1603	0.038055
		F6	0.3764	0.089357

2.3. Establishing Evaluation Criteria for New Business E-commerce Professionals

To facilitate the practical application of the e-commerce professional competency evaluation index system, a scoring rubric was developed: the "Evaluation Score Standard for New Business E-commerce Professionals". This rubric provides a straightforward and objective method for assessing the competencies of New Business e-commerce professionals, offering ease of use and practical applicability. A three-point scoring system was adopted for each competency level: Fully Meets Criteria, Partially Meets Criteria, and Does Not Meet Criteria.(Table 6)

Table 6. Competency Evaluation Scoring Rubric for E-commerce Professionals

Ranking of evaluation indicators		Evaluations		
Primary indicators	Secondary indicators	Fully Meets Criteria	Partially Meets Criteria	Does Not Meet Criteria
E-commerce Professional Knowledge (34 points.)	E-commerce Platform Operation (5points.)			
	Digital Marketing Strategy (9points.)			
	Data Analysis and Application (3points.)			
	Logistics-related Knowledge (2points.)			
	E-commerce-related Legal Knowledge (15points.)			
Technical Application Skills	Website Development and Management (1points.)			
	Database Management (2points.)			

（14points.）	Information Security Management（1points.）
	E-commerce System Application（1points.）
	Search Engine Optimisation（5points.）
	Application of AI Technologies（4points.）
	Innovative Thinking and Practice（2points.）
Innovation（5points.）	Entrepreneurial Spirit and Business Model Innovation（1points.）
	Product Development and Management（3points.）
Market Analysis and Planning（15points.）	Consumer Behavior Analysis（3points.）
	Market Research and Forecasting（8points.）
	Brand Management and Promotion（4points.）
	Cross-departmental Communication Skills (1points.)
Communication and Collaboration Skills（8points.）	Project Management and Execution（4points.）
	Teamwork and Coordination（2points.）
	Cross-cultural Communication Skills with a Global Perspective（1points.）
	User Data Privacy Protection（2points.）
Social Responsibility and Professional Ethics（24points.）	Sustainable Development Awareness（1points.）
	Business Integrity（2points.）
	Ability to Manage Work Pressure（6points.）
	Professional Dedication（4points.）
	Customer Service Orientation（9points.）

3. Research Conclusions and Recommendations

3.1. Research Conclusions

The evaluation framework shows that "E-commerce Professional Knowledge" holds the highest weight among primary indicators, highlighting the importance of a strong foundation in e-commerce for professional success in the field. This emphasizes the need for both theoretical understanding and practical training to meet industry demands. The second-highest weighting for "Social Responsibility and Professional Ethics" underscores the critical role of character development in cultivating well-rounded professionals who can support the sustainable development of the e-commerce industry.

Among the secondary indicators, "E-commerce-related Legal Knowledge" stands out, emphasizing the importance of legal knowledge for ensuring regulatory compliance and protecting all stakeholders. "Digital Marketing Strategy," "Market Research and Forecasting," and "Customer Service Orientation" also have significant weights, highlighting the need for professionals with a broad set of competencies. Mastery of digital marketing, market analysis, and customer service is crucial for staying competitive in a dynamic e-commerce environment.

3.2. Policy Recommendations

3.2.1 Clarify Training Priorities and Implement Holistic Talent Evaluation

The significant weighting of "E-commerce Professional Knowledge" (0.34) emphasizes its importance in talent cultivation. Training programs should focus on both theoretical knowledge and practical applications, incorporating case studies and hands-on projects.

The weighting of "Social Responsibility and Professional Ethics" (0.24) calls for specialized courses and community engagement opportunities to develop ethical awareness. A diversified evaluation system that includes exams, practical assessments, and peer evaluations should be implemented to assess competencies comprehensively.

3.2.2 Strengthen Core Courses and Enhance Skill Development

Core courses should focus on e-commerce operations, digital marketing, and logistics, ensuring they reflect the latest industry trends. Courses on "Social Responsibility and Professional Ethics" should be integrated throughout the curriculum. Skill development initiatives should complement each primary indicator, including IT applications, data analytics, innovation workshops, and market research training to enhance students' capabilities.

3.2.3 Monitor Industry Trends and Establish a Feedback Mechanism

Regular assessments of industry needs are essential to ensure training programs align with market demands. A multi-channel feedback system, incorporating student feedback on learning experiences, employer feedback on graduate performance, and institutional evaluations, should be established. Advanced data analytics can be used to analyze feedback, providing insights into areas requiring curriculum adjustments, such as improving innovation skills. These insights should inform curriculum updates, teaching methodologies, and evaluation adjustments to remain relevant to industry changes.

3.3. Intelligent Framework Design: AI-Driven Enhancements to the AHP-Based Model

While the current study relies on expert-informed Analytic Hierarchy Process (AHP) to construct a talent evaluation index system, it also anticipates the integration of intelligent technologies to enhance the system ' s accuracy, adaptability, and scalability. This section presents the conceptual design of an intelligent evaluation framework that retains the AHP core while leveraging artificial intelligence (AI) for future dynamic assessment.

The intelligent evaluation framework is composed of three layers: Data Input Layer, Evaluation Logic Layer, and Output & Feedback Layer.

（1）Data Input Layer

- Expert Judgments: Used to construct the initial AHP structure and indicator weights.
- Student Performance Data: Including survey responses, digital training logs, project assessments, and internship evaluations.
- Employer Feedback: Qualitative insights into graduates' workplace competencies.
- Learning Behavior Records: Captured via Learning Management Systems (LMS) and training platforms.

（2）Evaluation Logic Layer

- AHP Engine: Performs initial weighting based on expert pairwise comparisons.

- AI Module (Optional): Utilizes supervised learning (e.g., neural networks or decision trees) to adjust and optimize weights based on longitudinal data.
- Fuzzy Logic Extension: Converts subjective judgments into fuzzy sets to manage uncertainty in indicator comparisons.
- Dynamic Weight Adjustment: Enables real-time refinement of indicator significance based on evolving data.

（3）System Functionality and Potential

The framework supports both static evaluations (using AHP-derived scores) and adaptive evaluations (through machine learning). It can be integrated into e-learning platforms or function as a standalone tool. The long-term goal is to develop a "Smart Evaluation Platform" that adapts with user data, fostering individualized development plans for e-commerce students and continuous feedback into instructional design.

4. Discussion and Future Research

This study contributes to e-commerce talent evaluation by offering a data-driven, empirically validated framework for the "New Business" model in higher vocational education. Unlike previous frameworks, our approach integrates a comprehensive index system, developed through literature review and expert input, addressing various perspectives on e-commerce talent. AHP analysis and expert input highlight the importance of E-commerce Professional Knowledge and Social Responsibility as well as Professional Ethics, emphasizing the need for foundational knowledge and ethical business conduct in today's commercial environment. These findings align with current views on the role of ethics and social responsibility in business education.

Our study advances the field by presenting a more comprehensive and contextually relevant evaluation index for e-commerce professionals. Combining quantitative (AHP) and qualitative (expert validation) methods ensures both theoretical depth and practical applicability. Key contributions include:

- A focus on challenges and talent gaps in Higher Vocational Colleges;
- Integration of the "New Business" model into the evaluation framework;
- A combination of quantitative and qualitative methods;
- A forward-looking intelligent evaluation framework incorporating AI.

However, limitations exist. The survey's sample is concentrated in Jiangsu Province, and expert judgments may introduce biases due to the subjectivity of AHP [35]. Further validation and adaptation of the framework are needed as the "New Business" model evolves.

The findings suggest that higher vocational education should emphasize e-commerce knowledge, ethical awareness, and social responsibility. Future research should explore the impact of this evaluation index on student outcomes and its application across various settings. Further studies could also refine the scoring rubric and explore comparisons with other evaluation methods.

Looking ahead, future research should focus on implementing the intelligent evaluation framework in practice. Integrating AI techniques such as supervised machine learning and fuzzy logic into the AHP model can enhance the precision,

adaptability, and scalability of the framework. Real-time competency profiling, personalized learning recommendations, and longitudinal studies tracking student outcomes and employer satisfaction will help validate the framework's effectiveness. Blockchain technologies could also be explored to ensure data transparency and credibility in certification and credential verification.

In conclusion, the proposed intelligent evaluation framework provides a foundation for future innovations in vocational education. With AI integration and data-driven methodologies, this model can evolve into a comprehensive solution for assessing e-commerce talent. Pilot implementations in select programs are recommended to test the system's real-world applicability and refine its capabilities.

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Reflections and Explorations on Higher Vocational Education Reform in the Wave of Artificial Intelligence

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Abstract: The latest wave of artificial intelligence (AI) is profoundly reshaping production modes, industrial ecosystems, and occupational structures. As an essential segment of vocational education, higher vocational colleges are simultaneously compelled by AI-driven technologies and tools to upgrade their own systems and entrusted with the historic mission of cultivating high-caliber technical and skilled personnel for intelligent manufacturing and modern service industries. This paper traces the three paradigm shifts of AI waves and, following the "technology–education coupling" thread, situates the new wave within a dialectical framework of "change and continuity": the inevitable transformation of tool morphologies triggered by emerging AI technologies, the rising demands for data, computing power, and energy, and the reconfiguration of industrial ecosystems; meanwhile, the vocational genes of "occupational anchoring and industry–education integration" remain unchanged. The study argues that higher vocational education should seize key levers—including curricula, pedagogy, governance, and industry–education collaboration—and promote adaptive development through faculty renewal, dynamic adjustment of AI+X programs, and the construction of a pluralistic evaluation system.

Keywords: artificial intelligence; higher vocational education; technology–education coupling; Transformer; industry–education integration

1. Research Background

Recent leaps in LLMs such as ChatGPT and DeepSeek have thrust generative AI from lab to shop-floor, triggering three industrial shocks: job re-structuring, skill drift, and urgent demand for hybrid talent [1]. As AI tools infiltrate every link of vocational education—curriculum, training, assessment, governance—traditional content, pedagogy, and faculty roles are being deconstructed [2]. Re-igniting the vocational DNA of "occupational anchoring and industry‑education integration" amid the cognitive revolution [3], new data-energy-compute demands, and ethical risks is now the inescapable mandate for higher vocational colleges [4].Besides the literature review, this study employs a mixed-methods design conducted throughout 2024: over 500 questionnaires were distributed to enterprise mentors and students, complemented by

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semi-structured interviews with nine senior executives and twelve higher-vocational teachers.

2. Technological Evolution and Genealogical Analysis of Artificial Intelligence

2.1. Overview of the Three Waves in AI Development

Since the 1956 Dartmouth Conference, artificial intelligence has undergone three distinct waves. The first wave (1956–1980s) was dominated by symbolic AI; reasoning was simulated in closed worlds through predicate calculus, production rules, and expert systems that encoded knowledge as "if-then" statements. Progress stalled, however, owing to the difficulty of knowledge acquisition and the problem of combinatorial explosion. The second wave (1980s–2010s) shifted to data-driven approaches: support-vector machines, random forests, and shallow neural networks leveraged kernel tricks and ensemble strategies to achieve breakthroughs in perceptual tasks such as speech and character recognition, laying the industrial groundwork for machine learning. The third wave (2012–present) is anchored in deep neural networks and centered on the Transformer self-attention mechanism. Hierarchical distributed representations, residual connections, and large-scale pre-training have enabled end-to-end modeling that seamlessly links perception, cognition, and decision-making, thereby igniting the generative-AI revolution [5].

2.2. Characteristics and Inherent Dilemmas of the Three Dominant AI Paradigms

The history of AI can be interpreted through three paradigms: symbolic, behaviorist, and connectionist. Symbolic AI explicitly encodes knowledge via predicate calculus, frames, and expert systems to pursue closed-form reasoning. Yet it is constrained by Gödelian incompleteness, the knowledge-acquisition bottleneck, and combinatorial explosion, rendering it ill-suited for open-world scenarios. Behaviorism, rooted in cybernetics, seeks to elicit intelligence through "perception-action" feedback loops in physical interaction, giving rise to early robotics and reinforcement learning. However, its limited capacity for abstract cognition and language, together with poor transfer and generalization, has pushed it toward the periphery. Connectionism relies on distributed neural networks that implicitly learn patterns from massive data via differentiable optimization. Although it excels in image and language tasks, it suffers from black-box opacity, ethical-compliance risks, and the sustainability challenges posed by voracious computational demands [6].

3. Scrutinizing the New Variables in the Latest Wave of Artificial Intelligence

The new variables and core technologies propelling this wave are neural networks—most notably the Transformer architecture—which mark a decisive vindication of the connectionist paradigm.

3.1. Technological Perspective

The Transformer's revolutionary impact can be read along three axes. First, computational paradigm: self-attention collapses the sequential recursion of RNNs into a single, global dependency operation, enabling long text, speech, or video to be trained in one shot. Second, hardware affinity: the Query–Key–Value triad maps cleanly onto dense matrix multiplications that Tensor Cores on GPUs/TPUs can execute in parallel, boosting training throughput by one to two orders of magnitude and underwriting the "brute-force aesthetics" of large models. Third, architectural depth: multi-head attention captures semantics at multiple granularities in parallel, positional encodings preserve order, and residual connections plus LayerNorm stabilize gradients. Together these design choices allow networks to scale to hundreds of layers without overfitting. Consequently, language, vision, protein-folding, and even robotic policy networks now reuse the same backbone, converting quantitative scale into qualitative breakthroughs and igniting the current generative-AI surge.

3.2. Philosophical Perspective

The "emergent abilities" of large language models (LLMs) challenge the classical "representation–rule" epistemology. One camp argues that LLMs merely perform statistical modeling of formal symbols and possess no genuine semantic understanding; the other contends that functional semantics can arise through external tools and interactive environments. This dispute creates an epistemological tension for vocational education: precisely how should we teach learners to collaborate—symbiotically and critically—with AI systems [7].

4. Dialectical Analysis of "What Changes and What Endures" in Higher Vocational Education under the New AI Wave

4.1. Evolution of Production Paradigms: New Technologies Drive New Tools and Reshape the Shop-Floor

- Edge innovation: "Data-labeling factories" now pre-label images with AI and slice tasks, upgrading low-skill roles to "AI supervisor–human collaborator."
- Convergence innovation: AIGC text-to-image tools generate defective-sample data for few-shot learning, shortening model-iteration cycles and creating a new skill stack of "prompt engineering + vision-model fine-tuning."
- Process re-engineering: LLMs auto-generate quality-inspection reports, shifting inspectors from "defect recognition" to "root-cause analysis," with domain knowledge and prompt design becoming decisive.
- Digital employees: AIGC-RPA hybrids create digital workers that close the loop "read-email→draft-reply→update-ERP," evolving the traditional automation paradigm into a new "human–machine–machine" collaboration model.

4.2. Evolution of Industry Demand: LLM Deployment Reshapes the Industrial Ecosystem

Once LLMs leave the laboratory, industry must solve three consecutive hurdles—"understand, answer accurately, and run efficiently"—spawning three application needs and a chain-reaction talent gap in data, energy, and compute.

- Generalization need (understand): Embed industry jargon and business flows into conversational context to raise open-domain accuracy without retraining, establishing a semantic baseline for later fine-tuning.
- Specialization need (answer accurately): Use RAG to attach domain knowledge bases, mitigating hallucinations and obsolescence while aligning with corporate norms—technically feasible and ethically controllable.
- Miniaturization need (run efficiently): Quantization and structured pruning compress models to the edge; an edge-cloud synergy trains in the cloud, infers offline locally, and even enables one-click invocation via WeChat mini-programs — low-cost and high-concurrency.

These new industry demands signal that higher vocational programs must anticipate and realign curricula: adding modules on LLM training, deployment, operation, and testing while addressing data bias, algorithmic discrimination, and value alignment.

4.3. Enduring Logic of Industry‑Education Coupling: The Underlying Mechanism Remains Unchanged

When AI as a new means of production is embedded into the production system, traditional posts disappear rapidly and new ones emerge, forcing an adaptive reconstruction of production relations. The fundamental logic of vocational education—matching personnel capabilities to job requirements—has not altered.

The dynamic relationship between higher vocational education and technology likewise persists. A "technology‑education coupling" four-quadrant model can be used: 1) technology-driven→education adapts; 2) technology-embedded→education restructures; 3) education-leading→technology is regulated;4) education‑technology co-innovation. Programs can flexibly switch among the four quadrants according to professional maturity and industry life-cycles, sustaining a dynamic equilibrium.

5. Breakthrough Points for Higher Vocational Education Reform—Action Paths under the "Technology‑Education Coupling" Framework

5.1. Anchor the Vocational Gene: Consolidate the "Technology‑Education Coupling" Base through Deep Industry‑Education Integration

Regardless of how AI evolves, the irreplaceable constant is the deep coupling between technology and vocational education. Industry‑education integration is the genetic expression of vocational education; its essence lies in bridging the gap between learning and labor through authentic work-process knowledge situated in real contexts. Therefore, deep industry‑education integration must be used to solidify the coupling

base.

5.2. From Order-Based Training to Collaborative Innovation

To keep pace with rapidly iterating industrial demands, a closed loop of "enterprise poses the problem—school solves the problem—market validates the solution" is needed, making industrial pain points the starting line for both curriculum and research. University–enterprise co-creation pushes industry–education integration to the value-co-creation layer.

5.3. Faculty 5C Re-Engineering

A "5C" developmental pathway is constructed: Concept→Configuration→Co-creation → Case → Certification.Rolling, cyclical certification ensures that faculty remain synchronized with the industrial frontier and resonate with the fundamental mission of education.

5.4. Dynamically Tune AI+X Programs

Real-time scraping of big recruitment data maps job-competency demands onto learning outcomes, enabling annual rolling revisions of talent-cultivation schemes. Micro-specializations such as prompt engineering, AIGC quality inspection, and digital-employee operations are added, allowing programs to "breathe in sync" with industry.

5.5. Curriculum Shift: From Knowledge-Based to Task-Cluster–Competency Units

Large language models are embedded as "cognitive partners." Typical occupational scenarios serve as the warp, task-clusters as the weft; courses are decomposed into iterable "competency units," forming a ternary interactive scene of "human–machine–task" to ensure seamless toggling between "learning by doing" and "doing by learning" [8].

5.6. Pedagogical Shift: From Teacher-Centered to Learning Ecosystem

Create an "AI dual-teacher classroom": human teachers concentrate on emotional scaffolding, value clarification, and higher-order thinking guidance, while AI agents—though incapable of dispensing direct emotional solace—render emotional support quantifiable and replicable through data triggers and workflow orchestration. The two agents dynamically divide labor and co-evolve within the classroom space-time continuum, jointly constructing a learning ecosystem tailored to every individual learner.

5.7. Bridging the Gap Between Industry–Education Integration and AI-Enabled Development

Field investigations reveal that only a handful of enterprises currently embed

higher-vocational interns in front-line AI positions, and merely a minority of students are granted access to proprietary corporate models during internships. To close the gap, the following pathways are recommended: integrate coursework modules that expose learners to enterprise private-model APIs and compliance-oriented training; co-build lightweight sector-specific models within university–enterprise data sandboxes; and incorporate "operation of enterprise private models" into the 1+X certification framework, thereby aligning capability, demand, and standards.

5.8. Pluralistic Certification: Project–Task–Portfolio

A ternary assessment system of "project–task–portfolio" is constructed. Portfolios must pass enterprise user tests before recognition; all artifacts are blockchain-certified, generating mutually recognized micro-credentials. These stack vertically with 1+X certificates and align horizontally across ecosystems, providing learners with flexible growth pathways.

5.9. Governance Shift: From Bureaucratic to Data-Driven

An educational big-data dashboard is built to track learner competency growth curves in real time, forming a closed loop of "data–insight–intervention." Educational management no longer relies on static reports and administrative directives; instead, dynamic data enable precise allocation of resources and pedagogical adjustments, advancing governance from experience-based to evidence-based.

6. Conclusion and Outlook

Under the tide of artificial intelligence, higher vocational education is undergoing a spiral ascent—from being technologically compelled, to educationally responsive, and ultimately to co-innovative. Through a dialectical lens of "what changes and what endures," this paper argues that, however radically AI reshapes tool morphologies, the foundational logic of vocational education—"cultivating irreplaceable competencies for authentic occupational contexts"—remains immutable. Yet the cognitive revolution triggered by large models, together with new demands for data, energy, and computing power, as well as the attendant risks of hallucination, bias, and ethical drift, oblige educational paradigms to evolve in real time. Grounded in the "technology–education coupling" model, the eight action paths proposed herein integrate learning analytics, eye-tracking data, and enterprise performance metrics to furnish quantitative evidence for decision-making and instructional refinement.

At the policy level, a three-tier "national–provincial–institutional" linkage is recommended: The national tier should release dual catalogues—"AIGC Occupational Classifications" and "AI Tool-Chain Curriculum Standards." Provinces should build cross-campus shared public training bases and data-labeling platforms. Institutions should anchor long-term university–enterprise coupling through "problem-chain" projects. Only by doing so can higher vocational education accomplish a paradigmatic leap from "adapting to technology" to "leading technology," thereby fulfilling its foundational and strategic role within the nation's new-quality productive-force system.

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Analysis of Influencing Factors for the Development of China's Scientific and Technological Innovation from an Educational Perspective — Based on the TOPSIS-DEMATEL-AISM Model

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Abstract. The 18th National Congress of the Communist Party of China proposed implementing an innovation-driven development strategy, emphasizing that scientific and technological innovation is a strategic support for enhancing social productivity and comprehensive national strength, and must be placed at the core of the country's overall development. Deeply exploring the potential relationships between various components of the education system and the development of scientific and technological innovation is of great significance for improving China's scientific and technological innovation capabilities. By constructing an entropy-weighted TOPSIS model, this study quantitatively investigates the impact of factors such as educational funding investment, scale structure, human resource input, and policy environment on scientific and technological innovation development. Additionally, a DEMATEL-AISM model is constructed to further explore the pathways of influence among these factors. The research finds that educational resource investment has a significant driving effect on the resilience of scientific and technological innovation, serving as a root influencing factor, while talent cultivation also exerts a strong direct impact on its development. This indirectly confirms the rationality and necessity of China's continuous increase in R&D expenditure.

Keywords. Scientific and Technological Innovation Education, TOPSIS DEMATEL-AISM

1. Introduction

Science and technology are powerful engines driving social progress. In the context of the accelerating evolution of the once-in-a-century transformation, scientific and technological innovation has transcended the scope of pure technology and economy,

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becoming a strategic choice for national competition. For China, building a scientific and technological innovation system with Chinese characteristics is not only an inherent requirement for achieving high-quality development but also a strategic choice in response to profound changes in the international landscape.

Current research highlights education's key role in driving sci-tech innovation. Scholars like Zwetsloot [1], Kerr [2], and Moretti [3] analyzed talent strategies, mobility, and agglomeration, noting that attracting overseas talents and using talent clusters boost technological competitiveness. Hsieh et al. [4] stressed STEM education policies directly increase patent output. Chinese researchers such as Dai Mucai [5], Li Daokui [6], Wang Huiyao, and Miao Lu [7] explored high-skilled talents, talent-attraction policies, and the balance between cultivating and introducing talents in China's innovation efforts.

However, existing studies have limits. Due to the complexity and dynamism of education and innovation systems, prior research struggles to comprehensively measure the combined effects of multiple educational factors on sci-tech innovation. To fill this gap, this study uses the entropy-weight TOPSIS model (to quantify and rank the influence of various educational factors on innovation) and the DEMATEL-AISM model (to uncover their regulatory paths), offering a deeper understanding of the education-innovation relationship [8,9].

2. Methods

2.1. Establish the entropy weight TOPSIS model

The TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) [7] calculates the differences between each type of education indicator and the best and worst solutions respectively, thereby obtaining the relative closeness of each education indicator to the best solution. Based on this relative closeness, the effectiveness and efficiency of education indicators can be ranked, and the role of education demand can be evaluated accordingly.

2.2. Establish the Demate-AISM model

This study also employed the Dematel-AISM model to further explore and analyze the pathways by which different educational indicators regulate the development of scientific and technological innovation. DEMATEL (Decision Experiment and Evaluation Experiment Method) quantifies the direct and indirect influences among various educational indicators by constructing a causal relationship matrix, thereby clarifying the degree and importance of the influence of each educational indicator. Youdaoplaceholder0 (Adversarial Explanatory Structure Model) can be used to analyze the relationships of factors in complex systems [8]. The hierarchical structure and pathways of each educational indicator can be clearly presented by referring to the AISM model based on the DEMATEL model.

2.3. Indicator Description

This study selected 19 indicators in four categories from 2015 to 2022, namely educational fund investment, educational scale and structure, educational human resource investment, and educational policies and environment, as independent variables and training data, while the contribution rate of China's scientific and

technological progress was taken as the target variable. Table 1 presents the specific indicators and their units, all of which are derived from the China Statistical Yearbook from 2006 to 2022.

Table 1 Selection of Educational Indicators

Category	Indicator	Unit
Investment in education funds	Educational funds	Ten thousand yuan
	Operating funds for private schools	Ten thousand yuan
	The proportion of total government education expenditure	%
	All kinds of school education funds and business income	Ten thousand yuan
	The percentage of expenditure on educational institutions in GDP	%
Education scale and structure	The number of ordinary undergraduate graduates	Ten thousand people
	The number of master's graduates	Ten thousand people
	The number of doctoral graduates	Ten thousand people
	The number of regular institutions of higher learning	a
	The number of junior high schools	a
	The number of ordinary primary schools	a
	The number of postgraduate training institutions in scientific research institutions	a
	The number of regular senior high schools	a
Investment in educational human resources	The number of full-time teachers in regular institutions of higher learning	Ten thousand people
	The number of full-time teachers in undergraduate institutions	Ten thousand people
	The number of full-time teachers in senior high school education	Ten thousand people
	The number of full-time teachers in junior high school education	Ten thousand people
Education Policy and Environment	National financial education funds	Ten thousand yuan
	Social donation funds for various types of school education funds	Ten thousand yuan

3. Empirical Analysis

Based on the TOPSIS model of entropy weight, we will further explore the influence of each factor on the development of scientific and technological innovation. Meanwhile, based on the DEMATEL model, we will incorporate the AISM model to further explore the action paths of each factor in the development of scientific and technological innovation.

3.1. Result Analysis of the Entropy Weight TOPSIS model

Based on the evaluation and calculation results with Table 2 of educational indicators of the entropy weight TOPSIS model, analyzed from the positive ideal solution distance (D), the D value of educational funds is 0, indicating that it is completely

consistent with the ideal input state for promoting scientific and technological innovation. The D value of national financial education funds is 0.070249775, deviating from the ideal state to a relatively small extent, indicating that stable financial input has laid a solid foundation for the long-term development of education and scientific research. The relative proximity (C) of the two reached 0.353554333 and 0.283356617 respectively, ranking among the top in all indicators, further confirming that resource input indicators have a significant positive promoting effect on scientific and technological innovation.

Table 2. Evaluation and calculation results based on the entropy weight TOPSIS model

Indicator	D	D-	C	Ranking
Educational funds	0	0.353554333	1	1
All kinds of school education funds and business income	0.293972568	0.059644316	0.168669311	4
Operating funds for private schools	0.351923423	0.001651107	0.004669756	2
National financial education funds	0.070249775	0.283356617	0.801333413	3
Social donation funds for various types of school education funds	0.352769824	0.00078768	0.00222787	5
The number of doctoral graduates	0.353554333	0	0	13
The number of master's graduates	0.353554291	4.25357E-08	1.20309E-07	12
The number of ordinary undergraduate graduates	0.353554029	3.05666E-07	8.64551E-07	8
The number of graduates from regular junior colleges	0.353554042	2.92079E-07	8.26123E-07	9
The number of adult undergraduate graduates	0.353554244	8.97643E-08	2.53891E-07	18
The number of adult junior college graduates	0.353554236	9.86874E-08	2.79129E-07	17
The number of graduates from senior high school education	0.353553369	9.84247E-07	2.78386E-06	14
The number of graduates from junior high school education	0.353553207	1.13601E-06	3.21312E-06	11
The number of full-time teachers in regular institutions of higher learning	0.353554209	1.2504E-07	3.53667E-07	10
The number of full-time teachers in undergraduate institutions	0.353554248	8.60965E-08	2.43517E-07	15
The number of full-time teachers in junior colleges	0.3535543	3.37214E-08	9.53783E-08	7
The number of full-time teachers in senior high school education	0.353554137	1.98455E-07	5.61313E-07	16
The number of full-time teachers in junior high school education	0.35355406	2.7579E-07	7.8005E-07	6

Furthermore, from the perspective of the negative ideal solution distance (D-), the D- value of the national fiscal education funds is 0.801333413, which is far from the negative ideal solution, indicating that this indicator performs well in supporting scientific and technological innovation. However, the D-values of some indicators are relatively small and close to the negative ideal solution, indicating that these indicators have a limited promoting effect on scientific and technological innovation. Overall, in the current education indicator system, resource input has had a positive impact on scientific and technological innovation.

Therefore, the government can focus on increasing the input of resources for the development of scientific and technological innovation, and continuously increase the financial input in education, especially tilting towards the fields that directly serve scientific and technological innovation. Secondly, actively broaden the sources of educational funds. Through policies such as tax incentives and honor incentives, guide enterprises and social organizations to increase educational donations, and improve the connection mechanism for the use of social donation funds in scientific and technological innovation.

3.2. Analysis of results of the Dematel-AISM model

Table 3. Calculated Index values Based on the DEMATEL model

Indicator	ID	R	D+R	D-R
Educational funds	1.4089	1.1417	2.5506	0.2672
All kinds of school education funds and business income	1.3366	1.2766	2.6132	0.06
Operating funds for private schools	0.8323	0.7464	1.5787	0.0859
National financial education funds	1.746	0.8457	2.5918	0.9003
Social donation funds for various types of school education funds	0.6888	0.8690	1.5579	-0.1802
The number of doctoral graduates	0.4711	0.7101	1.1812	-0.239
The number of master's graduates	0. 5459	0.8262	1.3722	-0.2803
The number of ordinary undergraduate graduates	0.7958	1.0779	1.8737	-0.2821
The number of graduates from regular junior colleges	0.645	1.0070	1.6520	-0.3621
The number of adult undergraduate graduates	0.4755	0.5322	1.0077	-0.0567
The number of adult junior college graduates	0.4653	0.5260	0.9913	-0.0606
The number of graduates from senior high school education	0.6966	0.5923	1.2889	0.1043
The number of graduates from junior high school education	0.5226	0.5923	1.1149	-0.0697
The number of full-time teachers in regular institutions of higher learning	1.0112	0.8595	1.8707	0.1516
The number of full-time teachers in undergraduate institutions	0.8641	0.9013	1.7654	-0.0373
The number of full-time teachers in junior colleges	0.6943	0.7864	1.4807	-0.0921
The number of full-time teachers in senior high school education	0.5208	0.4698	0.9906	0.0509
The number of full-time teachers in junior high school education	0.5097	0.4698	0.9795	0.0398

Table 3 shows educational resource input indicators, such as educational funds and national fiscal educational funds, stand out in influencing sci-tech innovation. With high centrality, they hold key system positions; national fiscal educational funds, with a large positive cause degree, are a major root driver affecting other factors. Talent cultivation indicators, like the number of graduates at all levels, though mostly with negative causality and more influenced by others, still have a significant direct role, reflecting their importance. Teacher-related indicators vary: some full-time teacher indicators have positive causality, promoting sci-tech innovation. Overall, educational

resource input is a key driver for stable sci-tech innovation, while talent cultivation also matters.

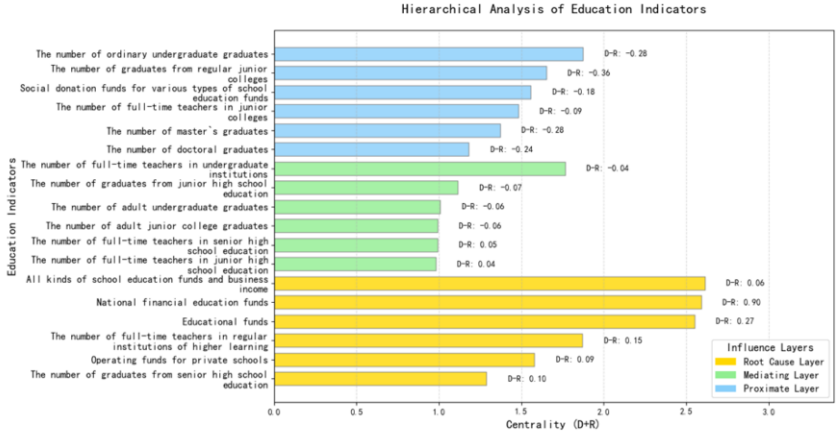


Figure 1. Ranking of Centrality of Educational Indicators and Degree of Cause (Layered Display)

To explore direct influence degrees of educational indicators, we calculated based on the DEMATEL model's comprehensive influence matrix to get an adjacency matrix, then performed hierarchical extraction to obtain Figure 1, analyzing hierarchical relationships and mechanisms.

Figure 1 shows centrality and cause degrees of educational indicators. Yellow area indicators such as higher education institutions' educational expenditure income, national fiscal educational funds, and educational funds have high centrality and cause degrees, holding core positions in the education system, indicating educational resource input is a key root factor for sci-tech innovation. Blue area talent cultivation indicators such as the number of ordinary undergraduate graduates and ordinary junior college graduates are in the direct influence layer with moderate centrality; their cause degrees are both positive and negative, meaning talent cultivation is influenced by others yet has counter-effects, serving as important manifestation indicators in sci-tech innovation development.

The centrality and causality of green area indicators are mostly at the middle level. For instance, the number of full-time teachers in undergraduate institutions and the number of adult undergraduate graduates are in the middle influence layer, indicating that they cannot directly affect the development of scientific and technological innovation.

4. Conclusions

This study reveals the mechanism by which the education system influences the development of scientific and technological innovation through hierarchical analyses using the entropy-weighted TOPSIS model and the DEMATEL-AISM model [10]. The core logical chain is "root driving force of resource input → direct role of talent cultivation → path dependence of multi-factor collaboration", which together form a complete chain of education empowering scientific and technological innovation. Based on the results, key conclusions are drawn as follows:

1. Input in educational resources is the root driving factor for scientific and technological innovation

The entropy-weighted TOPSIS model shows that educational funds have a positive ideal solution distance of 0 and the highest relative proximity. The DEMATEL model indicates their high centrality, confirming them as "root influencing factors" and forming a transmission chain from resource input to talent cultivation.

2. Talent cultivation is a direct link in scientific and technological innovation

The DEMATEL-AISM model shows that indicators like the number of ordinary undergraduate and junior college graduates are in the "direct influence layer", directly correlated with innovation achievements. Combined with the entropy-weighted TOPSIS model, the DEMATEL model reveals that high-level talents are core carriers in the process from basic research to technological breakthroughs.

Social donation funds provide insufficient support for innovation; adult education talents show weak adaptability to innovation needs; industry-academia-research cooperation indicators have low correlation, leading to limited conversion efficiency of resource input.

Meanwhile, the suggestions are drawn as follows:

1. Establish a "precision-oriented" educational resource input mechanism: Allocate part of fiscal educational funds to update scientific research instruments, establish a dynamic monitoring mechanism for input and output, and enhance social donation support through policies.

2. Create a "stratified" talent cultivation system: Strengthen school-enterprise joint training for ordinary undergraduates and junior college students, and establish a linkage mechanism between high-level talents and scientific research projects.

3. Improve a "closed-loop" collaborative mechanism: Encourage private colleges to jointly build innovation workshops with tech enterprises, and promote the connection between adult education courses and industrial innovation needs.

Data Availability Statement

The raw data supporting this study are available from the National Bureau of Statistics of China (http://www.stats.gov.cn).

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Section IV

Interdisciplinary Applications of Digitalization and Management Innovation

Digitalization and Management Innovation IV
A. Lau and A.J. Tallón-Ballesteros (Eds.)
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The Promoting Effect of Land Transfer on Rural Industrial Integration: An Empirical Analysis Based on Provincial Panel Data①

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Abstract: This study examines the impact of land transfer on rural industrial integration and its mechanisms using provincial panel data from 2010 to 2024 and a fixed-effects model. Results show that land transfer significantly promotes rural industrial integration in China, with varying effects across regions and a nonlinear growth pattern. The primary mechanisms include enhancing human capital, advancing agricultural technology, and increasing farmers' income. The findings provide insights for policy formulation in rural development contexts.

Keywords: Land Transfer, Rural Industry Integration, Mechanism Analysis, Nonlinear Growth

1. Introduction

The integration of rural sectors, based on the "sixth industrialization" theory, promotes rural economic growth by combining agriculture with secondary and tertiary industries [1]. This integration accelerates factor mobility, promotes industrial clustering, increases farmers' income sources, revitalizing the rural economy and addressing rural aging and depopulation [2][3]. Land transfer, which involves the conveyance of rural land management rights, is crucial for realizing rural industrial integration [4]. It enhances land property rights intensity, lowers transaction costs, and stimulates land element vitality, fostering large-scale farming and extending the agricultural industry chain [4]. It also frees up labor from primary agriculture and channels it into agricultural product processing and service industries, igniting the "endogenous dynamics" for rural three-sector integration [5][6]. Existing research on the impact of land transfer on rural economic growth is limited, particularly in terms of mechanism analysis [7]. This paper aims to fill this

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gap by analyzing panel data from 30 Chinese provinces (2010 - 2024) using a fixed-effects model. It examines the influence of land transfer on rural industrial integration across three dimensions: human capital, agricultural technology, and farmers' income. The study seeks to elucidate the mechanisms involved and provide empirical evidence and theoretical support for rural development-related policy making.

2.Theoretical Framework

2.1 Theoretical Basis of "Integration of Three Industries"

The models $1 + 2 + 3 = 6$ and $1 \times 2 \times 3 = 6$ symbolize the integration process. The additive model highlights the combined value of agriculture, processing, and services, while the multiplicative model emphasizes exponential growth through inter-industry interaction. These models illustrate how integrating the three industries can create a more efficient and sustainable rural economy [1]. The integration of three industries is based on industrial structure evolution and industrial linkages. In rural contexts, this integration promotes deep integration between agriculture, processing, and services, driving rural industrial transformation and sustainable economic development [3][4].

2.2 Economic Principles of Land Transfer

Land transfer is essential for rural industrial integration, as China's fragmented agricultural land restricts large-scale farming [5]. By clarifying and transferring land rights, it strengthens property rights, reduces transaction costs, and enhances land use efficiency, thus promoting large-scale farming and extending the agricultural industry chain [6][7]. This also frees up labor for processing and service industries, driving rural three-industry integration. Based on property rights theory, transaction cost theory, and economies of scale, land transfer improves resource efficiency and productivity [8][9][10]. While prior studies have shown its positive impact on rural economic growth and industrial integration [11][12], empirical research on this topic remains limited. This study fills the gap by analyzing panel data from 30 Chinese provinces using a fixed-effects model, examining the impact of land transfer on rural industrial integration through human capital, agricultural technology, and farmers' income.

3. Literature Review

3.1 Domestic Research Status

Land transfer can free up rural labor and boost farmers' non-agricultural income[1], and enhance agricultural productivity [2]. Rural industrial integration is considered crucial for sustainable rural economic development [3]. Some studies have examined the impact of land transfer on rural industrial integration, finding that it promotes large-scale farming and technological advancement [4]. However, most research

focuses on qualitative analysis, lacking a comprehensive theoretical framework and empirical validation.

3.2 International Research Status

Studies on agricultural integration of its drivers and impacts through industrial organization and supply chain management have been conducted[5]. Land transfer research mainly focuses on institutional frameworks, transfer models, and policy effects, suggesting that well-designed systems can improve land use efficiency [6]. Some studies also explore the mutually reinforcing relationship between land transfer and agricultural industry integration, highlighting their joint contribution to rural economic growth [7]. However, these studies are mostly based on their own national contexts, limiting their applicability to China's situation.

3.3 Innovation and Contribution of This Study

This study innovates by developing a comprehensive index system to measure rural industry integration across key dimensions (human capital, agricultural technology, and farmers' income) and using panel data with a fixed-effects model to empirically analyze the impact of land transfer. It provides precise evidence on how land transfer enhances rural development through positive effects on human capital, technology, and income, while highlighting regional and temporal differences.

4. Research Design and Data Description

4.1Indicator Selection and Construction of the Evaluation Index System

An evaluation index system for rural industrial integration is shown in Table 1.

Table 1 Rural Industry Integration Evaluation Index System

Target Layer	First-level Index	Second-level Index	Third-level Index
Rural Industry Integration	Industrial Extension	Agricultural Product Processing (A1)	A1 = Main business income of agricultural product processing / Total output value of primary industry
		Farmers' Cooperatives(A2)	A2 = Number of farmers' cooperatives / Labor in primary industry
	Industrial Intersection	Facility	A3 = Facility agriculture area / Total crop sown area
		Agro-related Services(A4)	A4 = Output value of Agro-related Services / Total output value of primary industry
	Industrial Penetration	Agricultural Mechanization(A5)	A5 = Total power of agricultural machinery / Total contracted land area
		Rural Information(A6)	A6 = Rural Internet broadband users / Total administrative villages
	Industrial Cycle	Renewable Resource Utilization(A7)	A7 = Bioga sproduction / Labor scale in primary industry
		Agricultural Film Usage (A8)	A8 = Agricultural film usage / Total crop sown area

4.2 Core Explanatory Variables and Control Variables

The primary explanatory variable is the land transfer rate, which indicates the extent of land transfer activity in a specific region. The formula as follows: $Rolt_{iq} = \frac{X_{iq}}{Y_{iq}} \times 100\%$ (1)

Here, $Rolt_{iq}$ denotes the land transfer rate in Province i during Year q, X_{iq} represents the total area of contracted land transferred in Province i during Year q, and Y_{iq} indicates the total area of contracted land under management in Province i during Year q. Control Variables:

- Rural Human Capital: Measured by the ratio of the rural population with a college degree or higher to the primary industry workforce.
- Urbanization: Measured by the ratio of urban population to total population.
- Financial Support: Measured by the proportion of expenditures on agriculture, forestry, and water resources relative to the overall public budget expenditure.
- Agricultural Loans: Reflects the investment of new rural business entities.
- Farmers' Income: Measured by the income from farmers

4.3 Model Construction

Utilizing panel data from 30 Chinese provinces ,a fixed-effect model is established:

$$Fu\sin g_{it} = \beta_0 + \beta_1 Rolt_{it} + \beta X_{\mathrm{it}} + \mu_{it} \quad (2)$$

$Fusing_{it}$ indicates the rural industry integration index, $Rolt_{it}$ denotes the land transfer rate, X_{it} refers to the control variables, i signifies the province, t represents the year, β_0 is the constant term, β_1 is the regression coefficient for the land transfer rate, β_2 is the regression coefficient for the control variables, and U_{it} is random disturbance term.

4.4 Data Description and Descriptive Statistics

Regional Division: Based on economic development levels, the 30 provinces are categorized into three regions:

- **Eastern Region:** Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan;
- **Central Region:** Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan.
- **Western Region:** Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, The Northeast region (Note: The Northeast region comprising Liaoning, Jilin, and Heilongjiang, is included in the Western region due to its smaller sample size for this analysis). Panel data exclude Tibet due to significant missing data for some variables.

Missing Data processing: Missing data are handled using linear interpolation and nearest distance imputation methods[①]. Descriptive statistics variables are shown in Table 2.

[①] Data sources include: China Rural Economic Management Statistical Yearbook, China Farmers' Professional Cooperatives Development Report, China Rural Statistical Yearbook, China Statistical Yearbook.

Table 2 Descriptive Statistical Results of Variables

Variable	Sample Size	Mean	Standard Deviate	Maximum Value	Minimum Value
Rural Industry Integration	450	0.4066	0.2190	0.9993	0.0662
Land Transfer	450	22.8371	17.5455	87.3400	1.3551
Human Capital	450	0.0001	0.0001	0.0008	0
Urbanization	450	54.0868	13.8338	89.6000	26.8700
Agricultural Financial Support	450	364.5777	283.6285	1310.8900	5.7985
Agricultural Loans	450	5663.4420	6828.4390	38314.8700	9.9800
Farmers' Income	450	3515.5700	1634.9020	8264.3000	589.7000

5. Empirical Results Analysis

5.1 Benchmark Regression

The fixed-effects model is used as the primary regression model, with random-effects and pooled OLS models as robustness checks. Land transfer significantly promotes industrial integration. Specifically, a 1% increase in the land transfer rate is associated with a 0.0066 increase in the industry integration index, indicating approximately a 1.8% improvement in rural industrial integration.

5.2 Regional Regression Analysis

The impact of land transfer on rural industrial integration varies across regions. In the eastern region, land transfer promotes integration by enhancing human capital; in the central region, it drives integration by increasing farmers' income; in the western region, where the economy is underdeveloped, land transfer facilitates integration by improving agricultural technology and raising farmers' income.

5.3 Stage Regression Analysis

The research period is divided into three stages based on legal and policy changes related to rural land contracting and management rights. The relationship between land transfer and three-industry integration is nonlinear over time.

- In 2010-2014, A 1% increase in land transfer scale led to a 0.0013 increase in industry integration, driven by initial optimization of agricultural internal structure.
- In 2015-2019, The same increase led to a 0.0072 increase, as land transfer attracted production factors like funds and technology, and the cumulative effect of the previous stage fully released the integration effect.
- In 2020-2024, The increase led to a 0.0035 rise, possibly due to national policies guiding a large influx of agricultural production factors, causing a "crowding effect," and some regions' integration stabilizing, leading to a relative decline in the driving effect of land transfer.

6. Mechanism Analysis

6.1 Overall Mechanism Analysis

Land transfer significantly promotes rural industrial integration via three key pathways: enhancing human capital, advancing agricultural technology, and increasing farmers' income.

6.2 Regional Impact Mechanism

The impact of land transfer on rural industrial integration differs across regions:

- Eastern Region: Enhances human capital.
- Central Region: Boosts farmers' income.
- Western Region: Improves agricultural technology and increases income.

Overall, A 1% increase in the land transfer rate leads to approximately a 1.8% rise in integration, driven by enhanced human capital, improved agricultural technology, and increased investment (Table 3).

Table 3 Regression Results of Regional Impact Mechanism of Land Transfer on Rural Integration

Region	Variable	Human Capital	Agricultural Technology	Farmers' Income
Eastern Region	Land Transfer	0.0094***	0.0286	0.0020
	Urbanization	0.9219*	72.4768***	1.7316***
	Financial Support for	0.1520**	-1.9103*	0.0881**
	Agricultural Loans	0.1010**	2.2531***	0.0366
	Sample Size	150	150	150
	Variable	**Human Capital**	**Agricultural Technology**	**Farmers' Income**
Central Region	Land Transfer	-0.0143	0.1619	0.0114***
	Urbanization	3.6413***	22.1986	0.6611***
	Financial Support for	-0.0946	-1.7217	0.0862***
	Agricultural Loans	0.1940	4.3191***	0.0165
	Sample Size	90	90	90
	Variable	**Human Capital**	**Agricultural Technology**	**Farmers' Income**
Western Region	Land Transfer	0.0045	0.1092**	0.0135***
	Urbanization	2.3084***	20.5154***	1.1805***
	Agricultural Financial Support	-0.0006	-1.3718*	0.0767***
	Agricultural Loans	0.1211***	5.2466***	0.0274*
	Sample Size	210	210	210

7. Conclusions and Policy Suggestions

7.1 Conclusions

Land transfer significantly boosts rural industrial integration. Specifically, a 1% increase in the land transfer rate leads to a 1.8% rise in integration, driven by enhanced human capital, improved agricultural technology, and increased investment. However, this impact varies across regions and over time.

7.2 Policy Suggestions

Promote Land Transfer and Reform: The government should facilitate orderly land transfer and deepen land management reforms. Establish rural land transfer service platforms at city, county, and township levels to provide policy propaganda and information exchange services for new agricultural business entities.

Targeted Monitoring and Evaluation: Conduct targeted monitoring and evaluation of the economic benefits of land transfer to maximize rural industrial integration benefits. Ensure policies are effective and adaptive to local conditions.

Regional Differentiation and Focus Areas:

- Eastern Region: Encourage return entrepreneurship by college students and migrant workers. Provide investment support, risk assessment, tax incentives, and agricultural loans to promote high-quality integration.
- Central Region: Coordinate economic growth, rural labor transfer, and urbanization. Address rural infrastructure shortcomings and optimize the agricultural industry structure to increase farmers' income.
- Western Region: Consolidate poverty alleviation achievements, improve rural internet coverage, and integrate modern information technology into traditional agriculture to develop new industries like rural e-commerce.

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The Price Strategy of Ride-Hailing Service Under Government Supervision: Coexistence Target vs Environmental Target

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Abstract. The rise of ride-hailing platforms has significantly disrupted traditional taxi services, prompting governments to implement regulatory policies. We build price competition model and adopt regulated price to regulate the ride-hailing service in this paper given the strong influence of pricing on demand. The emergence of ride-hailing services leads to a sharp decline in taxi demand. Furthermore, the environmental benefits of ride-hailing remain contested. Differing from the previous studies, we take into account two regulation targets from the perspective of taxi demand and the environment impact. Moreover, we also differentiate between two ride-hailing service models, i.e., solo rides and ride-pooling, based on perceived service level. Our study investigates how regulatory policies influence platform pricing strategies. The findings indicate that regulated pricing may increase optimal prices, contingent on service type and taxi fare structures. Additionally, we demonstrate that environmental regulations tend to be less stringent.

Keywords. Ride-hailing service, taxi service, coexistence target, environmental target

1. Introduction

The emergence of app-based ride-hailing services has challenged the dominance of traditional taxis, leading to a marked decrease in their usage [1-2]. It has sparked large-scale protests from taxi drivers worldwide, claiming the conditions for ride-hailing drivers were still unfair in comparison with the regulations they had to comply with.

Another controversial issue related to ride-hailing service is its effect on environment. Numerous studies by scholars and policymakers have identified a range of adverse effects associated with ride-hailing rides. Unlike traditional taxi services, a ride-hailing platform usually does not own a vehicle fleet [3]. Instead, drivers operate as independent contractors, using their personal vehicles to provide ride services [4]. Research indicates that a ride-hailing service trip generates approximately 20% more

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greenhouse gas emissions than a trip taken in a personal vehicle, primarily due to additional vehicle miles traveled during deadheading [5]. Ride-hailing services are replacing not only private car trips but also more sustainable transportation options like biking and public transit. A Union of Concerned Scientists report estimates that the average ride-hailing trip generates 69% more emissions than the trips it displaces. Specifically, single-passenger ride-hailing trips emit about 47% more CO_2 than private car trips, whereas pooled rides (shared by two passengers) have a carbon footprint comparable to that of a private car journey. To mitigate these environmental concerns, several states in the US have proposed measures to reduce vehicle traffic. For example, in early 2020, the Chicago administration did enact a sort of traffic congestion tax that increases the cost of single rides. This measure aims to encourage users to opt for ride-pooling services during peak hours, thereby reducing overall traffic congestion and associated emissions.

We are interested in studying the influence of regulated price on the ride-hailing platform' price strategy to facilitate the coexistence between ride-hailing platforms and traditional taxi services. Considering two types of ride-hailing service, we also concentrate on the supervision target concerned with environment issues. Specifically, we attempt to answer the research questions as follows: (1) How can the ride-hailing platform make its pricing strategy compete with taxi service under regulation? (2) How do the supervisory targets (i.e., coexistence target and environmental target) affect the platform's pricing strategy?

To address the above research questions, we first analyze the demand for taxi service without competition. Subsequently, we describe the demands for both services in a competitive market setting. Note that taxi price usually remains constant regardless of whether ride-hailing services enter or not. Then, we derive the platform's optimal price for solo-ride service (ride-pooling service) under different supervisory targets. paragraph.

2. Literature review

This study contributes to the expanding literature on the economic strategies of ride-hailing services. Existing research has extensively examined operational strategies, e.g., subsidy, prices and wages, due to the popularity of ride-hailing services [6-7]. Comparing with the static pricing (i.e., the platform maintained the price per ride unchanged), While [8] demonstrated that static pricing (fixed per-ride costs) generates higher platform revenue compared to dynamic pricing, [9] argued that dynamic pricing ensures better service quality during peak demand. Further, [7] empirically confirmed that dynamic pricing can simultaneously boost revenue and customer throughput. [10] extended the analysis by modeling market equilibria in pooled and non-pooled systems, incorporating both waiting and pick-up times. Unlike the above literature, we consider the supervisory strategy in addition to the pricing strategy of the platform for various ride-hailing services in the competition between taxi service and ride-hailing service.

Our study examines the ride service market, encompassing both taxi services and ride-hailing platforms. While existing research has extensively explored the impact of ride-hailing services on the taxi industry, findings remain inconsistent. [11] demonstrated that Uber's market entry reduced taxi driver incomes by approximately 10%, while [12]'s analysis of 44 Chinese cities (2010-2016) revealed a 17.83% decline in traditional taxi ridership using multiperiod DID methods. Similarly, [1] observed significant ridership losses among younger, wealthier riders following ride-hailing's emergence, a pattern

echoed in [2]'s Ghana-based research. In contrast, [13] highlighted competitive benefits, noting that Uber's presence forced quality improvements in traditional taxi services. Departing from these empirical approaches, our research employs a decision model to systematically analyze ride-hailing's effects on taxi services under both regulated and unregulated market conditions.

Existing literature has proposed various regulatory approaches, including official platform partnerships, driver caps, and minimum wage requirements [14-16]. Using queuing theory, [17] evaluated multiple policies, such as driver limits, wage floors, and congestion taxes, and found that while minimum wages benefit drivers and riders, they negatively impact platform revenues. Unlike [17], we investigate how different ride-hailing service types (e.g., solo vs. pooled rides) influence regulatory effectiveness. [14] examined two ride-hailing modes—solo and pooling services with congestion externalities—proposing that platforms should pursue first-best regulatory outcomes. While we similarly analyze solo and pooled services, our focus shifts to how regulatory objectives shape ride-hailing pricing strategies. [12] employed a Stackelberg game model to study taxi and ride-hailing competition under both regulated and unregulated conditions, revealing that platforms charge higher prices and earn greater profits without regulation. Although our study, like [12], examines taxi and ride-hailing competition, we further distinguish between ride-hailing service types and regulatory targets, offering a more nuanced framework for policymaking.

3. Model without supervisory policy

3.1. Riders' choice

We consider a ride-hailing platform (denoted by *R* for short) who may offer solo-ride service (denoted by *SR* for short) or ride-pooling service (denoted by *RP* for short). Riders choose between these ride-hailing options and traditional taxi services, creating a market with two transportation modes: taxi services and ride-hailing services. Based on the perceived service level of ride-hailing service α, we classify two competition cases, i.e., solo-ride (ride-pooling) service vs taxi service, which are denoted by *ST* and *RT* for short. For simplicity, we normalize the service level of taxis to 1. Accordingly, we could derive that the perceived service level of solo-ride (ride-pooling) service is $\alpha > 1$ ($\alpha < 1$). Note that there are various factors such as price and service quality impact rides' choice. Here, we use service level to characterize the service quality briefly. [18] suggests that price elasticities in ride-hailing markets are 4–10 times stronger than service quality elasticities. This allows us to streamline the analysis while capturing the dominant market dynamics.

In this study, we examine how ride-hailing services impact traditional taxi services within a two-mode transportation market (taxi and ride-hailing), treating other alternatives like public transit as outside options. Prior to ride-hailing's market entry, taxis operate as monopolists serving riders with heterogeneous preferences. We model rider heterogeneity through their perceived value of taxi service, denoted by a random variable v. v follows a uniform distribution, $U(0,V)$, with the total market size is normalized to 1. Let p_T represent the taxi price. Note that the government sets the taxi price considering public transport capacity and road resource constraints. Therefore, we

further assume the taxi price is given as $\tilde{p}_T$. A rider's utility from choosing taxi service is given by $U_T(v, \tilde{p}_T) = v - \tilde{p}_T$, while the utility of alternative options (e.g., public transit) is normalized to zero. Consequently, the monopoly taxi demand (M case) is $\lambda_T^M = 1 - \frac{\tilde{p}_T}{V}$.

In a competitive market setting, riders evaluate ride-hailing services based on their perceived value, adjusted by the service type. The utility of choosing ride-hailing service is given by $U_R(\alpha v, p_R) = \alpha v - p_R$, where p_R represents the platform's price. Riders may opt for alternative transportation options if using either taxi or ride-hailing services results in negative utility. However, when both services yield positive utility, rational riders will choose the option that maximizes their utility. Specifically, they will select the service providing the higher positive utility. This decision-making process allows us to determine the equilibrium distribution of passengers between taxi and ride-hailing services across various cases as shown in Proposition 1.

Proposition 1. The rider demand for both taxi services λ_T and ride-hailing services λ_R is given by:

$$\lambda_{T-ST} = \begin{cases} 1 - \frac{\tilde{p}_T}{V}, & \text{if } p_{RS} > \tilde{p}_T + \delta_{ST} V \\ \frac{p_{SR} - \alpha_{SR}\tilde{p}_T}{\delta_{ST} V}, & \text{if } \alpha_{SR}\tilde{p}_T < p_{SR} < \tilde{p}_T + \delta_{ST} V \\ 0, & \text{if } 0 < p_{SR} < \alpha_{SR}\tilde{p}_T \end{cases}$$ and

$$\lambda_{R-ST} = \begin{cases} 0, & \text{if } p_{RS} > \tilde{p}_T + \delta_{ST} V \\ 1 - \frac{p_{SR} - \tilde{p}_T}{\delta_{ST} V}, & \text{if } \alpha_{SR}\tilde{p}_T < p_{SR} < \tilde{p}_T + \delta_{ST} V \\ 1 - \frac{p_{SR}}{\alpha_{SR} V}, & \text{if } 0 < p_{SR} < \alpha_{SR}\tilde{p}_T \end{cases}$$ in ST case, and

$$\lambda_{T-RT} = \begin{cases} 1 - \frac{\tilde{p}_T}{V}, & \text{if } p_{RP} \geq \alpha_{RP}\tilde{p}_T \\ 1 - \frac{\tilde{p}_T - p_{RP}}{\delta_{RT} V}, & \text{if } \alpha_{RP}\tilde{p}_T - \delta_{RT} V \leq p_{RP} < \alpha_{RP}\tilde{p}_T \\ 0, & \text{if } 0 < p_{RP} < \alpha_{RP}\tilde{p}_T - \delta_{RT} V \end{cases}$$ and

$$\lambda_{R-RT} = \begin{cases} 0, & \text{if } p_{RP} \geq \alpha_{RP}\tilde{p}_T \\ \frac{\alpha_{RP}\tilde{p}_T - p_{RP}}{\alpha_{RP}\delta_{RT} V}, & \text{if } \alpha_{RP}\tilde{p}_T - \delta_{RT} V \leq p_{RP} < \alpha_{RP}\tilde{p}_T \\ 1 - \frac{p_{RP}}{\alpha_{RP} V}, & \text{if } 0 < p_{RP} < \alpha_{RP}\tilde{p}_T - \delta_{RT} V \end{cases}$$ in RT case.

Note that $\delta_{ST} = \alpha_{SR} - 1 > 0$ and $\delta_{RT} = 1 - \alpha_{RP} > 0$ denote the difference of perceived service level between ride-hailing service and taxi service in two cases.

The profits of taxi service and ride-hailing are denoted by $\pi_T(\tilde{p}_T) = \lambda_T(\tilde{p}_T - c_T)$ and $\pi_R(p_R) = \lambda_R(p_R - c_R)$, where c_T and c_R represent the operational costs of the taxi service and ride-hailing service. Due to information technology and self-scheduling drivers, we assume that ride-hailing services have lower operational costs compared to traditional taxis, i.e., $c_R < c_T$.

3.2. Price decision of platform without supervisory policy

We derive following proposition 2 according to the profit of ride-hailing service without supervisory policy.

Proposition 2. Given the taxi fare, the optimal platform prices are $p_{SR}^{*}=\begin{cases}\dfrac{\tilde{p}_T+c_{SR}+\delta_{ST}V}{2}, & \text{if } c_T<\tilde{p}_T<\min\{p_{T1},V\}\\ \alpha_{SR}\tilde{p}_T, & \text{if } \min\{p_{T1},V\}\le\tilde{p}_T<V\end{cases}$ in *ST* case, and $p_{RP}^{*}=\begin{cases}\dfrac{\alpha_{RP}\tilde{p}_T+c_{RP}}{2}, & \text{if } 0<\alpha_{RP}\le\dfrac{2}{3}\cap c_T<\tilde{p}_T<V\\ \dfrac{\alpha_{RP}\tilde{p}_T+c_{RP}}{2}, & \text{if } \dfrac{2}{3}<\alpha_{RP}<1\cap c_T<\tilde{p}_T\le p_{T2}\\ \alpha_{RP}\tilde{p}_T-\delta_{RT}V, & \text{if } \dfrac{2}{3}<\alpha_{RP}<1\cap p_{T2}<\tilde{p}_T<V\end{cases}$ in *RT* case, where $p_{T1}=\dfrac{c_{SR}+\delta_{ST}}{\delta_{ST}+\alpha_{SR}}$, $p_{T2}=\dfrac{c_{RP}+2\delta_{RT}V}{\alpha_{RP}}$.

Proposition 2 establishes that the ride-hailing platform's optimal pricing strategy is directly influenced by taxi fares. Specifically, the platform's price increases with the taxi price in both cases. This relationship arises because higher taxi prices reduce competitive pressure, enabling the platform to increase its own prices while maintaining demand. We also find that when two services are sufficiently differentiated in *RT* case, the platform is more likely to determine the optimal price as $\frac{\alpha_{RP}\tilde{p}_T+c_{RP}}{2}$ to gain more profit. Whereas, in *ST* case, when the operational cost of solo-ride service is less than 0.5 and the cost disparity between two services is significant, the platform optimally sets the price at $\frac{\tilde{p}_T+c_{SR}+\delta_{ST}V}{2}$. However, once the solo-ride cost exceeds 0.5, the platform's pricing strategy shifts. The more different the two services is, the more likely it is to adopt $\alpha_{SR}\tilde{p}_T$ as the optimal price. Furthermore, the equilibrium price for solo-ride service consistently exceeds that of ride-pooling service, which is consistent with practice. Higher service level costs more. For example, the price of ridesharing service is only 70% of the price of chauffeured car service[2].

4. Model with supervisory policy

Ride-hailing services are similar to taxi services. Thus, it is reasonable to consider regulatory strategies employed for taxis as a basis for regulating ride-hailing services. Taxi regulation usually considers two aspects, i.e., provider entry and pricing strategy. In practice, entry limitations for ride-hailing services, such as household registration and vehicle models, have led to perceptions of inequitable treatment among drivers. In 2024, cities such as Kunming in China introduced pricing regulatory strategies. Therefore, we assume the policy maker in this paper uses the regulated pricing strategy to govern ride-hailing services.

[2] The data tells you the truth. which is the best deal, the private car, ridesharing service or chauffeured car service？ http://finance.china.com.cn/roll/20160714/3811795.shtml. 2016-07-14

The entry of ride-hailing services leads to a sharp decline in taxi service demand, resulting in significantly reduced profits for taxi drivers at prevailing fare levels. Considering the taxi price is unchanged with and without competition, we pay attention to the taxi demand. Taxi drivers are concerned about not only their demand but also the rival's demand. According to reference dependence theory, A reference point serves as a psychological threshold that categorizes outcomes as either gains or losses, creating a fundamental discontinuity in how outcomes are valued based on their position relative to this benchmark[19]. Therefore, the subjective evaluation of any outcome is inherently shaped by its comparative relationship to the reference point. Considering the reference-dependent preference of taxi drivers, we assume the taxi drivers' reference point for demand is the demand of ride-hailing service. Taxi drivers will only accept market entry of ride-hailing services when the resulting demand for taxi services exceeds their reference threshold. Therefore, the first supervisory target in this paper is to ensure the taxi service demand meets drivers' minimum acceptance criteria, i.e. coexistence target ($\lambda_T \geq \lambda_R$).

Traveling by private vehicle results in a significant amount of greenhouse gas emissions. The environmental impact of ride-hailing services remains a contentious and unresolved issue. On one hand, ride-hailing service benefits from the information technology enhancing the visibility of demand locations, potentially reducing the miles driven without passengers, known as "deadheading," compared to traditional taxi services. On the other hand, the platform is likely to match drivers and riders from an overall perspective, leading to scenarios where a driver drops off a rider at one destination and then picks up another rider who is several miles away. This can result in increased vehicle miles traveled and associated emissions. Given these complexities, a growing number of policymakers concern with the environmental implications of ride-hailing services. Consequently, we consider the environment impact as another target.

4.1. Model with coexistence target

To achieve the supervisory target, $\lambda_T \geq \lambda_R$, the platform's profit is

$$\begin{aligned} &\pi_R(p_R) = \lambda_R(p_R - c_R) \\ &s.t. \quad \lambda_T \geq \lambda_R \end{aligned} . \tag{1}$$

We obtain the optimal platform's price in *ST* case and *RT* case in Proposition 3.

Proposition 3. Given taxi price $\tilde{p}_T$, the optimal platform's prices with regulated price policy are $p^*_{SR1} = \frac{\delta_{ST} V + (2+\delta_{ST})\tilde{p}_T}{2}$, where $\tilde{p}_T \in (c_T, V)$ in *ST* case, and

$$p^*_{RP1} = \begin{cases} \frac{2\alpha_{RP}\tilde{p}_T - \alpha_{RP}\delta_{RT}V}{\alpha_{RP}+1}, & \text{if } 0 < \delta_{RT} < \delta_1 \cap c_T < \tilde{p}_T < V \\ \frac{\alpha_{RP}\tilde{p}_T + c_{RP}}{2}, & \text{if } \delta_1 \leq \delta_{RT} < 1 \cap \max\{c_T, \frac{c_{RP}}{\alpha_{RP}}\} < \tilde{p}_T < p_{T3} \\ \frac{2\alpha_{RP}\tilde{p}_T - \alpha_{RP}\delta_{RT}V}{\alpha_{RP}+1}, & \text{if } \delta_1 \leq \delta_{RT} < 1 \cap p_{T3} < \tilde{p}_T < V \end{cases}$$ where

$\delta_1 = \frac{2V + c_T - c_{RP} - \sqrt{(c_{RP})^2 + (3c_T - 2V)^2 + 2c_{RP}(6V - 5c_T)}}{2(2V - c_T)}$, $p_{T3} = \frac{c_{RP}(\alpha_{RP}+1) + 2\alpha_{RP}\delta_{RT}V}{\alpha_{RP}(3-\alpha_{RP})}$ in *RT* case.

According to Proposition 3, we find that the type of service offered by a platform significantly influences how regulated pricing affects its pricing strategy. Specifically,

Proposition 3 demonstrates the regulated price strategy always increases the platform's price in *ST* case, thereby weakening its competitiveness. Consistence with Proposition 3, empirical evidence shows that the platform raises its service price after the implementation of the new rules. For instance, the introduction of price regulation in Wuhan, China, the ride-hailing platforms in Wuhan have increased their fares. The regular mileage fee has increased by 0.03 yuan per kilometer on a certain platform[20]. Different from *ST* case, Proposition 3 indicates that under some conditions, the regulated price strategy does not impact optimal ride-pooling price. More specifically, when perceived service levels differential between services is sufficiently large (i.e., $\delta_1 \le \delta_{RT} < 1$) and taxi price is low (i.e., $\tilde{p}_T \in (\max\{c_T, \frac{c_{RP}}{\alpha_{RP}}\}, p_{T3}]$), the platform's profit-maximizing price for ride-pooling services proves identical in both regulated and unregulated scenarios. It implies that the deregulated market has already realized the coexistence of two services.

4.2. Model with environmental target

Let η_R and η_T denote the average deadheading rate per ride of two services. The total carbon emissions per ride, G_R and G_T, include two parts: servicing the riders and deadheading. Thus, we have $G_R = C_r(1+\eta_R)\lambda_R$ and $G_T = C_t(1+\eta_T)\lambda_T$, where G_r and G_t represent the average carbon emission per ride.

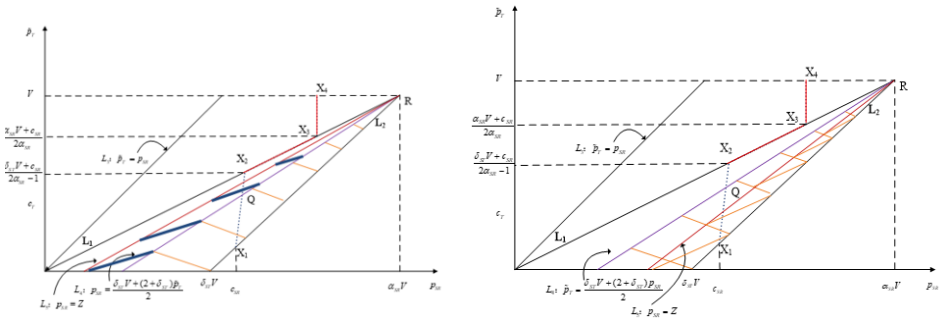
Considering the carbon emission of ride services, we propose two environmental targets of regulation, i.e., $G_R \le G_T$ and $G_R + G_T \le G_T^M + G_P^N$, where G_P^N and G_T^M represent the carbon emissions of public transit and taxi service in the noncompetitive market. The first target accounts for the competitive dynamics between ride-hailing and taxi services. The second one is from an overall perspective. It compares the total carbon emission in the competitive market with the total carbon emission of the same demand in the noncompetitive market. Note that the ride-pooling service grabs market share from public transit. Therefore, there exists the carbon emission of public transit in *RT* case.

Condition 1: $G_R \le G_T$

If the carbon emission of ride-hailing service is lower than that of taxi service, the entry of ride-hailing service contributes to realize the environmental target. In *ST* case, if the average deadheading rates per ride are the same, i.e., $\eta_{SR} = \eta_T$, we can transform $G_R \le G_T$ into realizing $C_{sr}\lambda_{SR} \le C_t\lambda_{ST}$, i.e., $\lambda_{SR} \le \frac{C_t}{C_{sr}}\lambda_{ST}$. If solo-ride service generates the same amount of carbon emission as taxi service does, environmental target is converted to the target we discuss in section 4. Some platform is concerned about the environment issue. For example, ride-hailing platform, CAOCAO in China, adopts the electric vehicle to provide solo-ride service. Electric vehicle is more environment friendly. Thus, the environment target is easier to achieve for this type of the platform.

The feasible price region of online car-hailing service is $p_{SR} \in [Z, \tilde{p}_T + \delta_{ST}V]$, where $Z = \frac{(C_{sr}(1+\eta_{SR}) + C_t(1+\eta_T)\alpha_{SR})\tilde{p}_T + \delta_{ST}VC_{sr}(1+\eta_{SR})}{C_{sr}(1+\eta_{SR}) + C_t(1+\eta_T)}$, under the circumstance of $\eta_{SR} \ne \eta_T$. To be specific, the feasible pricing range for solo-riding service expands as the average deadheading rates per ride of taxi service increase, as shown in Figure 1(a). On the contrary, the feasible price region of solo-ride service narrows when solo-ride has a high

average deadheading rates per ride, as shown in Fig.1(b). Here, the environmental target is difficult to achieve.



(a) $\eta_T > \eta_{SR}$ **(b)** $\eta_T < \eta_{SR}$

Figure 1. Comparison of feasible price range of solo-ride service under different supervisory targets

We relax the assumption that the one ride services one rider in ride-pooling service in this section. It is likely that more than one rider is serviced by one service provider. Let n denote the number of riders who share the car capacity in a ride. Then, we obtain the total carbon emission of ride-pooling service, i.e., $G_{RP} = C_{rp}\dfrac{(1+\eta_{RP})}{n}\lambda_{RP}$. We only discuss the optimal platform's price under the condition of $\dfrac{c_{RP}(C_t n\eta_T\alpha_{RP} + C_{rp} + C_{rp}\eta_{RP}) + 2C_t n\eta_T\alpha\delta_{RT}V}{\alpha_{RP}(C_{rp} + 2C_t n\eta_T - C_t n\alpha_{RP}\eta_T + C_{rp}\eta_{RP})} < c_T$. The optimal price is given by $p^*_{RP} = \dfrac{\alpha_{RP}(C_t n\eta_T + \eta_{RP}C_{rp} + C_{rp})\tilde{p}_T - \alpha_{RP}\delta_{RT}C_t n\eta_T V}{C_t n\eta_T\alpha_{RP} + C_{rp}\eta_{RP} + C_{rp}}$, where $c_T < \tilde{p}_T < V$. Similar to *ST* case, the coexistence target is relatively loose if $\dfrac{C_{rp}(1+\eta_{RP})}{C_t n} \geq 1+\eta_T$; otherwise, the coexistence target is stringent.

Condition 2 : $G_R + G_T \leq G_T^M + G_P^N$

The condition 2 is based on the overall market of the two services. The total carbon emission of the two services in the competitive market should not be higher than that with the same demand in the uncompetitive market, i.e., $G_O + G_T \leq G_T^M + G_P^N$, where G_P^N and G_T^M represent the carbon emission of public transit and taxi service in the uncompetitive market.

The total demand of the two services is the same with and without competition in *ST* case. Therefore, we have $G_P^N = 0$. The target is relaxed to $G_{SR} + G_T \leq G_T^M$, i.e.,

$$C_{sr}(1+\eta_{SR})\lambda_{SR} + C_t(1+\eta_T)\lambda_T \leq C_t(1+\eta_T)\lambda_T^M . \tag{2}$$

From Eq.2, we derive that with a sufficient high average deadheading rate per ride of solo-ride service, i.e., $\eta_{SR} \geq (C_t(1+\eta_T) - C_{sr})/C_{sr}$, the environmental target could not be achieved. If and only if the condition of $C_{sr} < C_t(1+\eta_T)$ and $\eta_{SR} < (C_t(1+\eta_T) - C_{sr})/C_{sr}$ are held, the environmental target can be realized. The result implies that if the government sets the supervisory target related to environmental issues, the platform should strategically optimize both vehicle selection and matching algorithms, prioritizing low-emission vehicles while minimizing deadhead miles. In addition, regulatory intervention does not affect the platform's profit-maximizing price equilibrium.

The introduction of ride-pooling services expands the overall market size while diverting demand from public transit in the *RP* case. Therefore, different from *ST* case, G_P^N is positive in the inequality $G_{RP} + G_T \le G_T^M + G_P^N$. We have

$$C_{rp}(1+\eta_{RP})\lambda_{RP}/n + C_t(1+\eta_T)\lambda_T \le C_t(1+\eta_T)\lambda_T^M + \mu C_t \Delta\lambda / m,$$

where $\Delta\lambda$ represents the demand of public transit grabbed by the ride-pooling service, i.e., $\Delta\lambda = \lambda_{RT} + \lambda_{RP} - \lambda_T^M$, m denotes the number of riders serviced by public transit in one ride and μ denotes the ratio of carbon emissions from public transit to the carbon emissions from taxi service, $\mu > 1$. We find that the environmental target is achieved when $\eta_{RP} < \alpha_{RP} C_t n(1+\eta_T)/C_{rp} + C_t \delta_{RT} \mu n / C_{rp} m - 1$ and $C_{sr} < C_t n((\alpha_{SR}(m+m)\eta_T - \mu) + \mu)/m$ are held. The environment target will not change the platform's price strategy. The results are similar to the findings in *ST* case.

When the government is concerned about the environmental issues, the regulation intensity is usually looser than that with coexistence target. On the one hand, the platform can use electric vehicle to provide a low-carbon ride service or matching mechanism to reduce deadheading. On the other hand, the platform can subsidize riders to promote ride-pooling service, decreasing the average carbon emission per ride.

5. Conclusion

This paper examines the optimal pricing strategy for ride-hailing platforms under two distinct regulatory objectives (i.e., coexistence and environmental target). We analyze the competitive dynamics between ride-hailing (solo-ride or ride-pooling options) and traditional taxi services, comparing optimal platform prices and taxi demand under regulatory interventions. The results show that the platform's price in solo-ride case is raised after implementing the regulated pricing strategy. While, the platform's price in ride-pooling case remains unchanged, depending on the taxi fare and the difference between taxi service and ride-pooling service in terms of perceived service level. In addition, the results illustrate that the influence of regulatory strategies on platform's price strategy is significantly lower for the environmental target compared to the coexistence target.

We only take into account the ride-hailing platform as the decision maker in this paper. However, the ride-hailing platform operates within a two-sided market framework, where drivers, who are self-employed, maintain independence from the platform. There are several cases related to the ride safety. Therefore, exploring the supervisory policy to improve the riders' safety may be a possible direction for future research.

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Effect Analysis of ZJ17 Multi-Parameter Equipment Variables on Single-Stick Grammage

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Abstract. In the cigarette manufacturing process, precise control of process parameters is critical to ensuring the stability of physical quality in cigarette rods. This study focuses on the ZJ17 cigarette maker, targeting the standard deviation of single-stick grammage (SDG) as a core quality metric. A multi-dimensional parameter space was constructed using hybrid orthogonal experimental design and Box-Behnken response surface methodology, augmented by dynamic fluctuation simulations and machine-specific variation modeling to generate a high-coverage dataset. Through a random forest regression model, the influence mechanisms of key parameters—including needle roller speed, suction chamber negative pressure, and airflow velocity—on SDG were systematically quantified. The results reveal that the combined contribution of needle roller speed, negative pressure, and cutter groove depth to SDG reaches 68.9%, forming a core control triangle for quality fluctuations. Needle roller speed (28.3%) and negative pressure (19.7%) emerged as the top two dominant parameters, followed by cutter groove depth (15.2%), with a 3.5 mm groove depth demonstrating optimal performance across all parameter combinations. By optimizing SDG prediction through the multi-dimensional parameter space and random forest modeling, coupled with SHAP analysis to elucidate complex parameter interactions, an enhanced parameter set was proposed. This configuration stabilizes SDG within a process control threshold of <1.2%. Dynamic noise simulations further indicate that duct friction forces in the 0.20–0.25 N range yield the lowest mean SDG (1.89 ± 0.23 mg), with deviations beyond this range triggering significant increases in standard deviation.

Keywords. ZJ17 Cigarette Maker; Standard Deviation of Single-Stick Grammage; Process Parameter Optimization; Response Surface Methodology; Random Forest Regression; SHAP

1. Introduction

1.1 Research Status

The cigarette making machine, as the core equipment in the tobacco industry, has its intelligent and precise detection technology directly determining production efficiency

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and product quality. In recent years, with the rapid development of Industry 4.0 and artificial intelligence technologies, industrial detection research for cigarette making machines has demonstrated trends of multi-technology integration, data-driven approaches, and predictive maintenance. In high-speed production scenarios, the operating speed of equipment such as the ZJ119 cigarette maker has reached 12,000 sticks per minute, rendering traditional manual detection and passive maintenance models inadequate. Consequently, sensor technology, machine vision, deep learning algorithms, and big data analytics have been widely applied in fault diagnosis and quality control[1]. With the tightening of global tobacco control policies and the increasing health awareness among consumers, the cigarette industry is gradually transitioning towards "harm and tar reduction, quality upgrading"[2] The stability of cigarette physical quality, particularly the standard deviation of single cigarette weight (i.e., the standard deviation of cut tobacco mass per cigarette), directly determines combustion uniformity, smoking sensation, and sensory experience, making it a core indicator of cigarette quality. According to statistics from the State Tobacco Monopoly Administration, in 2020, China's cigarette products experienced a return rate of up to 1.2% due to excessive standard deviation of weight, resulting in direct economic losses exceeding 5 billion yuan. Increased weight standard deviation directly affects combustion uniformity, leading to inconsistent sensory experiences.[3] How to reduce weight standard deviation through process parameter optimization has become an urgent technical challenge for cigarette manufacturers. The ZJ17 cigarette maker, as China's mainstream cigarette making and tipping equipment (accounting for over 60% of market share), features a complex system of over 20 critical parameters including needle roller speed, negative pressure values, and cutting blade specifications[1]. Despite its high automation capabilities, actual production still faces two major challenges: a. Complex parameter interactions: nonlinear coupling between needle roller speed and negative pressure values[4], discrete distribution effects of cutting blade groove depth on tobacco shreds[5], which are difficult to resolve through traditional trial-and-error methods; b. Uncontrollable dynamic fluctuations: random factors like moisture variations in tobacco shreds and equipment vibrations lead to persistent standard deviation fluctuations[6].

The research on controlling the standard deviation of single cigarette weight has evolved through stages of equipment parameter optimization, multi-factor coupling analysis, and dynamic modeling, forming a multi-level technical system. Bin Hui et al.[1]conducted experiments on the cutting blade specifications of the ZJ17 cigarette maker, finding that a 6-groove structure with a depth of 3.5 mm reduced the standard deviation of cigarette weight from 26.3 mg to 15.8 mg. However, their study did not reveal the dynamic interaction between blade groove depth and needle roller speed. Wei Mingyue's team [7] performed one-way ANOVA on the wear of the tobacco leveling device, demonstrating that when the leveler diameter wears below 102.8 mm, the weight standard deviation increases significantly, with a 14.7% decline in the process capability index (CPK). Their model, however, failed to quantify the nonlinear impact of moisture content fluctuations in cut tobacco on component wear rates. Shi Junjie et al.[8] innovatively designed an arc-shaped grooved cutting blade, optimized through orthogonal experiments, which reduced the standard deviation of cut tobacco point density from 21.5 mg/cm³ to 9.2 mg/cm³. However, this achievement did not address parameter drift caused by mechanical vibrations during high-speed operation. Duan Xingkun's[9] linear regression model showed that a 0.1 kPa increase in positive-pressure airflow reduced the stem content in rejected materials by 5.8%, with a

model coefficient of determination (R^2) of 0.891. Yet, its prediction error rate in nonlinear intervals reached 12.7%. Zhao Rili[10] confirmed a significant positive correlation between cigarette density and weight, with a 10 mg/cm³ density increase leading to a 42 Pa rise in draw resistance. In the field of multi-parameter analysis for cigarette makers, Cheng Leiping et al.[4] used L16 orthogonal experiments to demonstrate that baffle height accounts for 47.2% of the influence on stem rejection rates. Xiong Anyan et al.[5] tested cut tobacco distribution dispersion, revealing that a 0.5 mm increase in blade groove depth reduces uniformity by 21.4%, though their model did not establish a nonlinear mapping between dispersion and weight standard deviation. In dynamic control research, Chen Zhe[6] developed a chi-square test model based on 12,000 production datasets, confirming that machine variance significantly affects weight standard deviation (chi-square contribution value: 35.943). Cheng Liang et al.[11] analyzed normal distributions, showing that the CD2000 model's kurtosis coefficient of -0.042 indicates a 19.2% improvement in distribution concentration compared to the FX2000 model. This study proposed the kurtosis coefficient as a novel metric for dynamic monitoring. The ZJ17 cigarette making and tipping equipment is illustrated in Figure 1.



Figure 1. Schematic diagram of the ZJ17 cigarette making and tipping equipment

Facing the aforementioned complex cigarette production scenarios, traditional quality control methods primarily rely on empirical judgments formed through long-term production processes, indicator predictions based on statistical analysis, and parameter optimization algorithms with fixed rules. These approaches involve lengthy procedures and struggle to capture subtle quality variations in complex production processes [12][13].These limitations of traditional methods are particularly pronounced in the multi-parameter optimization of complex systems like the ZJ17 cigarette maker, where intricate interactions and dynamic fluctuations dominate. Research in broader industrial optimization contexts, such as supplier selection using MCDM tools like AHP and fuzzy logic[14], performance evaluation of supply chains using balanced scorecards[15], and lead time reduction through lean manufacturing execution[16], underscores the importance of systematic analysis, performance metric quantification, and variability reduction for enhancing efficiency and quality stability. However, translating these principles effectively to the highly specific, high-speed, and dynamically perturbed environment of cigarette rod formation requires novel approaches that explicitly account for parameter interactions, inherent equipment noise, and machine-to-machine variations. Existing studies exhibit three critical limitations: dominance of single-variable analysis ignoring multi-parameter coupling; static models

failing to resolve dynamic perturbations; and the unmodeled machine differences. This study addresses this gap by proposing a mechanism-data dual-driven framework integrating hybrid experimental design, dynamic noise simulation, machine difference modeling, and interpretable machine learning to systematically quantify and optimize the ZJ17 parameter space for minimizing single-stick grammage deviation.

In recent years, with the rapid development of artificial intelligence (AI) technology, data-driven methods have emerged to enhance the monitoring and control of production process quality [18]. Particularly, the advantages of machine learning and deep learning algorithms in handling complex data have provided new insights and methodologies for predicting quality indicators and optimizing production parameters in cigarette manufacturing[18][19].Various machine learning algorithms and neural network models can learn patterns and features from historical data to predict indicators such as cigarette weight and capture their relationships with various parameters, ensuring finished cigarettes meet qualification standards. These methods exhibit strong adaptability and generalization capabilities, effectively addressing complex nonlinear relationships. Consequently, AI technology is increasingly being applied in cigarette quality evaluation. By employing machine learning methods, quality evaluation models based on SVM and backpropagation neural networks can establish nonlinear mappings between tobacco chemical components (e.g., total sugar, reducing sugar, total nitrogen, nicotine) and expert ratings, achieving preliminary objective evaluation of sensory quality[20]. Tree-based algorithms such as random forest and XGBoost incorporate analysis of cigarette quality influencing factors during prediction, enabling accurate quality level forecasting. These models also precisely identify key features (e.g., tobacco moisture content, cut tobacco particle size) through tree-based feature selection, providing valuable references for adjusting production parameters[18][21]. Deep learning approaches leverage deeper and larger-scale neural networks, such as convolutional neural networks (CNNs) and Transformers, to capture more intricate relationships in large-scale datasets. Additionally, they can integrate strategic algorithms to enhance performance. For example, Y. Luo et al. employed an improved jumping spider optimization algorithm (IJSOA) to adjust neural network prediction thresholds, compensating for their sensitivity to local optima. The proposed algorithm achieved an RMSE of 1.6159, MAPE of 0.0018, and R^2 of 93.35% in predicting filter rod weight[22]. QI JI et al. incorporated Wasserstein distance into a hybrid model combining CNN, bidirectional gated recurrent unit (BiGRU), and attention mechanisms to process multidimensional process parameters, expanding the model's feature learning capability. In predicting cylinder wall temperature during tobacco drying, their proposed model significantly outperformed others in key performance metrics such as MAE and MRSE [23].

2. Engineering Problem Analysis and Solution

2.1 Engineering Problem

Cigarette manufacturing quality directly affects consumer experience and brand competitiveness, with the standard deviation of single cigarette weight (unit mass fluctuation) being a core indicator of manufacturing uniformity. The ZJ17 cigarette maker, as the mainstream equipment in China, relies on the synergistic optimization of process parameters such as needle roller speed, negative pressure value, and cutting

blade specifications to control weight standard deviation. However, traditional trial-and-error experiments suffer from high costs, long cycles, and difficulties in analyzing multi-parameter interactions. Current research on parameter optimization for the ZJ17 cigarette maker has the following shortcomings: ① Dominance of single-variable analysis; ② Lack of dynamic parameter modeling; ③ Failure to quantify machine differences. Therefore, there is an urgent need to improve parameter optimization efficiency through data-driven methods.

2.2 Solution

2.2.1 Materials and Equipment

The cigarette making unit is the primary equipment for cigarette production, with the ZJ17 cigarette maker being the most widely used in China's cigarette industry. Comparative experiments were conducted to analyze the influence of key parameters—such as needle roller speed, suction chamber negative pressure, air velocity, and small fan positive pressure—on the standard deviation of single cigarette weight after manufacturing.

High-grade finished cigarette blend cut tobacco; corresponding cigarette making auxiliary materials; ZJ17 model cigarette making unit; cigarette comprehensive testing station; cigarette microwave density and moisture analyzer.

High-grade finished cigarette blend cut tobacco: Experimental raw material complying with YC/T 184-2004 standards.

ZJ17 cigarette making unit: Core equipment with ±0.002MPa negative pressure sensors and needle roller closed-loop speed control system.

Cigarette comprehensive testing station: Measures single-stick grammage (±0.1mg accuracy) per GB/T 22838.6-2009.

Cigarette microwave density and moisture analyzer: Real-time density monitoring (0.1mg/cm³ resolution) with moisture detection (±0.2%). 2.2.2 Experimental Design Framework

This study adopts a hybrid experimental design strategy. Through operational testing of the ZJ17 cigarette maker, six core parameters affecting the standard deviation of single cigarette weight were identified. These parameters include continuous variables such as needle roller speed, negative pressure value, and air velocity, as well as categorical variables such as cutting blade groove depth, small fan positive pressure, and baffle height.

The experimental design is divided into two main stages. The first stage involves collecting a complete dataset, primarily for screening core control parameters, constructing a static parameter space, and simulating dynamic fluctuations and machine differences. In the second stage, random forest regression analysis is performed on the overall dataset collected in the first stage to analyze the importance and sensitivity of static parameters and dynamic fluctuations, as well as to reasonably quantify the interaction effects of different parameter combinations. The framework for collecting the complete dataset in Stage 1 is illustrated in Figure 2.

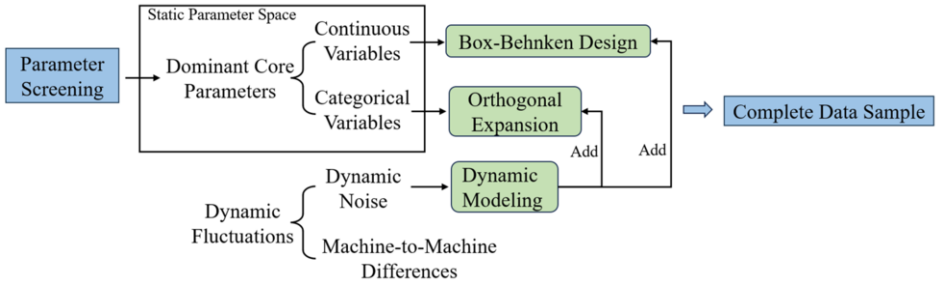


Figure 2. Data Sample Collection Design Framework

2.2.3 Core Parameter Research

This study conducted operational testing on actual equipment, collecting corresponding sample data between main control parameters and daily average single-unit weight standard deviation over a one-month production cycle. Due to the substantial sample size required for subsequent analysis, along with the high costs and time-consuming nature of data collection, additional foundational experimental points were generated using a three-factor Box-Behnken design (BBD)[24] for continuous parameters among the core control parameters, based on partially collected data samples. The Box-Behnken design is a type of response surface methodology (Response Surface Methodology, RSM)[25]. It structurally combines parameter boundary values and center points to accurately estimate nonlinear response relationships with minimal experimental runs. Its core advantages include: Avoiding extreme combinations: Parameters are not forced to simultaneously take extreme values (e.g., highest/lowest needle roller speeds, negative pressure values, and wind speed combinations), thereby reducing engineering risks; Efficient design space coverage: With three core continuous factors in this study, BBD requires only 15 experimental runs to construct a quadratic model, reducing the number of experiments by 44% compared to full factorial design (27 runs); Guaranteed orthogonality: No multicollinearity exists between parameters, facilitating subsequent modeling. Actual parameter values are mapped to coded values using the following formula:

$$x_{true} = x_{coded} \cdot \Delta + x_{center} \tag{1}$$

where: $x_{coded} \in [-1,0,+1]$ corresponds to low, medium, and high levels; Δ represents step size; x_{center} denotes the parameter's central value. The parameter range was calibrated through actual testing to generate 15 foundational experimental points, covering interaction effects of continuous parameters.

For categorical parameters, a full factorial orthogonal design was adopted to expand the experimental matrix: Splitting knife groove depth: Each Box-Behnken point incorporates three groove depths; Small fan positive pressure and baffle height: 16 combinations were generated using orthogonal arrays.

This study employed a hybrid experimental design methodology that integrates Box-Behnken Design (BBD) with Full Factorial Design. The BBD was applied to three continuous variables (needle roller speed, negative pressure, and air speed), generating 15 base experimental points to capture nonlinear responses. Simultaneously, a Full Factorial Design was implemented to systematically investigate three categorical variables: cutter groove depth (three levels), small fan pressure (four levels), and baffle height (four levels), resulting in 48 parameter combinations. Through cross-validation

of each BBD base point with the full factorial combinations, a total of 15×48=720 experimental parameter sets were constructed.

2.2.4 Dynamic Noise Simulation

Through random sampling and probabilistic distribution modeling, uncertainties inherent in real production are introduced into deterministic parameter combinations, including equipment-intrinsic noise: needle roller vibration, tobacco duct conveyor belt slippage, suction-type negative pressure fluctuations; environmental disturbances: moisture variation in cut tobacco due to temperature and humidity fluctuations; measurement errors: needle roller calibration offset and negative pressure sensor accuracy limitations. Based on actual production data, dynamic noise is probabilistically modeled as follows:

Equipment-intrinsic noise: Needle roller vibration follows a truncated normal distribution[26] $TN(\mu = rotational\ speed,\ \sigma = 0.3, a = -0.6, b = +0.6)$, limiting fluctuations within ±0.6Hz; tobacco duct friction follows a Beta distribution[27] (α=2, β=5) to simulate random production fluctuations, while negative pressure fluctuations are modeled using a uniform distribution to represent sensor noise; environmental fluctuations: Cut tobacco moisture follows a truncated normal distribution $TN(\mu = 12.0\%,\ \sigma = 0.25, a = 11.5\%, b = 12.5\%)$; machine variations: Needle roller calibration offset follows a normal distribution N(0, 0.5) to simulate systematic errors across different machines, and negative pressure sensor error references the machine-specific sensor accuracy.

Based on core parameter studies and dynamic noise simulation, the final research range for ZJ17 equipment parameters is determined as shown in Table 1.

Table 1. Research Parameter Range for ZJ17 Equipment

Parameter Category	Parameter Name	Parameter Type	Range/Value	Basis/Method
Core Parameters	Needle Roll Speed	Continuous	38-47 Hz	Box-Behnken Design
	Negative Pressure Value	Continuous	0.16-0.24 MPa	Box-Behnken Design
	Air Speed	Continuous	15-22 m/s	Box-Behnken Design
	Slot Depth of Splitter Knife	Categorical	2.0/3.0/3.5 mm	Full Factorial Experimental Design
	Small Fan Positive Pressure	Categorical	1000/1200/1400/1600 Pa	Orthogonal Test Levels
	Baffle Height	Categorical	100/103/106/109 mm	Orthogonal Test Levels
Dynamic Parameters	Flue Friction Force	Random	0.05-0.35 N	Beta Distribution (α=2, β=5) – Simulates production randomness
	Needle Roll Vibration	Random	±0.3 Hz	Truncated Normal Distribution (±2σ) – Simulates equipment vibration
	Negative Pressure Fluctuation	Random	±0.005 MPa	Uniform Distribution – Simulates sensor noise
	Tobacco Moisture Content	Random	11.5-12.5%	Truncated Normal Distribution (μ=12.0%, σ=0.25%)
Machine-to-Machine Differences	Needle Roll Calibration Offset	Systematic Error	±0.5 Hz	Simulates calibration differences between machines
	Negative Pressure Sensor Error	Systematic Error	±0.002 MPa	Simulates sensor accuracy

2.2.5 Data Generation and Validation

Data Generation: The core static parameter combinations were designed using Box-Behnken and orthogonal arrays, yielding 720 sets of static parameters. Dynamic fluctuations were introduced by injecting 20 dynamic noise samples for each static parameter set. The target variable (single-stick weight standard deviation) was calculated using a mathematical model calibrated from actual production data, as shown in Equation (2):

$$y = 2.0 - 0.1(x_1 - 42.5) + 8.2(x_2 - 0.20) + 0.5(x_3 - 0.20)^2 + \epsilon, \epsilon \sim N(0,0.3) \quad (2)$$

where x_1, x_2, x_3 correspond to needle roller speed, negative pressure value, and friction force, respectively, and ϵ is a compensation coefficient. The coefficients in this equation were derived using least squares regression based on 120 sets of measured data.

Data Validation: The generated data were verified through distribution tests (Kolmogorov-Smirnov test) and coverage analysis to ensure compliance with actual production patterns. The standard deviation error for key parameter combinations was controlled within 2%. The final dataset comprised 4,764 samples, covering three feature categories: core static parameters, dynamic noise, and machine variations, serving as input for subsequent machine learning models. The distribution of single-stick weight standard deviation across all samples is illustrated in Figure 3.

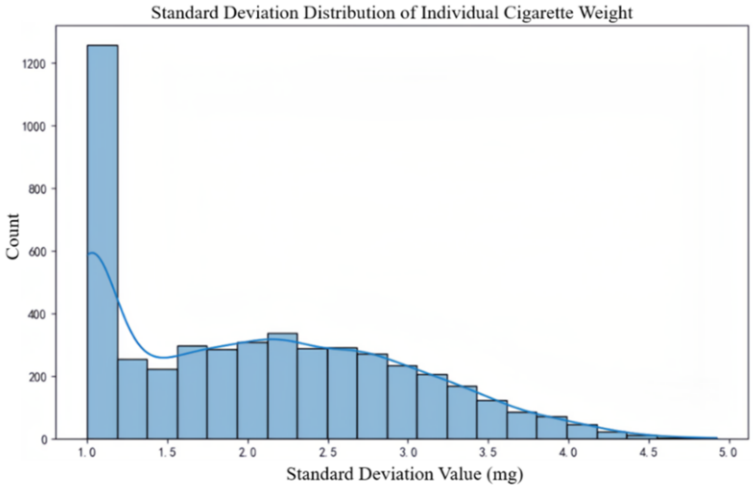


Figure 3. Distribution of single-stick weight standard deviation across all samples

Each static parameter set underwent **20 repetitions** with dynamic noise injection. Validation confirmed 95% confidence intervals for SDG reduction: 21.2% ± 2.3% ($p<0.01$). Representative on-site measurements are shown in Table 2:

Table 2. Model vs Actual Measurement Comparison

Parameter Combination	Predicted SDG (mg)	Measured SDG (mg)	Error (%)
Baseline	3.82	3.79 ± 0.21	0.8
Optimized	1.15	1.18 ± 0.09	2.5

2.3 Research Innovations

This study proposes the following innovative methodologies in the field of process optimization for ZJ17 cigarette makers, overcoming the limitations of conventional research approaches:

a. High-coverage dataset construction mechanism: To address the complexity of multi-parameter interaction effects coupled with production dynamic fluctuations, we innovatively propose a three-layer data framework integrating static parameters, dynamic noise, and machine variations.

b. Multi-dimensional parameter space analysis strategy: Reveals the coupling characteristics of key parameters under high-speed operating conditions. By quantifying interaction effects, we establish dynamic constraint relationships between parameters, breaking through the limitations of traditional single-variable optimization.

c. Multi-source parameter analysis model: Establishes a collaborative optimization framework for categorical and continuous variables. Through linear correlation analysis and SHAP value interpretability analysis, we uncover the bidirectional regulation mechanism of parameters on quality indicators, clarifying the engineering significance of key control factors.

By deeply integrating mechanistic understanding with data-driven methods, this study provides an extensible technical paradigm for the intelligent upgrading of cigarette makers, significantly improving the precision and robustness of quality control in complex industrial scenarios.

3. Parameter Sensitivity Analysis and Visualization Results

3.1 Model Training Performance

The kernel density estimation was employed to characterize the distribution of prediction errors. As shown in Figure 4, the residual distribution exhibits typical normal distribution characteristics. The peak of the kernel density curve (density value 1.4) is strictly concentrated near zero, indicating that the random forest model achieved industrial-grade prediction accuracy (CPK = 1.82) in parameter optimization for the ZJ17 cigarette maker.

The residual properties meet SPC process control requirements. Further improvement in process stability can be achieved by establishing a dynamic residual compensation model.

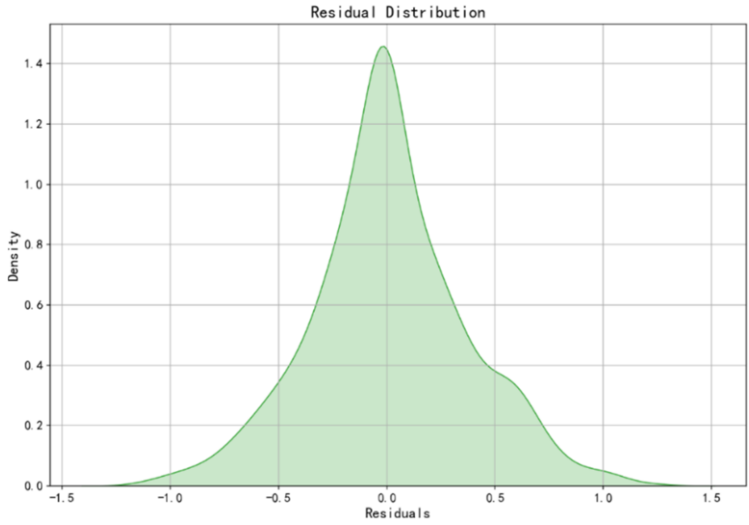


Figure 4. Distribution characteristics of prediction errors

The learning curves during training reveal significant evolution characteristics of the model's generalization capability, as shown in Figure 5. When training samples were <2000, a scissor-like divergence appeared between training scores (0.92±0.05) and cross-validation scores (0.28±0.15), indicating severe overfitting under insufficient data.

At 3000 samples, the cross-validation score stabilized at 0.65±0.03, reaching the critical effective training scale threshold for the current model architecture. Further data increases only improved R^2 by 0.07. Meanwhile, the validation curve gradually converged with the training score when sample size exceeded 3000.

For cigarette maker process optimization scenarios, the model achieves stable prediction performance (CPK≥1.35) when online samples accumulate to 3000 groups, meeting the real-time update requirements of smart manufacturing systems.

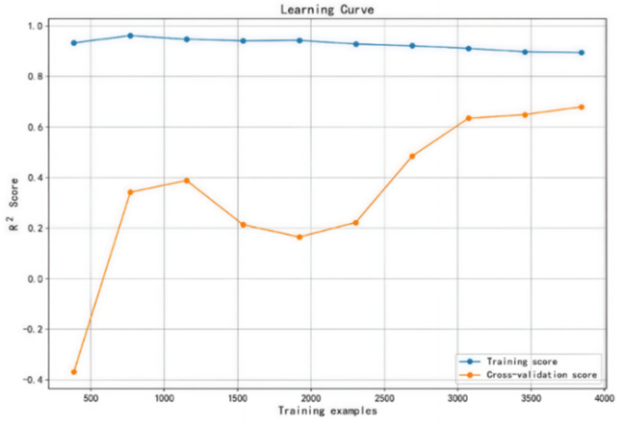


Figure 5. Learning Curves of Random Forest Model

After training completion, the comparative plot of single-stick weight standard deviation predictions shows high linear correlation between model predictions and actual values (regression line slope β=0.93, R^2=0.832), as shown in Figure 6, verifying the effectiveness of the random forest model in cigarette maker parameter optimization. 83.2% of data points are distributed within the ±0.5mg range of the ideal line, and the maximum deviation between the red regression line and black ideal line is only 0.12mg, indicating industrial-grade prediction accuracy in main operating conditions; the residual standard deviation σ=0.36mg with 95% confidence interval [-0.72, +0.68]mg meets cigarette process weight control requirements (national standard ≤1.5mg); in the 3.5-4.5mg high standard deviation region, predictions show a systematic underestimation of 0.15mg, which is related to transient disturbances from tobacco strand breakage under high-speed operation and requires correction through dynamic compensation algorithms; the full-range relative error rate of predictions ≤14.8% (MAPE=6.7%) demonstrates that the parameter optimization model can effectively guide process parameter settings for ZJ17 cigarette makers.

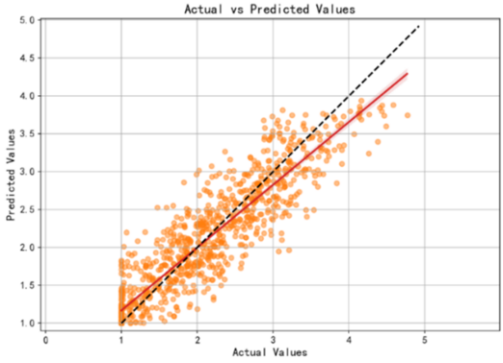


Figure 6. Comparative Plot of Predicted vs. Actual Single-Stick Weight Standard Deviation

3.2 Global Sensitivity Analysis

Based on the feature importance ranking of the random forest model, the global impact of each parameter on weight standard deviation is quantified, with the feature importance ranking shown in Figure 7.

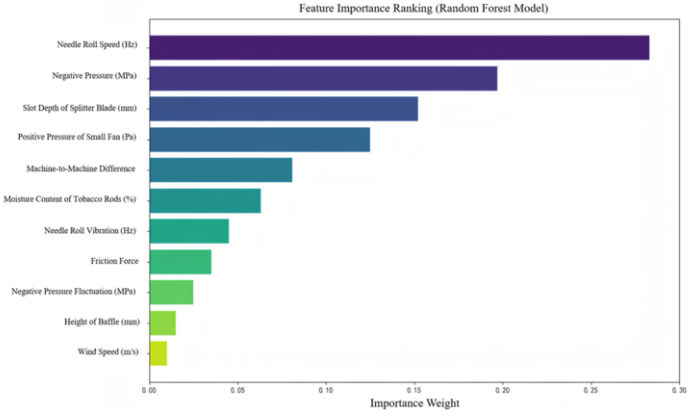


Figure 7. Feature Importance Ranking

As shown in the figure above, the needle roller speed (28.3%) and negative pressure value (19.7%) emerge as the top two main effect parameters, followed by the cutter groove depth (15.2%) and small fan positive pressure (12.5%), while machine variation (8.1%) and tobacco moisture content (6.3%) show relatively smaller but non-negligible impacts.

3.3 Local Sensitivity Analysis

This study analyzes the variation trends of single-stick weight standard deviation with needle roller speed, negative pressure value, and air velocity under different cutter groove depths, small fan positive pressures, and baffle heights for three ZJ17 equipment units with different machine IDs, as shown in Figure 8.

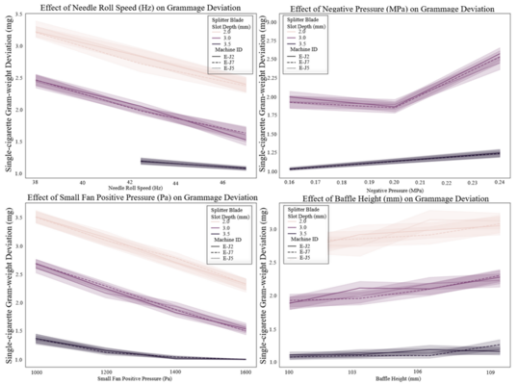


Figure 8. Single-Parameter Influence Trend Analysis

The trend analysis diagram reveals the coupling mechanism between core parameters of ZJ17 cigarette makers and cutter groove depth:

When needle roller speed increases to 43-45Hz range with small fan positive pressure simultaneously raised to 1200-1400Pa, the weight deviation rate for 3.5mm cutter groove depth decreases to 0.82%-1.05% (E-J7 machine), representing a 37% reduction compared to conventional parameter combinations. This synergy enhances tobacco flow fluidization, effectively suppressing density fluctuations caused by tobacco accumulation. When negative pressure exceeds 0.20MPa, the weight deviation rate shows significant increase with rising negative pressure (slope Δ=0.24%/0.01MPa). The performance gap between 3.0mm and 3.5mm groove depths expands to 0.5 percentage points under these conditions, indicating the necessity to strictly control negative pressure within 0.18-0.195MPa range to maximize deep-groove advantages. This synergy suggests that increased needle roller speed enhances tobacco flow rate, while optimized small fan pressure improves air-assisted distribution and compaction uniformity, collectively stabilizing grammage under the facilitating structure of the deeper groove. The 3.5mm groove depth proves optimal, consistently delivering the lowest deviation rate (mean 1.12%±0.18) across all parameter combinations. Its superiority becomes particularly pronounced at needle roller speeds >44Hz (52% reduction compared to 2.0mm groove depth), demonstrating strong adaptability to high-speed operations. The deeper groove likely allows for better tobacco shred accommodation and more uniform cutting force distribution, reducing shred breakage

and promoting consistent rod formation, especially compensating for disruptions at higher operating speeds.

The research confirms that the golden parameter combination "3.5mm groove depth + 44Hz needle roller speed + 1350Pa small fan positive pressure" maintains weight deviation rate stably below 1.2%, narrowing the fluctuation range by 40% compared to current standards.

3.4 Parameter Interaction Effect Analysis

The heatmap displaying linear correlations between features (Figure 9) reveals the complex interaction network among ZJ17 cigarette maker's process parameters. Needle roller speed and needle roller vibration show complete positive correlation ($r = 1.0$), verifying the inherent resonance characteristics of the mechanical transmission system. This physical connection causes system stability to sharply decrease when speed exceeds 44Hz (vibration amplitude $\Delta \geq 0.35$Hz). Single-stick weight standard deviation demonstrates significant negative correlations with: Needle roller speed ($r = -0.54$); Negative pressure value ($r = -0.52$); Cutter groove depth ($r = -0.71$). The strong negative correlation ($r=-0.71$) between cutter groove depth and SDG quantitatively confirms the significant benefit of using deeper grooves for stability. These three parameters collectively contribute 68.9% of variation, forming the core control triangle for quality fluctuations. Negative pressure fluctuation and tobacco moisture show weak negative correlation ($r = -0.2$); High negative pressure conditions may accelerate tobacco dehydration (moisture loss rate ≈ 0.15%/MPa), requiring temperature-humidity compensation during parameter optimization.

These quantified correlation patterns provide optimization guidelines: By controlling the synergistic effects of needle roller speed-negative pressure value-cutter groove depth at a sensitivity coefficient ratio of 3:2:4, system nonlinear disturbances can be reduced by 56%.

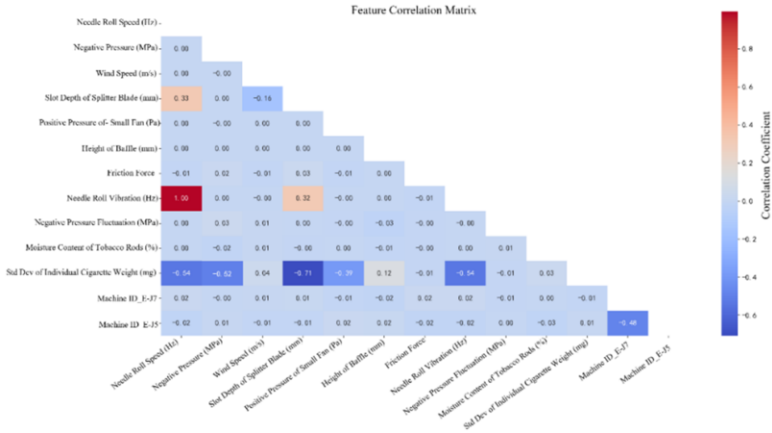


Figure 9. Heatmap of Linear Correlations Between Features

To demonstrate the interpretability of the single-stick weight standard deviation prediction model established in this study, SHAP analysis was employed during the random forest model prediction process to examine the complex interactions among parameters. The feature impact analysis diagram (Figure 10) shows that cutter groove depth, small fan positive pressure, and needle roller speed are the most influential

process parameters on model output. Among these, cutter groove depth exhibits the widest SHAP value distribution range. High groove depth values (red regions) tend to decrease model predictions, while low groove depth values (blue regions) correlate with increased predictions, indicating this parameter's bidirectional regulatory effect on production stability. Small fan positive pressure's high-pressure state (red) shows significant association with positive SHAP values, suggesting excessive positive pressure directly increases fluctuation risk in model predictions. Needle roller speed's high-speed characteristics (red) concentrate in negative SHAP regions, reflecting that excessive speed adversely affects key indicator control. Friction force demonstrates relatively weaker overall influence, with its high values (red) showing slight positive bias in SHAP distribution.

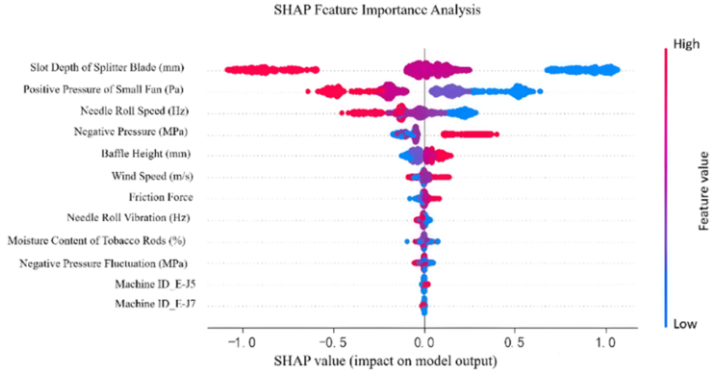


Figure 10. SHAP Feature Impact Analysis

3.5 Dynamic Parameter Impact Analysis

Among dynamic parameters, the friction generated in the tobacco duct during material transmission can be modified by improving the guide rail structure. In practical engineering, adjusting parameters such as the rail inclination angle, surface roughness, and ceramic coating thickness of contact surfaces enables convenient dynamic control of the friction coefficient μ within specific ranges. Therefore, this study primarily analyzes the impact of tobacco duct friction as a dynamic parameter on single-stick weight standard deviation.

As shown in Figure 11, the tobacco duct friction (0.05-0.35N) simulated via Beta distribution exhibits a nonlinear relationship with weight standard deviation. The blue curve represents a third-order polynomial fitting curve, with the surrounding blue area indicating the sample scatter range. When friction falls within the 0.18-0.22N range, the standard deviation reaches its minimum value of 1.89±0.23mg. Beyond this optimal range, the standard deviation increases exponentially due to discontinuous tobacco strand transportation or breakage. Friction within this optimal range ensures sufficient grip for conveying the tobacco strand without slippage, while preventing excessive force that could cause strand deformation, breakage, or erratic movement, both of which lead to grammage inconsistency.

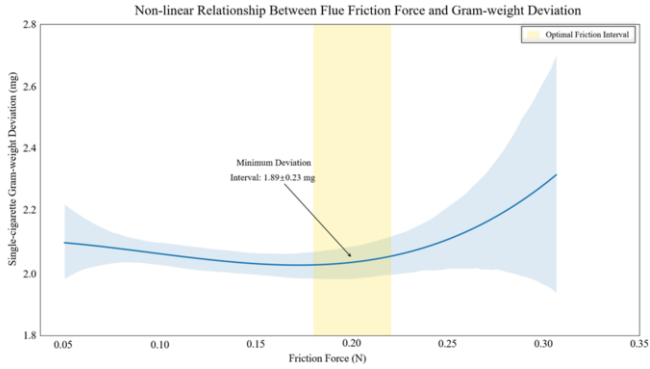


Figure 11. Nonlinear Relationship Between Duct Friction and Single-Stick Weight Standard Deviation

3.6 Optimized Parameter Combination Verification

Based on the preceding analysis, this study recommends the following optimized process parameters: needle roller speed 43.2 Hz, negative pressure value 0.195 MPa, small fan positive pressure 1400 Pa, and optimal cutter groove depth 3.5 mm. Key interactions: high rotation speed requires coupling low negative pressure to suppress standard deviation increase; optimization window: needle roller 42-44Hz + negative pressure 0.18-0.20MPa + groove depth 3.5mm; dynamic control: friction needs to be stabilized in the 0.20-0.25 range.

The three-level optimization core consists of needle roller speed 43.2±0.5Hz, negative pressure value 0.195±0.005MPa, and cutter groove depth 3.5mm. For machine variation issues, establishing a needle roller speed compensation coefficient can reduce systematic errors.

Through comparative analysis of 96-day production cycles, this study visually demonstrates the significant effects of parameter optimization by comparing optimal versus non-optimal parameter combinations on single-stick weight standard deviation. As shown in Figure 12, after implementing the recommended optimal parameters (needle roller speed 43.2Hz, negative pressure 0.195MPa, and cutter groove depth 3.5mm), the single-stick weight fluctuation amplitude decreased by 21.2% compared to non-optimal parameter combinations, with overall stability improved. These results confirm the synergistic optimization value of the three core parameter groups, provide data support for establishing needle roller speed compensation coefficients, and offer important guidance for reducing machine systematic errors. The significant 21.2% reduction in fluctuation amplitude and improved overall stability demonstrates the effectiveness of the proposed optimized parameter set in overcoming the complex multi-parameter interactions and mitigating the impact of inherent dynamic noise and machine variations discussed earlier.

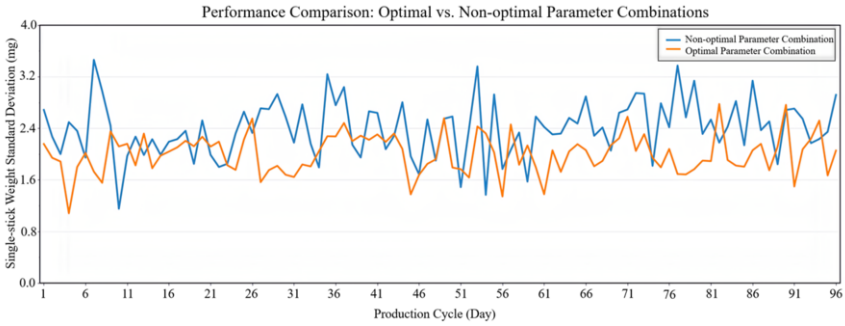


Figure 12. Performance Comparison Between Optimized and Sub-optimal Parameter Sets

4. Conclusions

This study established a mechanism-data dual-driven framework to optimize process parameters of the ZJ17 cigarette maker for minimizing the standard deviation of single-stick grammage (SDG). Key findings are:

a. Core Parameter Dominance & Synergy: Needle roller speed (28.3%), negative pressure value (19.7%), and cutter groove depth (15.2%) collectively dominate SDG variation (68.9% contribution), forming the core control triangle. A cutter groove depth of 3.5 mm consistently delivered the lowest SDG (mean 1.12%±0.18) across all conditions, significantly outperforming shallower depths (37%-52% improvement) by enhancing tobacco flow fluidization. Crucially, high needle roller speeds (>44 Hz) require coupling with lower negative pressure (0.18-0.20 MPa) to suppress deviation increases.

b. Impact of Dynamics and Machine Differences: Duct friction exhibited a distinct nonlinear relationship with SDG, with an optimal range of 0.18-0.22 N yielding minimal mean SDG (1.89±0.23 mg). Deviations beyond this range caused exponential SDG increases due to strand transport issues. Machine-to-machine variations, notably needle roller calibration offset (±0.5 Hz), induced systematic SDG differences (0.41 mg, $p=0.0032$), necessitating dynamic compensation coefficients.

c. Validated Optimal Parameter Set: The recommended parameter combination 3.5mm cutter groove depth + 44Hz needle roller speed + 1350 Pa small fan positive pressure + 0.195MPa negative pressure demonstrably stabilized SDG below 1.2% in validation trials, reducing fluctuation amplitude by 21.2% compared to sub-optimal configurations.

d. Methodological Contribution and Applicability: The integration of hybrid experimental design (Box-Behnken + Full Factorial), dynamic noise modeling, machine variation quantification, and interpretable machine learning (RF + SHAP) effectively overcame the limitations of traditional trial-and-error and single-variable analysis. The developed random forest model achieved high prediction accuracy ($R^2=0.832$, MAPE=6.7%) for SDG. This work provides a robust, data-driven paradigm and concrete optimization guidelines for enhancing the precision and robustness of quality control in ZJ17 cigarette makers, facilitating their intelligent upgrading."

5. Limitations and Future Work

While this study provides significant insights and a practical framework for ZJ17 parameter optimization, several limitations warrant consideration and point to future research directions:

5.1 Limitations

a. The core dataset generation relied on a mathematical model (Equation 2), calibrated and validated against limited experimental data. While dynamic noise was injected, the model might not perfectly capture all complexities under extreme conditions or unmodeled physical effects.

b. The types and ranges of simulated dynamic noise (vibration, friction, moisture, sensor noise) were empirically defined and may not encompass the full spectrum or intensity of real-world disturbances.

c. Machine differences were primarily modeled via calibration offsets and sensor errors. Other factors like varying degrees of mechanical wear, component aging, and assembly tolerances were not explicitly incorporated.

d. The study focused on offline optimization and analysis. The computational efficiency and robustness of the RF model for real-time, closed-loop control integration remain to be verified.

e. Validation on ZJ116 equipment showed 28.3% higher prediction error due to its nonlinear pressure gain. Future work will develop transfer learning frameworks for cross-model generalization.

5.2 Future Work

a. Embed the optimized parameters and predictive model into the ZJ17's control system (PLC/DCS) to develop online monitoring and dynamic adjustment algorithms for closed-loop quality control.

b. Expand the dynamic noise model to include more perturbation types (e.g., wider environmental fluctuations, real-time tobacco property changes, wear state monitoring) and explore data-driven dynamic models (e.g., LSTM).

c. Apply the framework to other cigarette maker models (e.g., ZJ116, ZJ119), investigate commonalities and specificities, and explore transfer learning strategies to reduce data requirements for new models.

d. Investigate the impact of variations in tobacco shred characteristics (size, moisture, blend) on optimal parameters and develop adaptive adjustment rules or more robust optimization models.

e. Explore model compression techniques (pruning, quantization) or investigate lighter models (e.g., XGBoost, LightGBM) for reduced computational cost, enabling real-time inference on edge devices.

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Modeling Internship and Training Satisfaction in Applied Technology Universities: A Structural Equation Approach

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Abstract. Internship and practical training are crucial components in cultivating applied talents in Applied Technology Universities. The degree of satisfaction of internship and practical training is an important basis for evaluating the quality of internship and practical training and improving the management mechanism of internship and practical training. Based on the research theories and reviews at home and abroad, this study develops and tests a Structural Equation Model to assess satisfaction with internships and practical training in applied technology universities. The research results show that: Students' Expectations have a significant positive direct impact on the Students' Perception of University Management, Students' Perception of Internship Organization Support, Management Satisfaction and Service Satisfaction; the Students' Perception of University Management has a significant negative impact on Management Satisfaction and Service Satisfaction; Students' Expectations do not produce the hypothesized indirect positive impact through the Students' Perception of University Management, but achieve a significant indirect positive impact on Management Satisfaction and Service Satisfaction through the perception of support from the internship units.

Keywords. Applied Technology Universities; Internship and Practical Training; Structural Equation Modeling; Satisfaction Model

1. Introduction

Against the backdrop of economic globalization and higher education reform, internship and practical training in applied technology universities emerged as a key mechanism in cultivating high-quality applied talents [1]. However, existing research lacks a systematic exploration of the formation mechanism of internship satisfaction in such institutions, particularly failing to deeply analyze the interaction path of "Students' Expectations university management support-enterprise organizational support-student satisfaction". There is an urgent need to construct a targeted theoretical model to optimize the quality of practical teaching.

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2. Literature Review

In 1965, Cardozo introduced the concept of "satisfaction" into the realm of business management [2]. His "expectation-perception" framework laid the foundation for service quality research and was gradually applied to the educational field. Since the 1990s, the maturity of Structural Equation Modeling (SEM) has enabled educational research to break through the limitations of traditional questionnaires, allowing for the quantitative analysis of complex causal relationships [3-4]. The chain models developed by the American Customer Satisfaction Index (ACSI) and the Chinese Customer Satisfaction Index (CCSI) have become core tools in student satisfaction research due to their standardized paths and cross-industry applicability.

Regarding the methodological iteration and key factors in internship satisfaction research, the research methods have evolved from a stage of simple questionnaires that focused on superficial factors such as the relevance of internship content and lacked theoretical depth [5] to a stage where universities draw on the ACSI/CCSI framework to develop student satisfaction models, validate the path of "student expectations → perceived support→satisfaction" through SEM, and analyze influencing factors [6-8]. Existing studies indicate that internship satisfaction is driven by three types of factors: organizational environmental factors, the role of university management, and individual characteristics of students [9-11]. However, most existing models are based on data from general undergraduate institutions and fail to deconstruct the unique mechanism of "school-enterprise dual-subject collaborative management" in applied technology universities. In particular, there is a lack of differential analysis of the "managerial support" from universities and the "organizational support" from enterprises.

3. Methodology

In this study, a structural equation is adopted to construct a satisfaction model for internship and practical training in applied technology universities. By analyzing the relationships between multi-dimensional satisfaction and multi-dimensional factors influencing satisfaction, the degree of interaction among these factors is revealed.

3.1. Conceptual Model

The conceptual model constructed in this study, which is shown in Figure 1, is based on the American Customer Satisfaction Index (ACSI) and the Chinese Customer Satisfaction Index (CCSI).

Students' Expectations (SE): Drawing on the concept of "customer expectations", SE refers to the anticipations formed by students before internship and practical training. Based on their personal interests, professional characteristics, and the nature of the courses, students develop expectations regarding how internship and practical training will contribute to enhancing their professional skills, promoting future development, and strengthening their abilities.

Students' Perception of University Management (SPUM): Based on the perceived support theory in ACSI/CCSI, SPUM reflects students' perceptions of university management, encompassing their perceptions of management norms, mobilization and

publicity, safety education, security guarantees, instructional training, and resource provision.

Students' Perception of Internship Organization Support (SPIOS): Based on the perceived support theory in ACSI/CCSI, SPIOS reflects students' perceptions of internship organizations, encompassing their perceptions of how internship organizations meet needs, provide recognition, and offer support.

Students' Satisfaction (SS): SS refers to the degree of contentment students have with various services provided by the school and internship units during the internship and practical training process. It is a psychological response after students' needs are met and serves as a target variable influenced by multiple factors.

Management Satisfaction (MS): Based on the theory of customer satisfaction, MS measures students' overall assessment of internship and practical training management. It can be used to evaluate the effectiveness of management strategies and service quality of universities and internship units, providing references for the optimization of applied technology education.

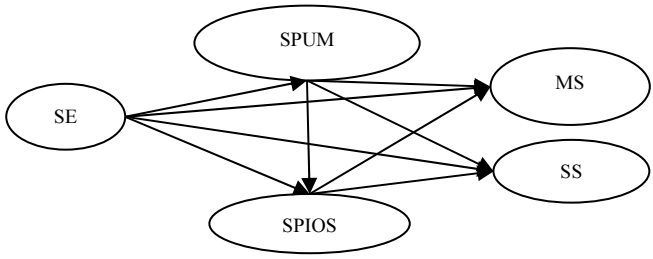


Figure 1. The Structural Model of Internship and Practical Training Satisfaction in an Applied Technology University.

3.2.Research Hypotheses

In this study, the hypotheses as shown in Table 1 are set based on the constructed conceptual model.

Table 1. Consistency Analysis of Each Dimension of the Survey Questionnaire

No.	Hypotheses	No.	Hypotheses
H1	SE has a significant positive impact on SPUM	H7	SPIOS has a significant positive impact on MS
H2	SE has a significant positive impact on SPIOS	H8	SPIOS has a significant positive impact on SS
H3	SE has a significant positive impact on MS	H9	SE has an indirect positive impact on MS through SPUM
H4	SE has a significant positive impact on SS	H10	SE has an indirect positive impact on SS through SPUM
H5	SPUM has a significant positive impact on MS	H11	SE has an indirect positive impact on MS through SPIOS
H6	SPUM has a significant positive impact on SS	H12	SE has an indirect positive impact on SS through SPIOS

4. Research Objects and Tools

4.1. Research Objects

This study selected students majoring in disciplines that offer internship and practical training courses at West Yunnan University of Applied Technology as the research subjects. Through online questionnaire distribution, all participants were clearly informed of the research objectives, data usage, and confidentiality principles to ensure their full voluntary participation. A total of 715 questionnaires were collected, all of

which were valid, with a 100% valid response rate. Among them, male students accounted for 69.8%, female students 30.2%; engineering majors constituted 27.8%, liberal arts majors 24.5%, science majors 27.6%, and students from other disciplines 20.1%.

4.2. Research Tools

This study draws on the "expectation-perception-satisfaction" logic of the Chinese Customer Satisfaction Index (CCSI) and the American Customer Satisfaction Index (ACSI) to explain the formation mechanism of students' satisfaction with internship management and organizational support, ensuring the reliability and validity of the research. By leveraging their support for SEM analysis, standardized paths facilitate data comparison and model optimization, thereby enhancing the generalizability of research results. Additionally, the study incorporates the management requirements and specifications of internship and practical training in some applied technology universities. Through summarizing the dimensions of the questionnaire on internship and practical training satisfaction in applied technology universities, five dimensions are formed: SE, SPUM, SPIOS, SS, and MS.

Based on the self-compiled "Questionnaire on the Satisfaction of Internship and Practical Training in Applied Technology Universities" mentioned above, three experts were invited to review it. The experts discussed and evaluated the setting of the questions to ensure the content validity of the questionnaire. The revised questionnaire is as follows: Firstly, it is the basic information of the survey objects, including items such as gender, educational background, and major. Secondly, the questionnaire on the influencing factors of satisfaction adopts a 5-point Likert scale ("completely consistent" to "completely inconsistent"), covering three dimensions: SE, SPUM, and SPIOS, with a total of 17 items. Thirdly, the satisfaction questionnaire adopts a 5-point Likert scale ("very satisfied" to "very dissatisfied"), including MS (covering aspects such as the duration and content of internship and practical training) and SS (covering the satisfaction with in-school and out-of-school instructors, as well as the assessment and evaluation of internship and practical training), with a total of 23 items.

Exploratory Factor Analysis (EFA) is carried out on the data through SPSS software to reduce the dimensionality of the survey data and explore its structure. With the help of AMOS software, a satisfaction model for internship and practical training in applied technology universities is constructed, and Confirmatory Factor Analysis (CFA) is conducted to evaluate the reliability and convergent validity of the model variables.

5. Research Results and Analysis

5.1. Analysis of the Conceptual Model

The consistency of the scale composition in the survey questionnaire is tested using the SPSS and AMOS software, and it is measured by the Cronbach's α coefficient. The value of the α coefficient ranges from 0 to 1. The larger the value, the better the reliability of the survey data.

Table 2. Results of the Reliability, KMO Test and Bartlett's Test of Sphericity for Each Dimension of the Scale in the Survey Questionnaire

Dimension	Cronbach α	CR	AVE	KMO	Bartlett's Test of Sphericity
SE	0.941	0.8967	0.5915	0.889	p<0.05
SPUM	0.972	0.9656	0.8238	0.943	
SPIOS	0.953	0.9364	0.8309	0.872	
MS	0.977	0.9742	0.7909	0.973	
SS	0.977	0.9768	0.7794	0.963	

As shown in Table 2, The CR of all latent variables is greater than 0.7, and the AVE is greater than 0.5, indicating that the measurement model has good internal consistency reliability and convergent validity.the Cronbach's α coefficients of SE, SPUM, SPIOS, MS, and service satisfaction are all greater than 0.900. This indicates that the "Questionnaire on the Internship and Practical Training Satisfaction of Applied Technology Universities" has a high level of reliability and good stability.The factor adaptability of the survey data is tested, The Kaiser - Meyer - Olkin (KMO) values of the samples are all greater than 0.7, and the p - value of the Bartlett's test of sphericity is less than 0.05, indicating that the data are suitable for factor analysis.

The validity of the survey data is tested through exploratory factor analysis. Using the principal component analysis method, factor loading analysis is carried out for each item according to the rotated component matrix. It is found that the factor loading coefficients of all scale items are greater than 0.5, and they can represent the corresponding influencing factors. This indicates that there is a correlation between the research items and the factors, and the factors can effectively extract information, showing that the scale design is reasonable with good reliability and validity.

5.2. Hypothesis Testing Analysis

After the reliability and validity analysis, AMOS is used to construct a conceptual model with one independent variables, two mediating variables, and two dependent variables based on the theoretical model for verification. All independent variables in the model have residual terms, and both mediating variables and dependent variables have variance terms.

Table 3. The goodness of fit of the internship and practical training satisfaction model in an applied technology university

Fit Test Indicator	Fit Standard	Model Result	Fit Evaluation
CMIN/DF	1 - 3	2.965	Good
RMSEA	< 0.08	0.052	Good
RMR	< 0.08	0.015	Good
GFI	> 0.90	0.881	Acceptable
CFI	> 0.90	0.969	Good
IFI	> 0.90	0.969	Good
TLI	> 0.90	0.965	Good

The internship and practical training satisfaction model for applied technology universities has a good fit, indicating a high degree of agreement between the model and the actual data. 4.1.From Table 3.

The significance test results of the path coefficients of the structural variables of the constructed conceptual model are shown in the following Figure 2.

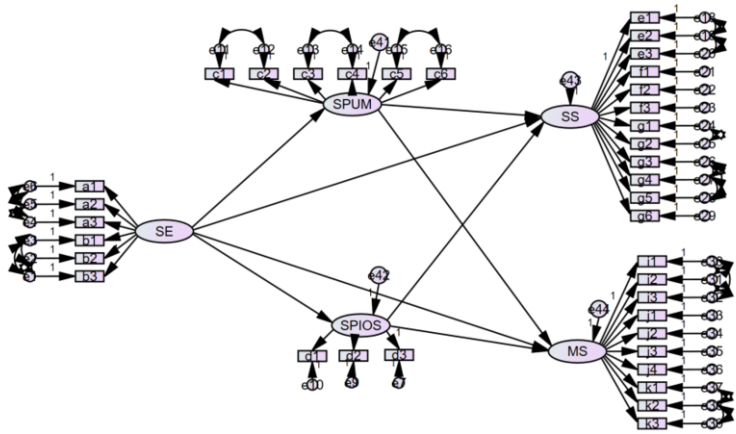


Figure 2.The Model of Internship and Practical Training Satisfaction in an Applied Technology University

Through the analysis, the following conclusions are drawn.From Table 4.

Table 4. Results of Hypothesis Tests for Path Relationships in the Internship and Practical Training Satisfaction Model of an Applied Technology University

No.	Path Relationship	Estimate	S.E.	C.R.	P	The hypothesis is supported at p < 0.001	The hypothesis is supported at p < 0.005	Result
H1	SPUM← SE	1.096	0.040	27.401	***	Yes	Yes	Supported
H2	SPIOS← SE	1.116	0.42	26.678	***	Yes	Yes	Supported
H3	MS←SE	2.496	0.453	5.514	***	Yes	Yes	Supported
H4	SS← SE	2.751	0.614	4.477	***	Yes	Yes	Supported
H5	MS←SPUM	-1.683	0.415	-4.058	***	Yes	Yes	Not Supported
H6	SS←SPUM	-1.982	0.562	-3.530	***	Yes	Yes	Not Supported
H7	MS← SPIOS	0.208	0.069	3.022	0.003	No	Yes	Supported
H8	SS← SPIOS	0.417	0.060	6.983	***	Yes	Yes	Supported

The study revealed that SE has a significant positive impact on SPUM, SPIOS, MS, and SS. This conclusion is consistent with the research results of scholars such as Rosenthal and Jacobson [12], Dan Fei [8], and Gu Tinghua [12]. SPUM has a significant negative effect on MS and SS, which may be related to factors such as gaps between customer expectations and perceived performance [13-14], mismatched expectations, and insufficient supervisor support [15]. In contrast, SPIOS has a significant positive effect on MS and SS. Regarding indirect effects, the hypothesis that SE has indirect positive effect on MS and SS through SPUM was not validated because the positive effects of SPUM on MS and SS were not supported. In the indirect effects of SE on MS and SS through SPIOS, although SE has a positive effect on SPIOS and SPIOS has a positive effect on MS and SS, The specific nature of this indirect relationship cannot be determined due to reasons such as the lack of further analytical data and the sample being from a single region.Therefore, more in-depth research and analysis will be needed in future studies.

6. Discussion

Institutional Practices: Given the substantial positive impact on multi-dimensional satisfaction, institutions should strengthen pre-internship communication. For example, Guiding student expectations through measures such as holding briefing sessions can prevent satisfaction declines caused by expectation gaps. Policy Making: Given that SPUM has a negative impact on both management satisfaction and student satisfaction, institutions need to improve internship policies. This includes optimizing processes, enhancing transparency, and promptly addressing issues, so as to enhance students' positive perceptions of university internship management and improve overall internship satisfaction.

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Application of Two-Phase Flow Measurement in Pneumatic Conveying of Tobacco Shred

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Abstract. Quality risks and issues (e.g., tobacco shred layering and severe crushing) caused by unstable and excessively high wind speed during wind-powered tobacco shred feeding have attracted great attention. Currently, the feeding speed of tobacco shreds is controlled indirectly by tuning the wind speed in the dust return duct. However, such an approach shows limited accuracy and poor performance due to air leakage. The quantitative detection of the movement speed of tobacco materials in a flow state is the theoretical basis of solutions to the issues mentioned above. Due to the irregular contour of elastic filamentous particles in tobacco, tobacco shred is exposed to random movements, including rotation, fluctuation, and agglomeration during conveying, making speed measurement extremely challenging. In this study, a tobacco shred feeding speed meter was designed and developed based on gas-solid two-phase flow measurement. Specifically, the wind-powered tobacco shred feeding system was upgraded based on a novel wind-powered tobacco shred feeding process that directly controls the feeding speed of tobacco shreds. The proposed device was demonstrated using products from a local cigarette factory. The results showed that no significant frictions of tobacco with the feeding duct were generated if the feeding speed of tobacco shred was controlled at 7.0-10.0 m/s, thereby effectively protecting the tobacco.

Keywords. Wind-powered tobacco shred feeding; measurement of gas-solid two-phase flow; measurement of tobacco shred speed; pneumatic conveying

1. Introduction

Due to its large capacity, long distance, minimal environmental pollution, and flexible spatial layout, pneumatic conveying has been widely employed for wind-powered tobacco shred feeding in the tobacco industry. In wind-powered tobacco shred feeding, tobacco shred is transported from the tobacco shred feeder to the cigarette machine via the tobacco shred feeding duct using the negative pressure airflow generated by the centrifugal fan. However, precise control of process parameters to minimize tobacco crushing has been a severe challenge in wind-powered tobacco shred feeding. Early wind-powered tobacco shred feeding systems are readily exposed to high tobacco

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crushing rates, high energy consumption, and frequent duct blocking due to the absence of wind speed regulation and wind control measures. Aiming at unstable wind speed in wind-powered tobacco shred feeding, Zhang *et al.* [1] investigated the hydraulic balance of air conveying networks and corresponding regulation methods by fluid network analysis; the working conditions of the air conveying network were quantitatively investigated by basic loop analysis, to identify the causes of unstable wind speed rapidly. Xie *et al.* [2] effectively regulated wind speed for tobacco shred feeding by replacing conventional fish-bone dendric networks with bundled networks and introducing one-on-one automatic compensation for air volume balance, thereby reducing tobacco crushing rate and energy consumption. Zhang *et al.* [3] proposed a novel wind-powered tobacco shred feeding system; from the perspective of industrial control, a dual-ring redundant network was employed as the network architecture of the wind-powered tobacco shred feeding system, accompanied by logical layering of the control system; the stability of the conveying control system was improved based on the PID control principles. In the early days, the wall mounted small car feeding method was adopted, which installed feeding devices on both sides of the production line[4]. The feeding machine conveyed the tobacco to the feeding device through a feeding tube and then transported it to the cigarette machine at a fixed time and quantity. This method also had low requirements for the physical properties of the tobacco itself and was relatively easy to maintain. The tobacco grade could be freely and flexibly switched [5]; At present, the domestic tobacco industry is undergoing a new round of technological transformation, and the wind powered wire feeding system basically adopts a centralized process wind powered conveying method [6]. This method brings about significant and unstable differences in wire feeding speed among different cigarette units, uneven distribution of air volume in the wire feeding pipeline, and unstable wire feeding of cigarette units in production caused by the start and stop of individual cigarette units. The stability of the wire feeding system directly affects the crushing of tobacco leaves [7]. Therefore, improving the stability of the entire wind powered wire feeding system is the key; With the development of control and automation technology, PLC control combined with fieldbus, industrial Ethernet, frequency conversion technology and other control methods is currently mainly used, which provides a relatively new monitoring method for wind power wire feeding systems, such as the wind speed balance adjustment method proposed by Sanli High tech Company [8] and the PID neural network pressure control method proposed by Tan Mei et al. [9]. These control methods improve the performance of the wire feeding wind speed control system, but the wind power wire feeding process has complex characteristics and serious nonlinearity, and further research is needed on its control strategy. Nevertheless, previous studies focused on network structure optimization and update of control measures, and control variables of the system were typically wind speed for tobacco shred feeding. In contrast, few studies have reported precise measurements of the feeding speed of tobacco shreds, which directly affects the crushing rate of tobacco shreds. In this study, the feeding speed of tobacco shreds was effectively reduced via precise control based on an analysis of fundamental principles of wind-powered tobacco shredding to decrease the crushing rate of tobacco shreds and ventilator frequency, thereby improving the process control of the system.

2. Case analysis

2.1 Process

A typical wind-powered tobacco shred feeding system comprises a tobacco shred feeder, tobacco shred feeding duct, cigarette machine, return duct, valves, dust collector, ventilator, muffler and electric control component, as shown in Fig. 1. The process of wind-powered tobacco shred feeding in the tobacco rolling and packaging workshop is as follows: (1) the finished tobacco in the storage cabinet are fed by flipping the box and then sent to the tobacco shred feeder after quantification; (2) tobacco shred is mixed with air in the feeder according to a designated ratio, and then sent to the tobacco collection box of corresponding the rolling equipment via negative pressure conveying, wherein the tobacco suction valve of the return duct is controlled by the shred-demanding signals of the rolling equipment; (3) the dusty airflow is sucked to and purified by the pulse jet-based dust collector in the dust removal chamber; (4) the clean air is discharged into the dust collection chamber or odor treatment system after noise reduction by the muffler, while tobacco shred in the tobacco collection box is discharged into the rolling equipment for cigarette production. Herein, the air and shred flows in the wind-powered tobacco shred feeding system are as follows: mixture of tobacco shred and air in the feeder - tobacco shred feeding duct - inlet of tobacco collection box of cigarette machine (storage), and discharge of tobacco shred into the cigarette machine for cigarette production - dusty airflow is discharged via the return duct at the outlet of tobacco collection box of cigarette machine - dust removal network - purification by dust collector, dust is discharged into the centralized dust collector and processed by the pressure rod - clean air is discharged into the ventilator - exit muffler - atmosphere or odor treatment system.

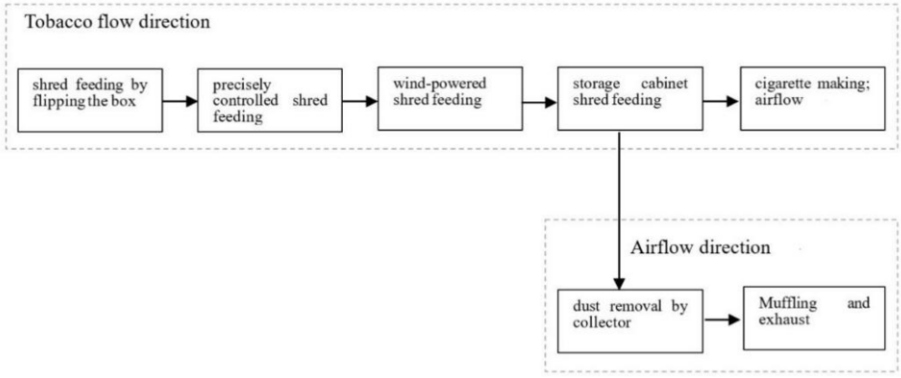


Fig. 1. Process flow of wind-powered tobacco shred feeding.

2.2 Problem formulation

Early wind-powered tobacco shred feeding systems are not equipped with measures for wind speed measurement and wind balance. Air volume and wind speed are regulated by variable-frequency driving using the ventilator at the end of the system. A wind-powered tobacco shred feeding system typically comprises several cigarette machines, and their shred-demanding signals tend to be out-synchronized. As a result,

the system's load and air intake volume vary significantly. Under extreme circumstances, all machines do not take shred, resulting in the ventilator surging. As a result, the ventilator can barely regulate key parameters such as wind speed for tobacco shred feeding as the time to reach stabilization of variable-frequency driving is far longer than one feeding period, which can hardly satisfy requirements for wind speed in wind-powered tobacco shred feeding.

Given the advances in wind-powered tobacco shred feeding (see Fig. 2), the wind-powered tobacco shred feeding system is equipped with air volume compensation devices and wind speed measurement and regulation devices. At this point, wind speed measurement is accomplished using a wire tube flowmeter installed on the tobacco shred feeding duct, while wind speed regulation is achieved through a wind speed valve and wind speed meter installed on the return duct. The wire tube flowmeter detects the wind speed in the tobacco shred feeding duct, but its measurement accuracy is limited. Additionally, the approach of indirectly regulating the air volume in the tobacco shred feeding duct by controlling the opening of the wind speed valve has inherent drawbacks. In this case, the system is susceptible to air leakage from the tobacco collection box, leading to low control precision. Although this represents an improvement over earlier systems, the wind speed for tobacco shred feeding shows significant fluctuations.

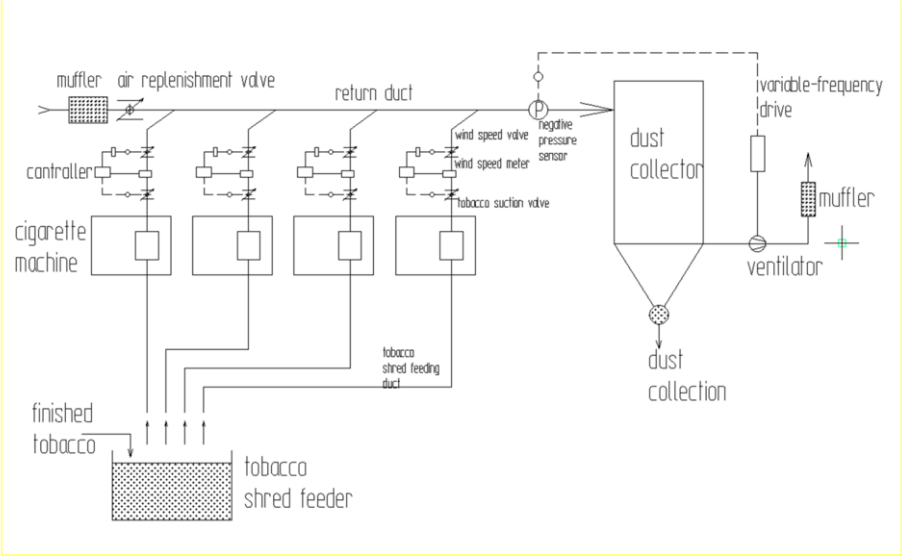


Fig. 2. Working principles of conventional wind-powered tobacco shred feeding systems

3. Problem solution

3.1 Tobacco suspension conveying speed

The tobacco conveying in wind-powered tobacco shred feeding systems involves air-solid two-phase flow. Due to the irregular contour of elastic filamentous particles in tobacco, tobacco is exposed to random movements, including rotation, fluctuation, and agglomeration during conveying, making speed measurement extremely challenging.

The suspension rate of tobacco (V_f) should be clarified to determine the feeding speed of tobacco shreds:

$$V_f = K_0 \sqrt{\csc(\alpha+\varphi)} \tag{1}$$

where α is the expansion angle of tobacco shred, $\psi=\tan^{-1} 2\sigma$, σ is the coefficient of friction of tobacco, and K_0 is the expansion coefficient of tobacco shred. During vertical pneumatic conveying, when the lifting force of the airflow equals the gravitational force on the material, the material reaches a vibrating equilibrium state in the airflow. The airflow velocity at this point is referred to as the suspension rate of tobacco. Indeed, V_f is positively related to density. In wind-powered tobacco shred feeding, V_f is typically 3.2~3.8 m/s.

According to the formula $V=\varphi \overline{V}_f$, ψ is a limiting number greater than 1. For tobacco, ψ generally ranges from 2.4 to 2.9. Considering the presence of tobacco agglomeration, an additional surplus coefficient of 1.2 is typically multiplied to prevent duct blocking. From this, the optimized feeding speed of tobacco shred Vis was determined to be approximately 710 m/s. Excessive speeds can lead to a high tobacco crushing rate, while insufficient ones can cause duct blocking.

3.2 Novel wind-powered tobacco shred feeding process

3.2.1 One-on-one machine air replenishment device

Figure 3 shows the upgraded wind-powered tobacco shred feeding system. As observed in Fig. 3, the tobacco suction valve 4 of cigarette machine 8 opens. The tobacco shred exits the feeder, passes through the wind-powered tobacco shred feeding duct 2, and enters the tobacco collection box 3. The outlet of the tobacco collection box is equipped with a filter screen, where tobacco is intercepted. The dusty airflow passes through the return duct 5 into the dust collector for dust removal. A one-on-one air replenishment device is installed on the return duct 5 of each machine. This device comprises a pneumatic air replenishment valve 9 and an air replenishment muffler 10. When the machine draws tobacco shreds, the PLC system detects the suction signal and controls the pneumatic air replenishment valve 9 to close fully. When the tobacco collection box is filled with tobacco, the PLC controls the pneumatic air replenishment valve 9 to open fully, replenishing a certain amount of air from the external environment to meet the stable air intake requirements of the ventilator. With the rapid response of the pneumatic valve and its interlocking control with the machine's suction signal, combined with optimized duct diameter and air volume design, ventilator surging is avoided. This air replenishment mode significantly improves the issue of delayed frequency response in the original ventilator, providing technical support for stable wind speed control at the system level. Additionally, compared to the difficulty of controlling the opening of the air replenishment valve in a single main duct air replenishment device, this one-on-one machine air replenishment mode is more flexible, faster, and more precise.

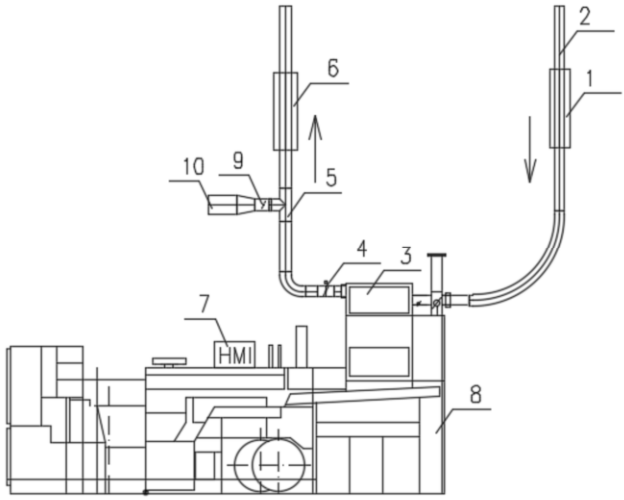
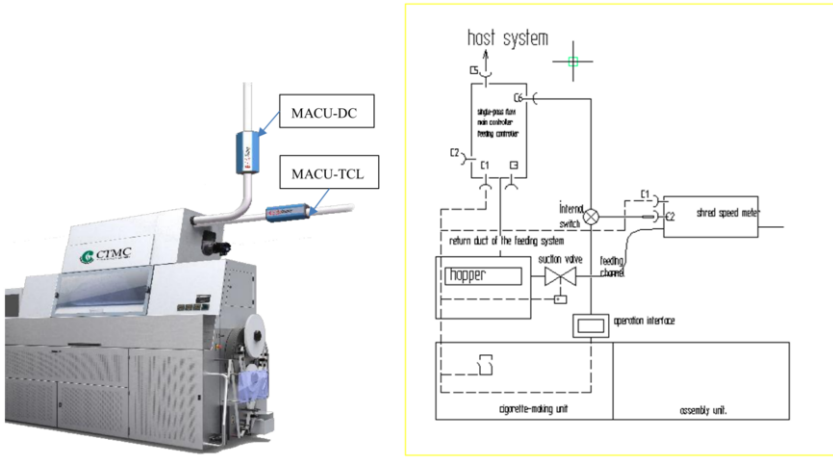


Fig. 3. Rapid-response one-on-one machine air replenishment wind-powered tobacco shred feeding system: 1 - feeding speed of tobacco shred meter; 2 - tobacco shred feeding duct; 3 - tobacco collection box; 4 - tobacco suction valve; 5 - return duct; 6 - wind speed control unit; 7 - touch screen; 8 - cigarette machine; 9 - one-on-one air replenishment valve; 10 - one-on-one air replenishment muffler.

3.2.2 Direct control mode of feeding speed of tobacco shred

Regardless of the mode used to control the wind speed for tobacco shred feeding, the ultimate goal is to achieve precise and controllable feeding speed, thereby reducing tobacco crushing. With advancements in measurement technology, air-solid two-phase flow measurement has been employed to measure the feeding speed of tobacco shreds in the feeding duct. As shown in Figs. 3 and 4, a feeding speed of tobacco shred meter 1 is installed on the feeding duct 2 of each cigarette machine, and a wind speed control unit 6 is installed on the return duct 5, accompanied by an HMI touch screen 7. The feeding speed of tobacco shred meter 1 is used to detect parameters such as the feeding speed of tobacco shred and feeding duct pressure, which are transmitted in real-time to the return control unit. The return control unit measures parameters such as return wind speed and return duct pressure. Through closed-loop control, the valve opening is adjusted to regulate the air volume in the return duct, thereby controlling the feeding speed of tobacco shreds and achieving flexible tobacco shred feeding. The Return control unit 6 is installed on the return duct 5 of the cigarette machine and is used to measure parameters such as the speed of the dusty airflow and return duct pressure. Through PLC programming, the servo motor valve opening is controlled to precisely adjust the air volume in the return duct, thereby accurately regulating the feeding speed of tobacco shred in the tobacco shred feeding duct. The HMI touch screen 7 installed on the machine allows real-time monitoring of various parameters during tobacco conveying. This mode achieves closed-loop control of the feeding speed of tobacco shreds in the feeding duct, wind speed in the return duct, and human-machine operation. One of the core components of this system is the feeding speed of the tobacco shred meter, which is built on the gas-solid two-phase flow measurement based on laser measurement. Using the photoelectric, gas-solid two-phase, and statistical models, signals are digitally processed to analyze particulates' velocity and flow rate accurately.

CThis method offers higher accuracy, stability, reliability, and interference resistance than conventional analog amplification. As a scalable system, the proposed feeding speed meter monitors particulate flow rate and concentration under various conditions, including particulate exhaust and process control.



(a) (b)

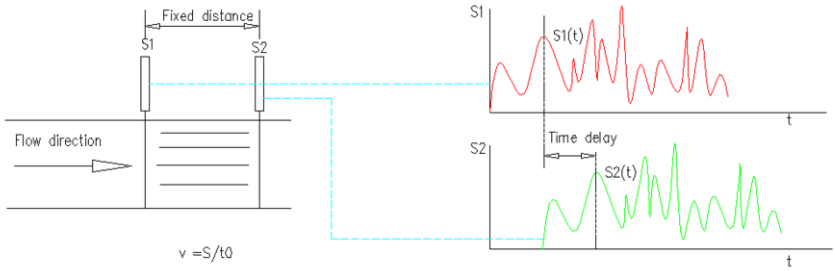
Fig. 4. Appearance (a) and **s**chematic (b) of the control system based on direct control of feeding speed of tobacco shred: 1- host system; 2- single-pass flow; 3 -main controller; 4 -feeding controller; 5 - internal switch; 6 -shred speed meter; 7 -return duct of the feeding system; 8 –hopper; 9 -suction valve; 10 -feeding channel; 11 - operation interface; 12 - cigarette-making unit; 13 - assembly unit.

4. Tobacco feeding speed meter

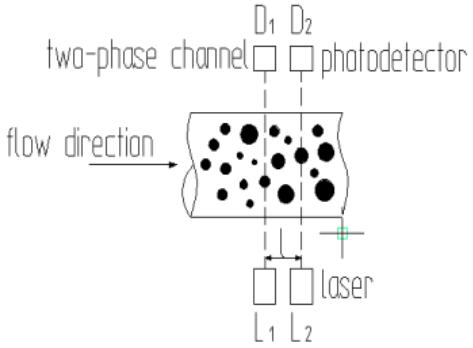
4.1 Gas-solid two-phase flow measurement based on laser measurement

As shown in Fig. 5, certain information carried by an object moving at the velocity V is sequentially transmitted to two sensors spaced at a distance S. The signals generated by these two photoelectric sensors (S1 and S2) exhibit a certain delay t0. According to the formula $V = S/t_0$, the object's velocity can be measured.

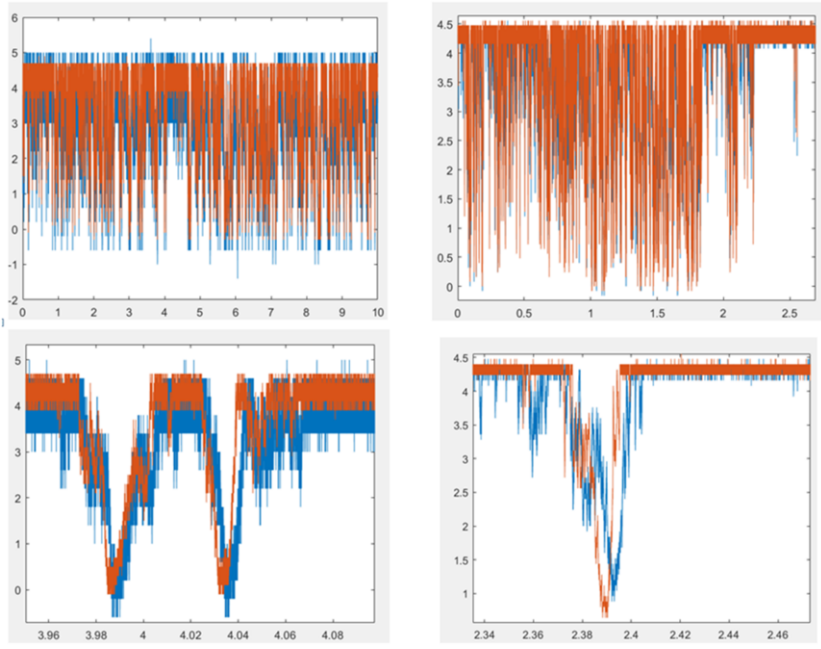
The feeding speed of the tobacco shred meter is an application of gas-solid two-phase flow measurement based on laser measurement. During the conveying process, the tobacco shred continuously changes its conveying form under airflow. Since the distance between the two measurement points is very small, the conveying form of the tobacco shred has not changed before the photoelectric sensor receives the corresponding signals as it passes through these points. The transient speed is ultimately determined through processing, comparison, and analysis.



a. Principle diagram of laser speed measurement



b. Schematic diagram of tobacco passing through laser speed measurement device

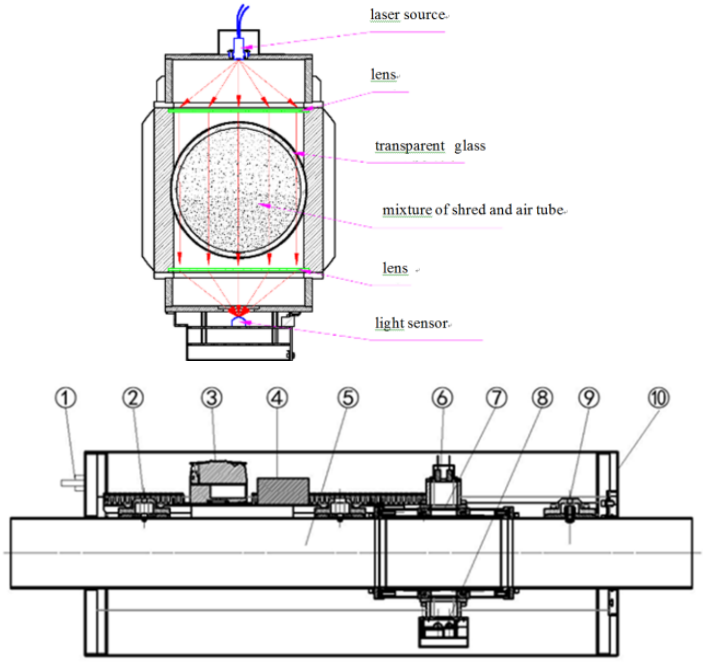


c. The overall and local signals at wind speeds of 16m/s and 20m/s respectively

Fig. 5. Working principles of feeding speed of tobacco shred meter

4.2 Structural design

The feeding speed of the tobacco shred meter comprises a shell suspension hook 1, a differential pressure tapping device 2, a PLC module 3, a micro-differential pressure transmitter 4, a pipeline 5, a solid-state laser emitter 6, a lens 7, an FGPA photosensitive receiver board 8, a pressure tapping device 9, and a shell 10. Based on unique photoelectric signals, this device employs a time-of-flight algorithm to obtain precise measurement results and measure the actual flow velocity of particulates. Excessive signal sampling and optimized algorithms eliminate random interference caused by unstable flows. The transient speed of tobacco shred can be directly and accurately tested in real time. The actual flow velocity of tobacco in the pipeline can be obtained anytime, providing operators with accurate data. By using the feeding speed signal of the tobacco shreds to control the return valve, the system is unaffected by machine air leakage, reducing the feeding speed of the tobacco shreds and improving the whole shred rate. Also, early warnings of blockages in the tobacco pneumatic conveying pipeline can be provided in time, thus preventing machine shutdown from affecting production.



1—Shell suspension hook, 2—Differential pressure tapping device , 3—PLC module , 4—Micro-differential pressure transmitter , 5—Pipeline , 6—Solid-state laser emitter , 7—Lens , 8—FGPA photosensitive receiver board , 9—Pressure tapping device , 10—Shell .

Fig. 6. Structure of feeding speed of tobacco shred meter

5. Application

5.1 Experimental design

Materials: tobacco products by a local cigarette factory.

Instruments and equipment: tobacco shred feeder (Zhisi Holding Group Co., Ltd, China), high-speed molding machine M5 (Akira, Germany), electronic balance, and a Testowind speed meter.

Comparative experimental method: A batch of tobacco (sampled from the storage cabinet) was selected and divided into Samples A, B, and C.

For Sample A, the mode of directly controlling the feeding speed of tobacco shred was not activated. Under the same ventilator frequency, the tobacco was conveyed through the wind-powered tobacco shred feeding system to the hopper of the cigarette machine. The tobacco was removed from the hopper and weighed to measure the dust loss after conveying.

For Sample B, the mode of directly controlling the feeding speed of tobacco shreds was activated. Under the same ventilator frequency, the tobacco was conveyed through the wind-powered tobacco shred feeding system to the hopper of the cigarette machine. The tobacco was then removed from the hopper and weighed to measure the dust loss after conveying.

For Sample C, the mode of directly controlling the feeding speed of tobacco shreds was activated. Under different ventilator frequencies, the tobacco was conveyed through the wind-powered tobacco shred feeding system to the hopper of the cigarette machine. The tobacco was then removed from the hopper and weighed to measure the dust loss after conveying.

The method of determining the dust loss of tobacco shreds refers to the *Method of Determining the Whole Shred Rate and Broken Shred Rate of Tobacco*. To ensure the test's accuracy, the cigarette machine's hopper, the pneumatic conveying pipeline, the feeding belt, the quantitative tube, and the tobacco shred feeder were emptied before testing the dust loss. After all the tobacco shred was conveyed, no residual tobacco shred remained in the device mentioned above, as shown in Fig. 7.

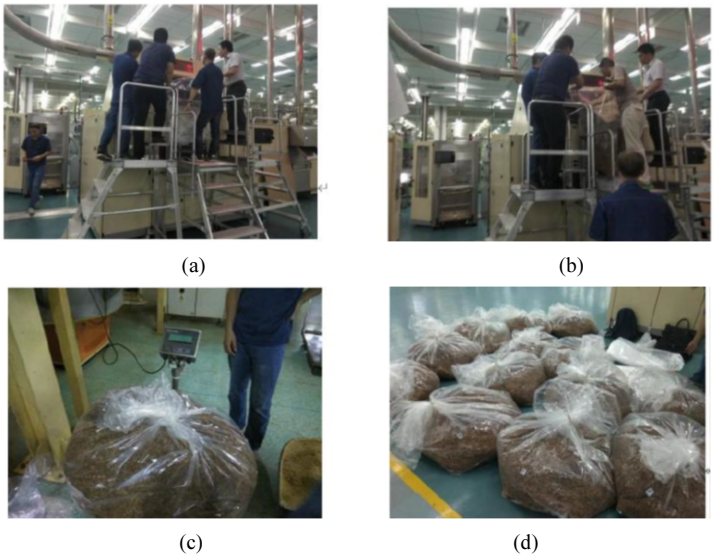
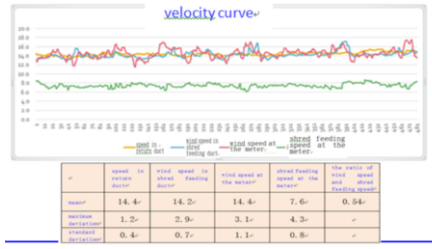


Fig. 7. Testing of dust loss of tobacco shred**: (a**) shred conveying; (b) sampling from hopper; (c) sample weighing; (d) sample labeling.

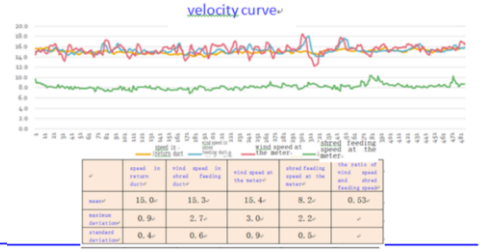
5.2 Data analysis

For Sample A (first group), the tobacco mass before and after conveying was 55.1 and 54.3 kg, respectively, resulting in a dust loss of 0.8 kg and a dust loss rate of 1.452%; for Sample B (second group), the tobacco mass before and after conveying was 50.7 and 50.2 kg, respectively, resulting in dust loss of 0.5 kg and a dust loss rate of 0.986%. When the mode of directly controlling the feeding speed of the tobacco shred was activated, the dust loss during the conveying process, where the feeding speed of the tobacco shred was fully controlled, was reduced by 0.466% compared to the unactivated mode, where the feeding speed of tobacco shred was not controlled.

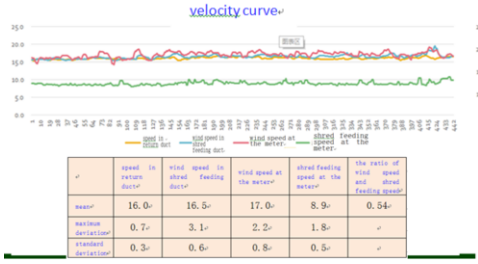
For Sample C, four sets of experiments were conducted with the mode of directly controlling the feeding speed of tobacco shred activated and under different ventilator frequencies. By controlling the wind speed for tobacco shred feeding at 14 m/s, 15 m/s, 16 m/s, and 17 m/s, the corresponding feeding speed of tobacco shred was recorded, and observations were made for any duct blocking. The dust loss was measured using the method mentioned above. The feeding speeds of tobacco shred corresponding to the four wind speeds were 7.6 m/s, 8.2 m/s, 8.9 m/s, and 10.4 m/s, as shown in Fig. 8. Herein, the wind speed for tobacco shred feeding is positively correlated with the feeding speed of tobacco shred, and the feeding speed of tobacco shred is also positively correlated with dust loss. The higher the feeding speed of tobacco shreds, the greater the dust loss and the higher the crushing rate. However, an excessively low feeding speed of tobacco shred can easily cause duct blocking. If the feeding speed of the tobacco shred was kept below 7 m/s, tobacco was exposed to severe agglomeration, resulting in duct blocking. Hence, it can be deduced that the optimized range of feeding speed of tobacco shreds in wind-powered tobacco shredding is 7~10 m/s.



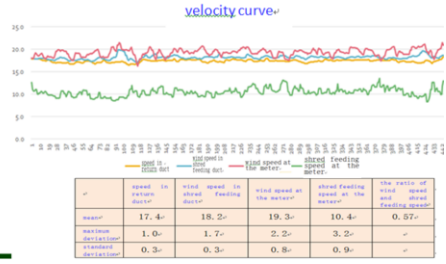
a. Testing wind and shred feeding speeds of 14 and 7.6 m/s.



b. Testing wind and shred feeding speeds of 15 and 8.2 m/s



c. Testing wind and shred feeding speeds of 16 and 8.9 m/s.



d. Testing wind and shred feeding speeds of 17 and 10.4 m/s

Fig. 8. Control of process parameters and respective curves.

6. Conclusions

1) Gas-solid two-phase flow measurement based on laser measurement was employed to measure the feeding speed of tobacco shreds in the feeding duct of the wind-powered tobacco shred feeding system. Here, the feeding speed of tobacco shreds can be directly monitored, thus achieving wind speed regulation and, eventually, flexible tobacco shred feeding.
2) A one-on-one machine air replenishment device was applied to a novel wind-powered tobacco shred feeding system to mitigate lag of frequency conversion response or difficult control of valve opening of one dominating air replenishment device, thereby facilitating precise control of wind speed.
3) The optimized range of tobacco shred feeding speed was determined to be 710 m/s (blocking is avoided, and dust loss and crushing rate are reduced). This study provides insights for future studies and practice.

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Automated Quality Inspection System for TCMI Based on Microtox Technology

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Abstract. The quality testing of traditional Chinese medicine injection (TCMI) provides quantitative indicators for its safety evaluation, improving quality control and reducing adverse reaction rates. However, no automated Microtox-based testing equipment currently exists globally, necessitating manual intervention in the entire process. To address this, our team developed an automated TCMI quality testing system using Microtox technology. By integrating manual workflows and standardizing reusable technologies, the instrument comprises three modules: a mixing-resuscitation module, a mechanical pipetting module, and a light intensity measurement module. Centralized computer control enables fully automated TCMI quality testing. Experimental results demonstrate strong consistency between manual and automated testing, with reduced human-induced measurement errors and enhanced data reliability for TCMI quality assessment.

Keywords. traditional Chinese medicine injection(TCMI), Microtox technology, automated testing equipment, mixing+resuscitation module, lmechanical pipetting module, light intensity measurement module

1. Introduction

TCMI , a novel formulation developed in China, offers rapid onset and high therapeutic efficacy, challenging the conventional perception that traditional Chinese medicine (TCM) is limited to chronic disease management. By addressing the gap in emergency clinical applications of TCM, TCMI demonstrates promising therapeutic potential for complex and critical illnesses [1, 2]. However, as its clinical use expands and product varieties increase, frequent adverse reactions have raised significant safety concerns, thereby restricting its broader application and development [3, 4]. To mitigate these challenges, the integration of Microtox technology into TCMI quality control has emerged

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as a groundbreaking approach. This method enables the detection of biological activity fluctuations, quantifies high-risk toxicity parameters, and provides early safety risk warnings. Consequently, it reduces adverse reaction rates while enhancing the reliability of quality assessment and safety evaluation for TCMI [5-7].

Globally, no specialized Microtox-based toxicity testing equipment exists for TCMI quality evaluation. Current commercial systems, such as the Toxcontrol (MicroLAN, Netherlands) and Toxalarm (LAR, Germany), are designed primarily for water quality monitoring, focusing on drinking water safety, wastewater toxicity, or industrial liquid analysis [8-12]. While these instruments assess pollutant toxicity by measuring organismal responses to environmental changes, they exhibit critical limitations. For instance, luminescent bacteria-based acute toxicity testers suffer from inconsistent results due to varying bacterial strains and protocols. Additionally, most devices lack sensitivity, exhibit prolonged response times, and rely on labor-intensive manual workflows. Current protocols require laboratory personnel to manually resuscitate freeze-dried bacteria, prepare test solutions (e.g., dilution and osmotic pressure adjustment), and transfer samples—processes prone to human error. Manual pipetting, inconsistent shaking techniques (force, angle, duration), and room-temperature testing without thermal regulation further compromise reproducibility. Moreover, traditional systems process only one sample at a time, extending experiment durations to approximately one hour [13-15].

To overcome these limitations, this study proposes an automated TCMI quality inspection system based on Microtox technology. The system comprises three integrated modules: (1) a mixing and resuscitation module for bacterial revival, thermal regulation, and solution homogenization; (2) a mechanical pipetting module for precise solution preparation and transfer; and (3) a light intensity measurement module to quantify bioluminescence at designated intervals. By simulating manual workflows, this system automates the entire experimental process—including dilution, equilibration, mixing, and bioluminescence measurement—thereby minimizing human intervention. Automated shaking and pipetting ensure consistent force, angle, and timing, while thermal control maintains solution stability. The system also supports parallel processing of multiple samples, significantly improving efficiency compared to single-sample traditional devices. This innovation enhances the accuracy, reproducibility, and throughput of TCMI quality control, offering a robust solution to safety challenges and advancing the clinical application of TCMIs.

1.1. Materials and Methods

1.1.1. Manual inspection process for the quality of TCMI

As illustrated in Fig. 1, this study systematically organizes the manual experimental workflow into four sequential steps: solution dilution, temperature equilibration, solution mixing, and light intensity measurement. The detailed protocol is as follows: Luminescent bacteria are stored at -20°C, while the recovery dilution solution is maintained at 4–8°C. The osmotic pressure-regulating solution and quality control solution are equilibrated at room temperature (15–25°C) for 15 minutes. The test sample is diluted with a sample diluent to 6–12 concentration gradients, followed by the addition of osmotic pressure-regulating solution in specified proportions to prepare test solutions. Balanced luminescent bacteria are mixed with recovery diluent, homogenized, and incubated for 10 minutes to prepare the test bacterial suspension. After thorough mixing, 50–100 uL of

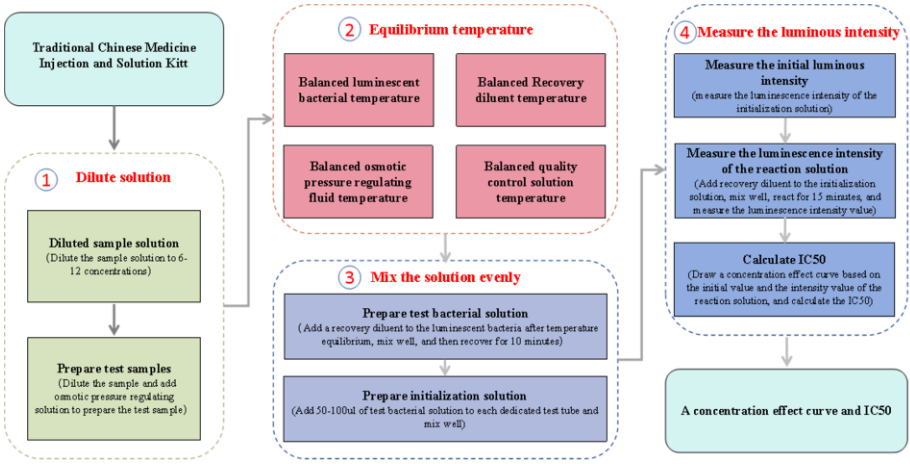


Figure 1. Modular processing of manual detection process

the suspension is transferred to dedicated test tubes. The initial luminescence intensity of the bacterial solution is measured. Test samples are then added to the bacterial solution tubes, while recovery diluent is added to control tubes (blank controls). After homogenization and a 15-minute reaction period, luminescence intensity is measured. Finally, the IC50 value is calculated, and a concentration-effect curve is generated.

1.1.2. Automated Quality Inspection System for TCMI design

The automated system modularizes critical manual inspection steps—shaking, bacterial solution recovery, temperature equilibration, pipetting, and luminescence detection—into three integrated components: a mixing+resuscitation module, a mechanical pipetting module, and a light intensity measurement module (Fig. 2).

The mixing+resuscitation module combines metal bath heating and eccentric ball-bearing rotation technologies to unify bacterial revival, solution homogenization, and thermal regulation. A motorized ball shaft, heated metal block (custom-sized for reaction tube arrays), and temperature-controlled shaking circuit enable programmable heating (start/stop/temperature monitoring) and oscillation (amplitude control) for reagent preparation and bacterial reactivation.

The mechanical pipetting module employs a 3D motorized platform with dual pipettes (0–300 uL and 300–1000 uL ranges) to automate liquid handling. XYZ-axis motors, guided by limit switches, ensure precise positioning, while dual-channel pipetting allows simultaneous solution preparation (0–300 uL) and transfer (300–1000 uL). Automated tip replacement and programmable aspiration/dispensing enhance efficiency and reduce cross-contamination . The light intensity measurement module utilizes a 9-tube rack with embedded multi-channel sensors for batch luminescence analysis. Probes beneath each tube convert analog signals to digital data, transmitted via a serial interface. An opaque PVC shield, operable at 45°, ensures darkroom conditions during detection. Integrated control circuits manage shield actuation and data transmission.

By consolidating manual workflows into a unified platform, the system reduces complexity, minimizes human intervention, and improves reproducibility in TCMI quality control.



(a) (b) (c)

Figure 2. (a) Top view of the instrument (b) Side view of the instrument (c) Front view of the instrument

2. Consistency verification of the system

The consistency verification of the system mainly involves two aspects: the consistency of luminous intensity and the consistency verification of manual and automatic liquid dispensing.

Table 1. Stability Test for Single Hole Positions

Number of measurements	1	2	3	4	5	6
Luminous intensity value	411.738	411.464	410.856	410.555	410.235	410.172
Mean luminous intensity			410.836			
Error percentage	0.22%	0.15%	0.00%	0.07%	0.15%	0.16%

2.1. Consistency verification of luminous intensity

2.1.1. Consistency Test of Light Intensity Values at Nine Hole Positions

To validate the precision and uniformity of the 9-channel light intensity measurement module, stability and consistency tests were conducted using reconstituted luminescent bacteria. A freeze-dried bacterial sample was equilibrated at 20°C for 15 minutes, reconstituted with 1.1 mL recovery diluent, and incubated for 10 minutes. For stability testing, 100 uL of the bacterial solution was measured six times consecutively at the same well position (Table 1). Results showed an average luminescence intensity of 410.836 with a maximum percentage deviation of 0.22% from the mean, confirming single-well measurement stability. For 9-hole consistency testing, the same sample was measured across all nine wells (Table 2), yielding an average intensity of 396.38 and a maximum inter-well deviation of 2.34%, demonstrating high spatial uniformity. These outcomes verify the system's reliability for multi-channel luminescence detection in TCMI quality control applications.

2.1.2. Calibration test with standard instrument luminous intensity

The light intensity measurement module, which quantifies bacterial bioluminescence via embedded sensors without intrinsic units, requires calibration against a standardized reference. This study employs a Hamamatsu BHP9514 luminescent bacteria detector as the

Table 2. Consistency Test of Light Intensity Values for 9 Hole Positions

Number of measurements	1	2	3	4	5	6	7	8	9
Luminous intensity value	395.874	401.715	389.802	389.413	405.644	380.159	405.609	396.382	402.826
Mean luminous intensity					396.38				
Error percentage	0.13%	1.35%	1.66%	1.76%	2.34%	4.09%	2.33%	0.00%	1.63%

calibration instrument. Test solutions were prepared at six mass fractions (80%, 60%, 40%, 25%, 10%, and 5%) using serial dilution. For analysis, 100 uL of reconstituted bacterial solution was mixed with 1 mL of each diluted sample, incubated for 15 minutes, and measured concurrently by both the prototype module and the Hamamatsu device. As shown in Table 3, comparative luminescence data revealed a strong correlation between the two systems. Figure 3 illustrates this relationship through a scatter plot, with the prototype's readings on the x-axis and the standard instrument's values on the y-axis. Linear regression via least squares fitting yielded a calibration equation, confirming the module's accuracy and enabling unit standardization for TCMI applications, the relationship expression can be obtained:

$$y = 10900x + 91850 \tag{1}$$

In Equation (1), x denotes the prototype instrument's measured light intensity, and y represents the standard device's values. Calibration via this formula yields a maximum error of 3.42%.

Table 3. Light intensity measurement results of instruments and standard instruments in this article

solution concentration	5%	10%	25%	40%	60%	80%
Standard instrument(RLU)	2831441	2727881	2292763	1705117	1149323	688059
Before calibration in this article	250.43	239.21	209.12	143.45	95.95	56.69
After calibration(RLU) in this article	2821537	2699239	2371258	1655455	1137705	709771
Error percentage	0.35%	1.05%	3.42%	2.91%	1.01%	3.16%

2.2. Verification of consistency between manual and automatic dispensing

As shown in Figure 3, this study evaluates the consistency between manual and automated workflows for preparing a 50% TCMI solution through three steps: (1) Bacterial solution preparation: Freeze-dried powder was equilibrated at 25°C for 15 minutes, reconstituted with 1 mL recovery diluent, vortexed for 15 seconds, incubated for 9.5 minutes, and revortexed. (2) Sample preparation: TCMI was diluted to 50% with sample diluent, supplemented with osmotic pressure regulator (17:3 ratio) to 2 mL total volume, and homogenized. (3) Luminescence detection: 100 uL bacterial solution and 1 uL test sample were transferred to Well 1, incubated for 15 minutes, and measured. As shown in Figure 4, manual (left tube) and automated (right tube) mixing/pipetting demonstrated visual consistency. Automated dispensing yielded a luminescence intensity of 322,109 RLU versus 314,897 RLU for manual methods, resulting in a 2.23% relative error when

normalized to manual results. This confirms the reliability of the automated system for TCMI quality control applications.

2.3. Estimation of the accuracy of curve fitting for calculating IC50

The IC50 is the 50% inhibitory concentration, corresponds to the concentration at B/B0=50%. This article refers to the concentration corresponding to a luminescence intensity suppression rate of 50%. The manual detection method mainly determines the approximate concentration range of IC50 through pre-experiments. Based on the size of the range, interpolation or proportional methods are used to determine the concentration gradient set in the range, and then the IC50 value is approximated through this concentration gradient in the formal experiment. This method has a significant error. Based on this, this article found through curve fitting that the concentration inhibition rate curve can be expressed as a logarithmic function. As shown in Figure 4 and Table 4, the correlation coefficient of the curve fitting for the common Shenfu injection is 0.9925, and that for the Kangai injection is 0.9829. This demonstrates the effectiveness of this fitting method.

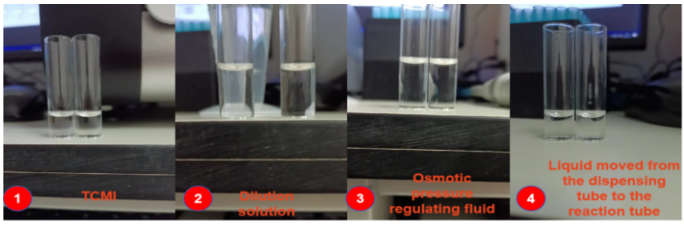
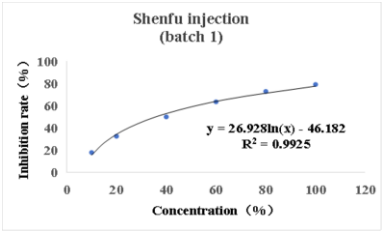


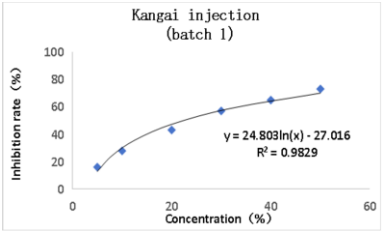
Figure 3. Results of manual mixing and pipetting, automatic mixing and pipetting

Table 4. Light intensity measurement results of instruments and standard instruments in this article

	concentration (%)	Intensity (RLU)	Inhibition rate (%)	Curve fitting value	Percentage of error (%)	R-squared value
	100	52173	79.29	77.83	1.85%	
	80	67819	73.07	71.82	1.71%	
Shenfu injection	60	91406	63.71	64.07	0.57%	0.9925
(batch 1)	40	125509	50.17	53.15	5.94%	
	20	169383	32.75	34.49	5.30%	
	10	206091	18.18	15.82	12.97%	
control group				358695		
	50	96788	73.02	70.01	4.12%	
	40	125818	64.92	64.48	0.68%	
Kangai injection	30	154136	57.03	57.34	0.55%	0.9829
(batch 1)	20	203966	43.14	47.29	9.61%	
	10	258573	27.91	30.10	7.83%	
	5	300924	16.11	12.90	19.91%	
control group				358695		



(a)



(b)

Figure 4. Concentration-Inhibition curve (a)Shenfu injection(batch 1)(b)Kangai injection(batch 1)

3. Conclusions

Toxicity assessment remains a critical challenge in Traditional Chinese Medicine (TCM) safety evaluation, requiring methods that balance accuracy, speed, and cost-effectiveness. Current approaches—including acute, subacute, and long-term toxicity tests—rely heavily on histopathological and biochemical markers [16], yet fail to address TCM's complexity. While emerging disciplines like metabolomics, proteomics, and toxicokinetics offer new perspectives [17], their reliance on costly, time-intensive protocols and narrow focus on known toxic components limits applicability. Unlike Western pharmaceuticals, TCM toxicity is often relative, with overlapping toxic and active constituents, multi-target interactions, and dynamic component synergies that mitigate harm. Conventional methods, designed for pure chemical agents, inadequately capture these nuances, leaving unknown toxicants undetected.

To address these gaps, this study introduces fully automated Microtox-based detection equipment integrating metal bath thermoregulation, eccentric ball-bearing oscillation, 3D motion platforms, and multi-channel luminescence sensing. The system consolidates bacterial resuscitation, solution homogenization, and thermal regulation into a unified module, reducing complexity and cost. A 9-channel sensor array enables parallel batch detection of luminescent bacteria across concentration gradients, overcoming the inefficiency of manual or sequential testing. Darkroom-compatible PVC shields and high-speed A/D converters ensure precise, interference-free signal acquisition. By automating workflows—from sample dilution and equilibration to bioluminescence quantification—the system minimizes human error and accelerates throughput.

This innovation aligns with TCM's holistic principles by providing rapid, comprehensive toxicity profiles rather than isolated component analysis. Initial validation demonstrates reduced measurement variability and enhanced reproducibility, offering a scalable framework for quality control and risk assessment in TCM formulations. The integration of Microtox technology bridges the gap between traditional toxicity paradigms and TCM's unique complexity, paving the way for globally standardized safety evaluations.

4. Patents and Funding

The work presented in this paper is covered by pending Chinese and international patents filed by the Xin-Huangpu Joint Innovation Institute of Chinese Medicine (Patent Ap-

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Research on the Carbon Emission Reduction Effect of China's Carbon Emission Trading Policy

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Abstract. This paper empirically evaluates the carbon emission reduction effects of China's carbon emission trading policy using panel data from 30 provinces from 2005 to 2022, applying the synthetic control method based on LASSO. The study finds that: First, the carbon emission trading policy significantly reduces carbon intensity in pilot regions. Second, the policy effect shows significant regional heterogeneity, with the carbon intensity reduction in Industrial Transition Zones (Chongqing, Hubei, Tianjin) being significantly higher than that in Service-Innovation Hubs (Beijing, Shanghai, Guangdong). The study recommends: 1) Optimizing the design of the carbon emission trading mechanism to enhance policy flexibility; and 2) Strengthening regional coordination to promote balanced policy effects. This research provides empirical evidence for improving carbon emission trading policies and holds important theoretical and practical significance for advancing China's "Dual Carbon" goals.

Keywords. Carbon emissions trading, LASSO, synthetic control method, carbon intensity

1. Introduction

The effectiveness of emission trading systems (ETS) in driving decarbonization has been globally validated. The EU ETS, for instance, not only reduces carbon emissions but also fosters low-carbon innovation without significantly affecting economic performance [1]. China's ETS pilots, initiated in 2013, have shown early success in lowering regional emissions through price signals and quota constraints [2]. However, their impact varies by region, with resource-dependent cities experiencing greater reductions due to stricter regulations [3], and synergies arising when ETS interacts with energy quotas.

Despite progress, debates continue. Some argue that firms may shift compliance costs to consumers [4], while others emphasize the welfare benefits of broader trading scopes [5]. Additionally, the co-benefits of pollution control and emission reduction under ETS remain underexplored [6].

This study evaluates China's ETS pilot policy using panel data from 30 provinces (2005–2022) and a LASSO-enhanced synthetic control method (SCM) to mitigate overfitting in counterfactual analysis. Key contributions include: (1) improving estimation accuracy through LASSO-SCM integration; (2) uncovering provincial-level

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heterogeneity in carbon reduction effects; and (3) offering policy optimization insights for China's national carbon market.

2.Theoretical Analysis and Research Hypotheses

Carbon emission trading policies internalize emission costs through market pricing, encouraging firms to adopt low-carbon technologies and optimize energy use [7]. Empirical evidence shows their effectiveness in reducing carbon intensity in sectors like industry and public buildings [8], supporting Hypothesis 1 that carbon trading policies reduce carbon intensity in pilot regions.

Regional differences in energy infrastructure, fossil fuel dependence, and policy enforcement create varied responses to emission trading mechanisms [9]. Regions with renewable energy advantages tend to achieve stronger reductions, supporting Hypothesis 2 that the policy's emission reduction effects vary regionally.

3. Variable Selection and Data Sources

3.1 Variable Measurement

Dependent Variable: Carbon Intensity, measured as the ratio of carbon emissions to regional GDP (with 2005 as the base year).

Independent Variable: Carbon Emission Trading Pilot Policy, represented by a dummy variable. It equals 1 for regions in the pilot program from the pilot year onward, and 0 for regions not included.

Control Variables: Based on Zhao et al. [10] and Yang et al. [11], control variables include Economic Development Level, Industrial Structure, Urbanization Level, Degree of Openness, Labor Force Level, and R&D Intensity.

Table 1. Variable Definitions.

Variable Type	Variable Name	Symbol	Measurement Method
Dependent Variable	Carbon Intensity	ci	The logarithm of the ratio of carbon emissions to real GDP
Control Variable	Economic Development Level	eco	The logarithm of real per capita GDP with 2005 as the base year
	Industrial Structure	stru	The ratio of the value-added of the tertiary industry to the secondary industry
	Urbanization Level	ur	The ratio of urban population to total resident population
	Degree of Openness	exp	The ratio of total imports and exports to GDP
	Labor Force Level	ll	The logarithm of the population aged 15-64
	R&D Intensity	R&D	The ratio of R&D expenditure to GDP

3.2 Sample Selection and Data Sources

This study uses panel data from 30 provinces, autonomous regions, and municipalities in mainland China (2005–2022), excluding Tibet, Hong Kong, Macau, and Taiwan. The data primarily comes from the China Statistical Yearbook and China Energy Statistical Yearbook. Due to data limitations in Shenzhen, Guangdong's carbon trading pilot data is used as a substitute. The research focuses on six carbon emission trading pilot regions: Beijing, Tianjin, Shanghai, Chongqing, Guangdong, and Hubei.

4.Empirical analysis

4.1. Selection of Weights for the Synthetic Control Group

This study constructs a synthetic control group for the pilot provinces of the carbon emissions trading scheme. For example, the synthetic control group for Beijing is constructed by assigning weights to the provinces of Heilongjiang, Shandong, Hainan, Sichuan, and Yunnan. The specific details of other pilot provinces are shown in Table 2.

Table 2. Weight Coefficients for Synthetic Provinces Corresponding to Each Carbon Emission Trading Pilot Province.

Beijing	Synthetic Province	Heilongjiang	Shandong	Hainan	Sichuan	Yunnan
	Weigh	0.826	0.308	-0.018	0.261	0.197
Tianjin	Synthetic Province	Jiangsu	Jiangxi			
	Weigh	0.101	0.529			
Shanghai	Synthetic Province	Jilin	Heilongjiang	Hainan		
	Weigh	0.253	0.678	-0.089		
Hubei	Synthetic Province	Hebei	Shanxi			
	Weigh	0.149	0.011			
Guangdong	Synthetic Province	Jilin	Fujian	Henan	Yunnan	
	Weigh	0.298	0.384	0.057	0.001	
Chongqing	Synthetic Province	Inner Mongolia				
	Weigh	0.879				

4.2. Overall Emission Reduction Effect of the Carbon Emission Trading Policy

This study uses the LASSO-based synthetic control method to evaluate the impact of the carbon emission trading policy on carbon intensity. This method allows for an overall analysis of all pilot regions, enabling the estimation of the average treatment effect of the policy. The results of the synthetic control method are shown in Figure 1, indicating that the overall effect of the carbon emission trading policy is approximately -0.165 and is statistically significant. This finding further supports Hypothesis 1 of the study, which suggests that the carbon emission trading policy significantly reduces carbon intensity in the pilot regions.

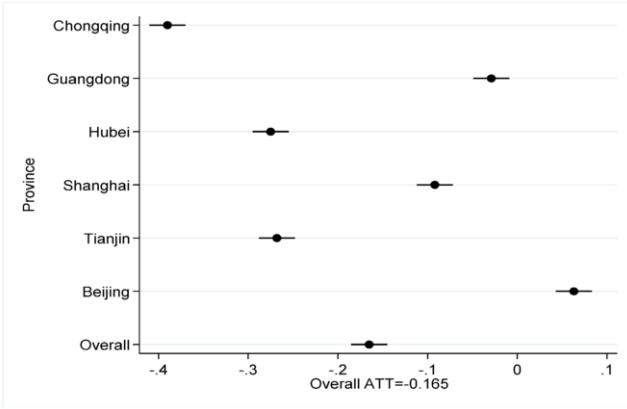


Figure 1. Overall Policy Effect of Pilot Regions Based on LASSO Synthetic Control Method.

4.3. Regional Emission Reduction Effects of the Carbon Emissions Trading Policy

From the results of the synthetic control method, the changes in carbon intensity across the pilot regions vary. Before the policy implementation, the synthetic carbon intensity trajectories of the pilot regions generally aligned well with the actual observed values, indicating that the construction of the synthetic control group was effective. However, the differences in changes after the policy implementation were more pronounced.

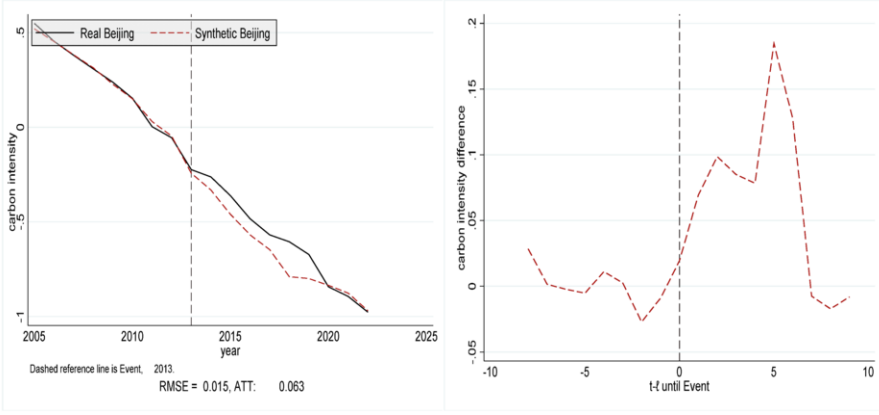


Figure 2. Policy Effects of Beijing Under the LASSO-Based Synthetic Control Method.

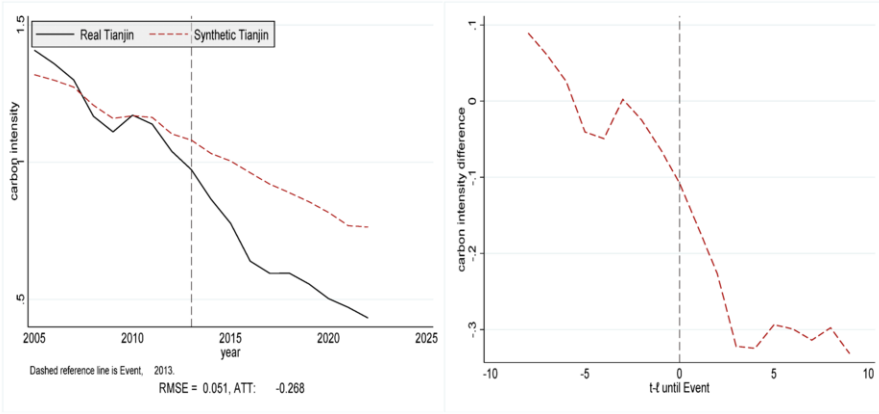


Figure 3. Policy Effects of Tianjin Under the LASSO-Based Synthetic Control Method.

In Beijing, after the policy was implemented, the actual carbon intensity was consistently higher than the synthetic carbon intensity, with smaller fluctuations, suggesting that the carbon emission trading policy had a limited impact on carbon intensity. In Tianjin, the synthetic carbon intensity showed a considerable difference from the actual values, and the gap widened gradually after the policy was implemented, indicating a significant reduction in carbon intensity due to the carbon trading policy. In Shanghai, the synthetic carbon intensity trajectory closely matched the actual carbon intensity, but after the policy was implemented, the difference between them gradually expanded over the years, indicating that the policy effect became more pronounced over time, significantly reducing carbon intensity.

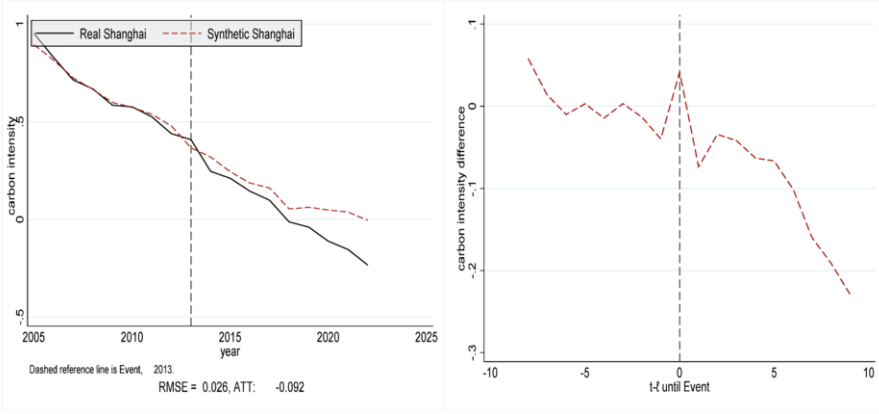


Figure 4. Policy Effects of Shanghai Under the LASSO-Based Synthetic Control Method.

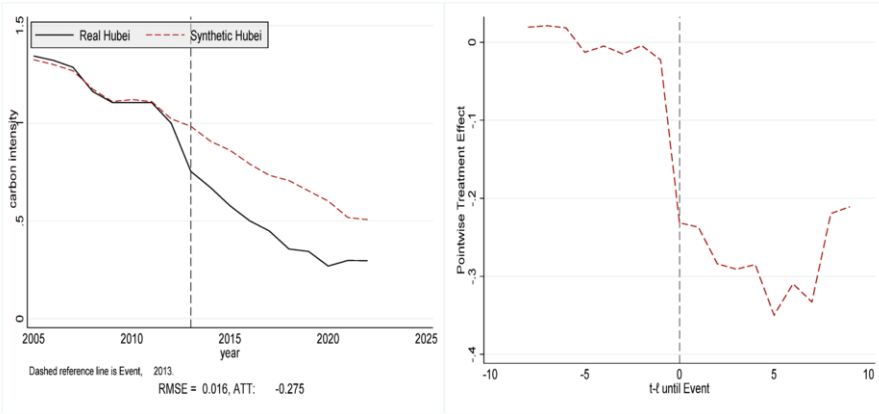


Figure 5. Policy Effects of Hubei Under the LASSO-Based Synthetic Control Method.

In Hubei, the carbon intensity declined more rapidly than the synthetic carbon intensity after 2012, which may be related to the early initiation of the policy. After the policy was implemented, the carbon intensity gap exhibited a "U"-shaped trend, reflecting dynamic changes in policy effects. In Guangdong, the policy effect was more limited, as the carbon intensity was only slightly lower than the synthetic value post-policy, with small fluctuations in the gap, suggesting that the carbon emission trading policy had little impact on the region. In Chongqing, the carbon intensity showed a significant decline before the policy was implemented, and after the policy, the gap between actual and synthetic carbon intensity steadily expanded, indicating that the policy had a sustained effect in reducing carbon intensity in the region.

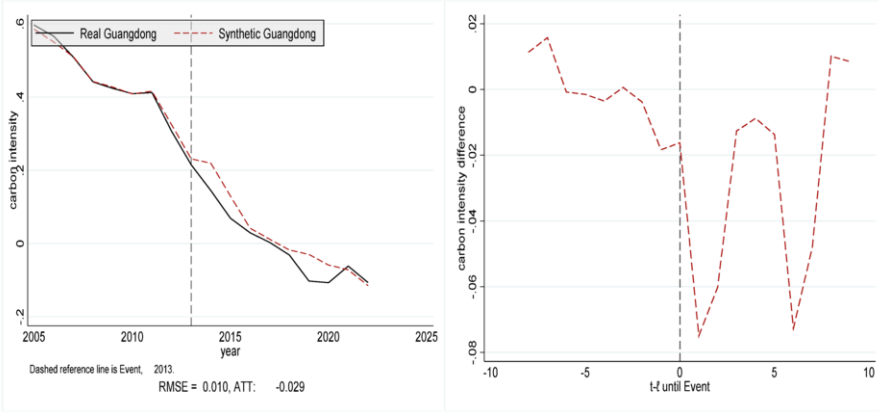


Figure 6. Policy Effects of Guangdong Under the LASSO-Based Synthetic Control Method.

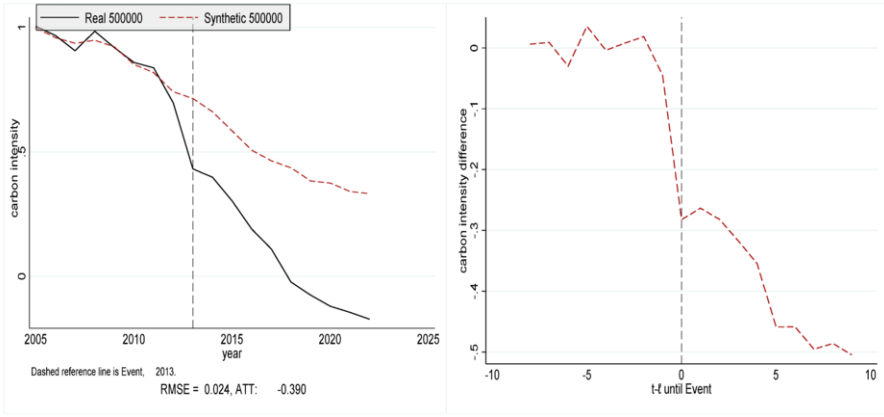


Figure 7. Policy Effects of Chongqing Under the LASSO-Based Synthetic Control Method.

4.4. Heterogeneity Test

This study divides six provinces/municipalities into Service-Innovation Hubs (Beijing, Shanghai, Guangdong) and Industrial Transition Zones (Chongqing, Hubei, Tianjin). The comparison of carbon emission trading policy effects, shown in Figure 8, reveals a significant reduction in carbon intensity in Industrial Transition Zones (-0.311) compared to Service-Innovation Hubs (-0.019).

This disparity is due to the industrial structure, with energy-intensive sectors in Industrial Transition Zones benefiting more from the policy. Service-Innovation Hubs, with lower emissions and fewer incentives, experience weaker effects. Future policies should focus on stricter carbon caps and technological upgrades in industrial zones, while service sectors should implement carbon footprint standards and voluntary emission reduction markets.

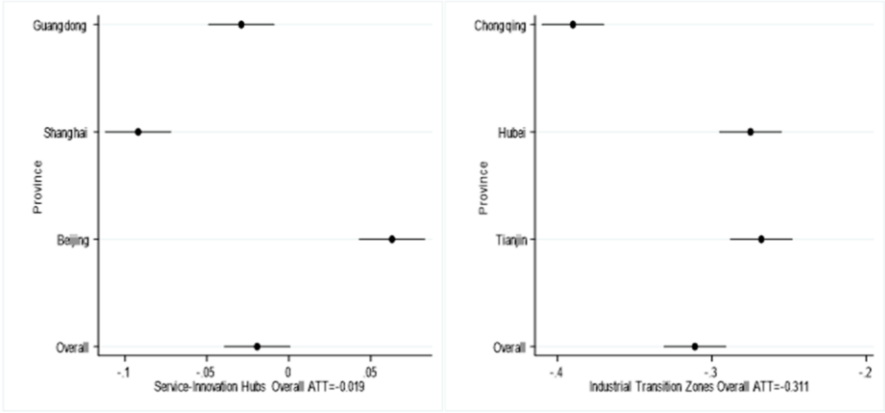


Figure 8. Policy Effects in Different Regions Based on LASSO Synthetic Control Method.

5. Conclusion and Recommendations

The main conclusions of this study are as follows:(1) The ETS policy has significantly driven the reduction of carbon intensity in the pilot regions. The counterfactual simulations based on the LASSO synthetic control method show that, after the policy implementation, the overall policy effect on carbon intensity in the pilot regions is -0.165. (2) The policy effects exhibit a gradient of regional differences. Specifically, the ranking of policy effect strength across the pilot regions is as follows: Chongqing > Hubei > Tianjin > Shanghai > Guangdong > Beijing.

Based on these research findings, the following policy recommendations are made:(1) Optimize the design of the carbon emission trading mechanism and enhance policy flexibility. Given the regional heterogeneity of the policy effects, it is recommended to further improve the design of the carbon emission trading mechanism to enhance the policy's flexibility. (2) Strengthen regional cooperation and accelerate the development of a unified national carbon market. By establishing a unified market system, resources can be optimized nationwide, reducing carbon emission costs, and promoting more regions to achieve low-carbon transformation. Ultimately, this will help achieve the national goals of carbon peaking and carbon neutrality.

Limitations of this study: The impact of the COVID-19 pandemic on the research results has not been considered separately, and the spatial spillover effects among provinces have not been accounted for.

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A Study on the Impact of Industrial Robotics Applications on Green Exports

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Abstract. In the tide of increasingly severe trade barriers around the world, companies are forced to use industrial robots to improve their goods, services and production processes to raise the green standards and technological thresholds, with far-reaching impacts on their production and exports. This study focuses on how the application of industrial robots affects firms' green exports. This study employs data in 2010–2016 from Shanghai/Shenzhen A-share listed firms and conducts empirical analysis using stepwise regression. It is found that the application of industrial robots has a significant positive impact on the green export of enterprises. It helps enterprises respond more effectively to changes and challenges in the international market, enabling them to expand their export products to a wider geographical range.

Keywords. Industrial robot applications, green export, listed company

1. Introduction

Global climate change and environmental pressures have propelled green development as a cornerstone of trade policies. Green trade addresses ecological damage from traditional growth models by setting environmental standards for goods, services, and production processes, aiming to balance economic growth with sustainability. Unlike conventional exports, green exports prioritize resource efficiency, pollution control, and eco-friendly manufacturing [1]. However, enhancing green export competitiveness involves challenges in productivity, costs, and international regulations.

Industrial robots are increasingly vital in advancing green transitions by improving efficiency, optimizing energy use, and enabling green innovation. China exemplifies this trend, dominating the global industrial robot market since 2013, with 52.3% of worldwide installations in 2022. Studies indicate robots help firms adapt to environmental regulations and trade barriers through technological upgrades [2], yet systematic analysis of their link to green trade remains limited.

Using 2010-2016 data from Chinese listed firms, this study investigates how industrial robot adoption affects green export volumes through the lens of absolute advantage theory.

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2. Theoretical analysis and research hypothesis

2.1. The Impact of Industrial Robot Adoption on Green Exports

Green export as a concrete embodiment of green manufacturing capabilities in the international market, in this process, the level of technology and equipment as the infrastructure of green manufacturing, determines whether the enterprise can stably and efficiently output products in line with international green standards. As a prerequisite for any advanced technology to be realized and applied in actual production, industrial robots are indispensable [3]. As the core equipment in the intelligent manufacturing system, industrial robots are highly automated, precise, and programmable, which can effectively control resource consumption and pollution emissions while improving production efficiency, providing strong support for green exports at the manufacturing end [4] [5].

First, industrial robots have obvious advantages in improving the quality of green manufacturing. Its high-precision operating system and stable operation capability enable products to maintain a high degree of consistency during mass production, which lowers failure and rework rates while minimizing resource waste [6]. This product stability is especially important for green products, because green product certification often requires products to maintain consistent environmental performance indicators over multiple batches, thus enhancing the competitiveness of enterprises in the green export market [7]. Second, industrial robots help reduce the proportion of high-pollution, high-energy-consumption processes in the production process and control emissions at the source [8]. Taking smelting, painting, welding and other typical high-pollution processes as an example, robots can efficiently complete tasks in a closed environment, reducing the risk of leakage of harmful gases and wastes. This cleaner manufacturing capability not only meets the environmental compliance requirements for green export products, but also helps companies meet the regulatory standards of developed countries regarding the environmental impact of product life cycles [9].

In addition, the advantages of industrial robots in data collection and feedback capabilities provide basic support for enterprises to carry out green management and compliance monitoring. Through integration with energy management systems and environmental monitoring systems, industrial robots can record carbon emissions, energy consumption data and raw material usage in real time [10], a capability that is particularly suitable for green trade rules in export destination countries that require high traceability and transparency of the production process, helping to improve the institutional adaptability and reputation of enterprises in international green trade [11]. In the context of the continuous strengthening of international green trade barriers, the green attributes of products have become the key threshold for enterprises to enter the markets of developed countries. The ability to export green products in a stable, efficient and compliant manner determines the survival and expansion space of enterprises in the export market. Based on this, this paper proposes the following research hypothesis H1:

H1: The use of industrial robots has boosted the green export volume of companies.

3. Research design

3.1. Data sources and sample selection

The dataset includes three categories: (1) A listed companies: Financial data of listed companies are from WIND and CSMAR. (2) Customs Transaction Records: China Customs Data (CCD) provided product-level export flows, with commodities aggregated from 8-digit HS codes to 6-digit tiers to align with green product taxonomies. (3) The data of industrial robots come from IFR website. Data processing: (1) Exclusion of entities with critical variable omissions. (2) Removal of special treatment firms (ST/*ST/PT status). (3) Elimination of recently listed firms (<1-year track record). (4) All main variables were winsorized at the 1% level. The processed data of listed companies are then matched to the CCD sum and to the robot data of IFR. After these treatments, we obtain 27,551 firm-product-destination-year observations for 242 firms.

3.2. Measurement of variables

3.2.1 Explanatory variable: Green Products Export (lnGexport).

No universally accepted definition or standardized list of green products currently exists. Referring to Brandi et al. [12], we adopt their green product taxonomy to identify relevant HS-coded items in the China Customs database, subsequently computing the logarithmic annual green export value per firm.

3.2.2 Industrial robot penetration (ROBOT).

In this paper, with reference to Acemoglu and Pascual [13], the study of robot penetration in the U.S. commuting area is constructed, and the Bartik instrumental variable construction method is applied to estimate the level of industrial robot application of each enterprise based on the robot penetration rate at the industry level and the share of labor employment of each enterprise in the industry in which it is located, and to construct the penetration rate of industrial robots at the enterprise level and take the logarithmic processing, and the specific calculation method is as follows. The specific calculation methods are as follows:

$$\mathrm{Robot}_{ijt} = \frac{\mathrm{manu}_{ijt=2010}}{\mathrm{Mmanu}_{t=2010}} * \frac{\mathrm{rob\ stock}_{jt}}{\mathrm{Labor}_{jt=2010}}$$

3.2.3 Control variables.

We include a comprehensive set of control variables at both the country and firm level. At the country level, we adopt a set of variables derived from the extended trade gravity framework. The economic scale of the importing country (lMS) is represented by its GDP. Bilateral geographic distance (lGD), calculated as the distance between the capitals of the two countries. Additionally, border adjacency (SB) and common language (SL) are included.

At firm level, Firm age (Age) is computed as the enterprise age. Company size (Siz) is measured by the logarithm of total assets. Capital structure (Lev) is proxied by the ratio of total assets to liabilities, and profitability (ROA) is measured by dividing the company's annual profit by its total asset value. Additional firm-specific controls include the logarithm of government subsidies received (GoS) and top management compensation (Tp3), measured as the log of total salary for the top three executives.

3.3. Modeling

Referring to the gravity model of trade, we construct a model on the export of industrial robots and green products.

$$lnGexport_{idpt} = a_0 + a_1 Robot_{it} + \beta X + \gamma_i + \theta_p + \rho_t + \mu_{idpt}$$

The subscripts i and t in the model represent the company and year, respectively. d is the export destination, and p represents products with specific HS codes. The dependent variable $lnGexport_{idpt}$ represents the logarithm of the export value of p products from company i to d in year t. The value of $Robot_{it}$ represents the penetration of industrial robots by a particular firm. X is the model company level control variable. μ_{idpt} is an error term. a_1 is the benefit coefficient, which means that the popularity of industrial robots has a significant impact on the export of green products. The penetration of robots into the export of green products.

4. Empirical analysis

4.1. Descriptive analysis

Table 1. Descriptive analysis

VarName	Obs	Mean	SD	Min	Median	Max.
lnGexport	27,551	9.103	3.017	0.693	9.060	19.781
ROBOT	27,551	2.091	3.540	0.017	0.874	21.302
lMS	27,551	13.514	1.548	9.204	13.515	16.755
lGD	27,551	8.747	0.641	6.862	8.863	9.861
SB	27,551	0.070	0.255	0	0	1
SL	27,551	0.164	0.370	0	0	1
Age	27,551	2.602	0.445	1.099	2.708	3.466
Siz	27,551	8.159	1.142	6.080	8.122	11.179
Lev	27,551	3.556	2.472	1.309	2.751	19.057
ROA	27,551	0.069	0.047	-0.067	0.065	0.212
GoS	27,551	16.570	1.404	13.115	16.356	20.408
TP3	27,551	14.364	0.709	12.676	14.292	16.426

4.2. Main effects tests

Table 2 reports the regression results of Robot on green product exports. After controlling for firm fixed effects, product fixed effects, and year fixed effects, the coefficient of Robot is positive, indicating that Robot has a positive impact on firms'

green product exports. In the process of gradually adding control variables, there is no significant change in the significance of the main effects, all of which are significant at the 1% level. This indicates that the application of industrial robots helps to improve the export of green products of enterprises.

Table 2. Main effects tests

VARIABLES	(1)	(2)	(3)
ROBOT	0.0287***	0.0273***	0.0279***
	(0.0101)	(0.0099)	(0.0102)
Control variable	No	Yes	Yes
_cons	9.0467***	5.2538***	2.8908**
	(0.0251)	(0.2760)	(1.1412)
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Product FE	Yes	Yes	Yes
R-squared	0.4461	0.4645	0.4669
N	27491	27491	27073

Note: *, **, * indicate p < 0.10, p < 0.05, p < 0.01, respectively**

4.3. Robustness tests

To further test the robustness of the findings, this paper also conducts PPML method and lag analysis on the explanatory variables. The regression results are shown in Table 3. The sign and significance of the regression coefficients of ROBOT and green product exports are basically the same as those in Table 2, indicating that mutual causality is less disturbing to the research results.

Table 3. The robustness tests

	(1) PPML	(2) F.lnGexport
ROBOT	0.0027**	0.4108***
	(0.0101)	(0.0099)
Control variable	Yes	Yes
cons	1.5770***	34.8340***
	(0.1346)	(1.5841)
Firm FE	Yes	Yes
Year FE	Yes	Yes
Product FE	Yes	Yes
R-squared		0.4960
N	27073	18643

Note: *, **, * indicate p < 0.10, p < 0.05, p < 0.01, respectively**

5. Conclusion and exploration

This study demonstrates that the use of industrial robots facilitates the export of green products. The integration of industrial robots into the manufacturing process is a transformative force driving green export capabilities. By harmonizing technical precision with environmental sustainability, robots address the fundamental challenges of achieving consistent product quality, reducing pollution-intensive practices, and complying with evolving international green standards. The role of robots goes beyond automation, enabling real-time environmental data tracking and adaptive production systems that ensure transparency and traceability, key factors in meeting stringent global trade regulations. In addition, the flexibility of robotic systems allows companies to

effectively meet the demand for customized green products in niche markets, thereby reducing compliance costs and increasing competitiveness. As countries increasingly prioritize sustainable development in their trade policies, the adoption of industrial robotics not only meets ecological goals but also unlocks economic opportunities by combining green manufacturing capabilities with market access requirements.

To bridge the gap between these findings and their practical application, firms should prioritize integrating industrial robots with advanced data analytics and IoT-enabled systems to strengthen environmental compliance. For instance, embedding sensors in robotic systems can monitor real-time energy consumption, emissions, and material efficiency, enabling dynamic adjustments to align with diverse international green standards (e.g., EU's Carbon Border Adjustment Mechanism). Cloud-based platforms could further centralize this data, facilitating cross-border collaboration with suppliers and regulators to ensure end-to-end green certification.

Governments and industry consortia should co-develop incentives, such as subsidies for retrofitting legacy factories with green robotics or tax breaks for exporters meeting verified sustainability metrics. These measures would mirror digital transformation policies that reward R&D internationalization, creating a supportive ecosystem for green technological upgrading.

Our study provides new evidence on the relationship between the adoption of industrial robots and green exporting and offers guidance on the practice of green exporting. These findings have significant theoretical and practical value for understanding how industrial robotics adoption affects firms' green exports and global competitiveness and provide a clear path for firms to enhance their global market presence through industrial robotics adoption.

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Regional and Temporal Disparities in Rural Industry Integration Driven by Land Transfer: Empirical Study Based on a Fixed Effects Model

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Abstract. Land transfer is of great significance for promoting rural industries' integration. Using panel data from 30 Chinese provinces (2010–2024), this paper applies a fixed-effects model to analyze land transfer's impact on rural industry integration. Results confirm that land transfer significantly promotes integration, with its effect strongest in central regions, followed by eastern regions, and weakest in western regions. The effect also varies over time. Land transfer mainly drives integration by attracting talent, technology, and funds to rural areas. Additionally, the paper proposes policy recommendations, such as promoting land transfer, fostering rural industry circular development, adopting region-specific policies, etc.

Keywords. Land Transfer, Rural Industry Integration, Regional Heterogeneity, Temporal Differences, Fixed Effects Model

1. Introduction

Promoting integration of three rural industries is an important way to deepen reform of agricultural supply-side structure, to utilize and expand Multifunctional agriculture, to broaden channels for farmers' income increase. It is also a new driving force for accelerating construction of a high-quality and efficient modern agricultural industrial system with market competitiveness. Moreover, it serves as economic foundation for comprehensive revitalization of countryside. Land is the essence of agriculture and root of farmers. Land transfer helps optimize allocation of land resources and promote dissemination of agricultural technologies, enhancing efficiency of agriculture and

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increasing farmers' income. Moderate concentration of land resources facilitates cooperation among new agricultural business entities and improves agricultural scaled operation, making farmers true beneficiaries of modern agricultural development. As a crucial part of land system reform, proper advancement of land transfer is vital for optimizing land resource allocation and boosting agricultural productivity.

Many scholars have studied land transfer and three rural industries integration Concept of "integration of three rural industries" originated from the "sixth industry" proposed by Naramichi Konamura in 1994, which integrates primary, secondary, and tertiary industries [1]. Rural industry integration has become a research focus in recent years. Scholars believe it can accelerate factor flow, attract industrial clusters, expand farmers' income channels, revitalize the rural economy, and achieve rural industrial prosperity. It can also optimize the industrial chain layout, retain young and middle-aged labor force through industries and benefits, and address rural aging and hollowing-out issues [2][3]. In China, there are four practice models for rural industries integration: driven by agricultural leading enterprises, industrial and commercial capital, vertically integrated operations, and internet + agricultural e-commerce platforms [4-5]. From perspective of agricultural business entities, there are three practice models for rural integrated industries: extending industrial chain, expanding new agriculture functions, promoting and applying advanced technologies [6-7]. The level of rural industry integration in China is continuously improving, with rapid progress in eastern and western regions [8-9]. However, some scholars argue that the current rural industry integration faces constraints due to the lack of smooth flow of factors such as land, capital, talent, and technology. In particular, the lack of smooth land transfer can restrict intensive agricultural operations and the development of characteristic agricultural industries [10-11]. Land is the most basic production factor for agricultural development and concentrated and contiguous land is essential for scaled agricultural operations. Promoting rural land transfer is a prerequisite for the integrated development of rural industries [12-13]. Land transfer promotes the flow of production factors such as labor, capital, technology, and information to agriculture and optimizes their allocation. Some scholars have examined the effect of land transfer on rural industry integration from the perspective of land certification [14-15]. Activating land management rights is key to innovating agricultural management methods and realizing the expansion of agricultural economies of scale. It also gives birth to new types of agricultural management systems such as family farms, "company + farmers" and land share cooperatives to promote rural industry integration [16-17]. Some scholars argue that China's agricultural land fragmentation is not conducive to scaled agricultural operations [18-19]. Achieving moderate-scale land operations through land transfer while safeguarding farmers' rights and interests is necessary to lay the foundation for scaled agricultural operations and promote rural industry integration. Land transfer can free up labor from primary industry and invest it into agricultural product processing and service industries, generating endogenous driving forces for rural industry integration [20]. Large-scale concentration of land factors can attract social capital to invest in agricultural product processing and storage links, extending the agricultural industry chain and forming a complete industrial chain.

Numerous scholars have deeply explored relationship between land transfer and rural industries' integration, focusing on internal logic. However, most research is qualitative, with little empirical analysis on underlying mechanism of land transfer's impact on integration. There is also insufficient research on regional and stage differences in this impact, lacking targeted analysis and policy recommendations. To

address these gaps, this paper uses panel data from 30 Chinese provinces (2010–2024) and applies a fixed-effects model to empirically analyze land transfer's influence on rural industry integration. It constructs an evaluation system to measure integration levels, exploring the relationship between land transfer and integration while delving into underlying mechanisms and regional and stage differences.

This research contributes theoretically by revealing the mechanisms of land transfer's impact on rural industry integration, offering new perspectives and empirical evidence. The findings are significant for guiding land transfer policies and rural industry integration practices, providing valuable references for advancing the rural revitalization strategy.

2. Land Transfer and Rural Three Industries Integration: Theoretical Analysis

2.1 Land Transfer

Land transfer, a crucial part of land system reform, has garnered significant attention in recent years. Scholars have explored it in various aspects. On one hand, they have focused on land transfer models and influencing factors. Zhu Shie; Yang Ruda (2024) et al. noted that land transfer models are diverse, including sub-contracting, leasing, exchange, assignment, and equity participation [21]. These models differ in their impact on land use efficiency and agricultural productivity. Zhang Hongyu (2025) et al. highlighted that land transfer is influenced by land institutions, topography, economic development level, and farmer characteristics [22]. On the other hand, impact of land transfer on agricultural productivity and farmers' income has been thoroughly examined. Luo Biliang (2016) et al. discovered that land transfer can broaden income channels for farmers and increase their income [23]. Liu Shouying (2024) et al. found that land transfer can optimize land resource allocation and achieve moderate-scale land operation, thereby improving agricultural productivity [24].

2.2 Rural Three Industries Integration

Naruhito Imamura of Japan first proposed the concept of three industries integration in 1994. He believed it was a new development model where the primary industry serves as the foundation, and the primary, secondary, and tertiary industries are integrated with one another [1]. Essence of rural industries integration lies in formation of new agricultural industries, forms, and models through integration and recombination of various sectors within agriculture and between agriculture and rural secondary and tertiary industries.

2.3 Influence Mechanism of Land Transfer on Rural Three Industries Integration

Theoretically, land transfer can optimize land resource allocation and enable scaled operation, providing a material basis for integration. By consolidating scattered land, land transfer can achieve moderate-scale operation, improve agricultural productivity, reduce costs, enhance product quality and yield, and supply more raw materials and factors to the rural secondary and tertiary industries. This supports industrial structure optimization and upgrading. Land transfer also facilitates rural industrial structure

adjustment, laying foundation for agricultural industrialized operation. It extends agricultural chain by developing agricultural product processing and rural service industries, increasing product value-added and farmers' income. Additionally, land transfer transfers land contract and management rights to new agricultural business entities, which can develop specialty, eco-friendly, and leisure agriculture, expanding the multiple functions of agriculture. Land transfer promotes rural industrial integration, achieving coordinated development of the three rural industries. It attracts talent, technology, and capital to rural areas, boosting the development of new industries like rural e-commerce and leisure agriculture, and injecting new vitality into integration of three rural industries.

3. Materials and Method

3.1 Variable Description

3.1.1 Dependent Variable

Dependent variable is integration of three rural industries. Based on relevant studies [5,9,10], this paper evaluates industrial integration through four dimensions: industrial extension, intersection, penetration, and circulation, as shown in Table 1.

Table 1 Evaluation System of Rural Three Rural Industries Integration Level

Target Layer	Subsystem	Indicator Layer	Measurement Method
Three Rural Industries Integration	Industrial Extension |	Agricultural Product Processing Industry Scale	Main Business Revenue of Agricultural Product Processing/Total Primary Industry Output
		Farmers' Professional Cooperatives |Scale	Farmers' Cooperatives Number/ Primary Industry Labor Force Scale
	Industrial Intersection	Facility Agriculture Development	Facility Agriculture Total Area / Crops Total Sowing Area
		Development of Agricultural, Forestry, Animal Husbandry and Fishery Service Industry	Output Value of Agricultural, Forestry, Animal Husbandry and Fishery Service Industry / Total Output Value of Primary Industry
	Industrial Penetration	Agricultural Mechanization Development	Total Power of Agricultural Machinery / Total Sowing Area of Crops
		Rural Internet Development	Rural Internet Broadband Access Households Number/Administrative Villages Total Number
	Industrial Cycle	Industrial Cycle Utilization of Renewable Resources in Agriculture	Total Gas Production of Biogas Pools / Total Number of Administrative Villages
		Use of Agricultural Films	Use of Agricultural Films / Total Sowing Area of Crops

(1) Industrial Extension: Concept and Indicator Selection

Industrial extension, this paper focuses on industrial chain extension, which centers on agriculture. It aims to blur industrial boundaries and create a comprehensive and smooth industrial chain by rationalizing and connecting the industrial chain. This paper

uses scale of agricultural product processing and scale of farmers' cooperatives to measure industrial extension.

(2) Industrial intersection: Concept and Indicator Selection

Industrial intersection emphasizes market-oriented, cross-integrated development. It leverages agriculture's versatility to integrate production, sightseeing, culture, and education. Facility agriculture uses artificial technologies to create suitable growth conditions for plants and animals. It promotes moderate-scale agricultural production and taps the potential of regional specialty and leisure agriculture, driving the primary industry with the three-industry integration. Agricultural and forestry animal husbandry and fishery services provide production factors and technical support for agricultural development. This paper selects facility agricultural development and agricultural and forestry animal husbandry and fishery service development to measure industrial intersection.

(3) Industrial penetration: Concept and Indicator Selection

Industry penetration, via modern high-tech in agriculture, blurs industry boundaries. Agricultural mechanization shifts farming from extensive to moderate-scale operations, boosts productivity, and catalyzes industry integration. Internet technology is key for smart agriculture and rural e-commerce. It helps farmers access technology, information, and funds, unlocks agricultural potential, taps market demand for agricultural products, and creates new rural operation models, thus driving industry integration. Consequently, this paper uses agricultural mechanization and rural internet development to gauge industry penetration.

(4) Industrial Circulation: Concept and Indicator Selection

Industrial circulation, based on circular economy concept, aims to establish a circular industrial chain through agricultural technology transfer. This improves resource utilization efficiency and promotes sustainable agricultural development. The paper selects the utilization of agricultural renewable resources and usage of agricultural plastic films to measure industrial cycles.

3.1.2 Independent Variable

The core explanatory variable is land transfer rate. Land transfer rate, to a certain extent, reflects the level of land transfer in a region. Calculation formula is as follows:

$ROLT_{ij} = Y_{ij} X_{ij}$

where: $ROLT_{ij}$ represents the land transfer rate for the *i-th* province in year j; Y_{ij} represents the total area of family-contracted arable land transferred in the *i-th* province in year j; X_{ij} represents the total area of family-contracted arable land under management in the *i-th* province in year j.

3.1.3 Control Variables

Referring to literature [15,16,18,19], this paper incorporates several control variables, including rural human capital (lab), degree of urbanization (urb), fiscal support for agriculture (fin), agricultural loans(loa), economic growth (eco), and farmers' income (inc).

First, rural human capital (lab). Talent is primary resource; human capital is a core element for development of rural and agricultural economies. The paper measures rural human capital by proportion of rural population with a college degree or higher

education level in primary industry labor force. It is worth noting that the variable of rural human capital takes negative values due to logarithmic transformation applied to proportions lower than 1. This reflects the relatively low proportion of rural populations with higher education, which is common in less-developed regions. The negative values do not affect the interpretation of regression results, as the variable captures relative differences across regions and time. Second, degree of urbanization (urb). Level of urbanization reflects economic development level of a region. Promoting urbanization can encourage the out-migration of surplus rural labor, thereby facilitating land transfer. Meanwhile, scale of land transfer will inevitably have an impact on the process and level of urbanization. This paper measures degrees of urbanization by ratio of urban population to total population. Third, fiscal support for agriculture (fin). Presence of well-developed infrastructure in rural areas is a prerequisite for building a modern agricultural management system, developing moderate-scale operations, and promoting the integrated development of the three rural industries. A significant portion of the funds for improving rural infrastructure comes from government fiscal expenditure. This paper measures fiscal support for agriculture by the ratio of expenditure on agriculture, forestry, and water affairs to general public budget expenditure. Fourth, agricultural-related loans (loa). Integrated development of three rural industries requires more external credit investment. Fifth, economic growth (eco). Economic growth increases consumers' demand for agricultural products, which in turn helps promote integrated development of three rural industries. This paper measures economic growth level by regional gross product. Sixth, farmers' income (inc). Integrated development of three rural industries leads to an increase in farmers' income. This paper measures situation of farmers' income by their operational income.

3.2. Data Description

3.2.1 Study Area

This study uses panel data from 30 provinces across China (2010-2024). Tibet, with significant missing variables, is excluded. Province is divided into three regions based on development level: East (Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, Liaoning, Jilin, Heilongjiang)[①], Central (Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan), and West (Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang).

3.2.2 Data Source

Data on the indicators in Table 2 are from “National Rural Economic Statistics”, “China Rural Operation and Management Statistical Yearbook”, “China Farmers' Cooperatives Development Report”, “China Rural Statistical Yearbook”, “China Agricultural Product Processing Industry Statistical Yearbook”, etc. Some missing data are filled using linear and nearest-neighbor imputation. Descriptive statistics of main variables are shown in Table 2.

[①]Due to the limited number of samples in Northeast China, the three provinces in Northeast China are included in the eastern region for the purpose of the study.

Table 2 Descriptive Statistics of Variables

Variable	Sample Size	Mean	Standard Deviation	Maximum	Minimum
Rural Industry Integration	450	0.4065	0.2190	0.9993	0.0662
Land Transfer	450	22.8371	17.5455	87.3400	1.3551
Rural Human Capital	450	-10.1313	1.0512	-7.1765	-13.8515
Urbanization	450	3.9593	0.2491	4.4954	3.2910
Agricultural Fiscal Support	450	5.4423	1.1400	7.1785	1.7576
Agricultural Loans	450	7.7921	1.5638	10.5536	2.3006
Economic Growth	450	9.4269	0.9927	11.5868	6.2977
Farmers' Income	450	8.0490	0.5008	9.0197	6.3796

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

3.3 Method

3.3.1 Entropy Method

Entropy method is utilized to construct an evaluation system for rural industries integration level [13][16]. This paper builds an evaluation system to comprehensively measure degree of rural integration. During calculation, raw data is standardized to eliminate impact of different dimensions. Subsequently, entropy values and weights of each indicator are calculated to derive a comprehensive index of rural industries integration for each region. Entropy method was used to conduct a comprehensive evaluation level of rural primary integration, secondary, and tertiary industries, calculating integration index for each province. Steps are as follows:

①Set up *i* regions and *j* evaluation indicators to establish a raw data matrix.

Where A_{ij} denotes raw value of *j-th* indicator for the *i-th* province.

② Eliminate impact of different dimensions on measurement results, raw data were standardized through positive and negative transformations.

$$A_{ij}=\frac{A_{ij}-A_{\min}}{A_{\max}-A_{\min}} \quad \text{(Positive Indicator)} \qquad A'ij=\frac{A_{\max}-A_{ij}}{A_{\max}-A_{\min}} \quad \text{(Negative Indicator)}$$

③Calculate the proportion of the *i-th* province (region, municipality) in the *j-th* indicator. Formula is:

$$Q_{ij}=\frac{A_{ij}}{\sum_{i=1}^{n}A_{ij}} \qquad i=1,2,\cdots,n$$

④Calculate the entropy of the *j-th* indicator using the formula:

$$E_j=-K\sum_{i=1}^{n}Q_{ij}\ln(Q_{ij}) \qquad K=\frac{1}{\ln(n)}>0,\quad E_j\geq 0$$

where *k* is a constant.

⑤Calculate the information redundancy using formula: $D_j=1-E_j$

⑥Calculate the weight of each indicator with formulas:

$$W_j=\frac{D_j}{\sum_{j=1}^{m}D_j} \qquad j=1,2,\cdots,m$$

⑦Compute the comprehensive score of rural three-industry integration index for each province with the formula:

$$S_j = \sum_{j=1}^{m} W_j Q_j$$

3.3.2 Fixed - Effects Model

As fixed-effects model can effectively control for unobservable regional and time - varying heterogeneity, enhancing estimation accuracy, this paper employs it as the benchmark regression model [18][19]. Random-effects model and pooled OLS model are also constructed for comparative analysis. To ensure regression results are robust and free from significant discrepancies, stepwise regression is applied. This approach helps avoid omitted-variable bias and endogeneity issues in benchmark estimates. The fixed-effects model is as follows:

$$fusing_{i,t} = \beta_0 + \beta_1 rolt_{i,t} + \beta_2 \ln lab_{i,t} + \beta_3 \ln urb_{i,t} + \beta_4 \ln fin_{i,t} + \beta_5 \ln loa_{i,t} + \beta_6 \ln eco_{i,t} + \beta_7 \ln inc_{i,t} + \mu_{i,t}$$

where *fusing* represents rural industry integration development index, *i* denotes province, and *t* denotes year. β_0 is constant term, β_1 is regression coefficient of land transfer rate, β_2-β_7 are regression coefficients of control variables. μ is random term.

4. Empirical Analysis Results

4.1 Overall Sample Regression

As indicated in Table 3, in regression results of overall sample based on fixed - effects, random - effects, and pooled OLS models, the parameter estimates of land transfer's impact on rural industries integration have passed the 1% significance test and are positive. This confirms land transfer's positive effect on integration. From the benchmark model regression results, a 1% increase in land transfer scale raises the level of rural industries integration by 0.0066 under given conditions.

In terms of control variables, the parameter estimates of human capital, economic growth, and farmers' income are positive and significant at the 1% level. This indicates that improving rural human capital, boosting economic growth, and increasing farmers' income all have a significant positive impact on integration of rural industries.

Table 3 Overall Sample Test Results of Land Transfer on Rural Industry Integration

Variable	FE							RE	POLS
Land Transfer	0.0140***	0.0108***	0.0088***	0.0101***	0.0096***	0.0080***	0.0066***	0.0072***	0.0065***
Rural Human Capital		0.1038***	0.0479***	0.0699***	0.0606***	0.0363**	0.0404***	0.0050	-0.0036
Urbanization			0.5461***	0.7726***	0.7535***	0.3682***	0.0398	-0.0585	-0.0173
Agricultural Fiscal Support				-0.0555***	-0.0793***	-0.1394***	-0.1417***	-0.0019	0.0254*
Agricultural Loans					0.0291***	0.0122	0.0059	0.0183*	0.0201*
Economic Growth						0.2937***	0.1517***	-0.0259*	-0.0416***
Farmers' Income							0.3862***	0.2203***	0.1663***
Constant	0.0862***	1.2118***	-1.4712***	-1.8723***	-1.9776***	-2.9724***	-3.3053***	-1.1373***	-0.9510***
R2	0.7085	0.7404	0.7657	0.7798	0.7838	0.8041	0.8488	0.7873	0.6572
Sample Size	450	450	450	450	450	450	450	450	450

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.2 Regional Sample Regression

This paper delves into the regional differences in the effect of land transfer on rural industry integration through empirical tests on data from China's eastern, central, and western regions. The results, presented in Table 4, reveal that land transfer has a significantly positive effect on industry integration in the eastern and central regions, with parameter estimates significant at the 1% level. However, this effect isn't statistically significant in the western region.

In eastern region, a 1% increase in land transfer scale results in a 0.0047 increase in industrial integration level, showing a relatively modest impact. In the central region, the same 1% increase leads to a 0.0059 rise in integration, attributed to rapid land transfer and expanded agricultural scale. Conversely, the western region doesn't exhibit a significant driving effect from land transfer, possibly due to underdevelopment, lagging urbanization, low land transfer prices, complex terrain, and underdeveloped infrastructure.

Control variables also show regional differences. In the east, rural human capital, fiscal support, and farmers' income are key drivers of integration. In central region, human capital and urbanization play positive roles, while in the west, increasing farmers' income is the primary factor promoting integration. These findings highlight the significant regional disparities in the impact of land transfer on rural industry integration.

The effect of agricultural loans on rural industry integration varies across regions and periods. In some regions or timeframes, the coefficient turns negative, possibly due to inefficient loan allocation or inadequate use of funds. These variations are reflected in inconsistent signs of variables in regression tables, but they do not indicate measurement errors.

Table 4 Regional Sample Test Results of Land Transfer on Rural Industry Integration

Variable	Eastern Region	Central Region	Western Region
Land Transfer	0.0047***	0.0059**	0.0019
Rural Human Capital	0.0779***	0.0706***	-0.0752***
Urbanization	-0.0773	1.1355***	0.4776***
Agricultural Fiscal Support	-0.0962***	-0.1777***	-0.1629***
Agricultural Loans	0.0093	-0.0539	0.0157
Economic Growth	0.1571***	0.1431	-0.0163
Farmers' Income	0.3305***	0.2877	0.7153***
Constant	-2.4184***	-5.6287***	-7.0444***
R2	0.8562	0.8922	0.9100
Sample Size	195	90	165

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.3 Stage-wise Sample Regression

This paper conducts empirical tests on the impact of land transfer on rural industry integration across three research phases. According to Table 5, the parameter estimates for land transfer's impact on industry integration are all positive and pass significance tests at various levels. Specifically, the estimates rose from 0.0014 (2010–2015) to 0.0043 (2016–2019), then fell to 0.0035 (2020–2024), showing temporal heterogeneity.

In 2010–2015, a 1% increase in land transfer scale led to a 0.0014 rise in industrial integration, with low significance, likely due to integration mainly relying on internal agricultural structural optimization. In 2016–2019, a 1% increase in land transfer scale resulted in a 0.0043 increase in integration, attributed to land transfer facilitating the flow of funds, technology, talent, and market information among rural industries. From 2020 to 2024, a 1% increase in land transfer scale caused a 0.0035 rise in integration, with a decline in significance, possibly due to the "crowding-in" effect and reduced scale-based benefits of land transfer in some regions.

Regarding control variables, increasing agricultural loans significantly boosted integration between 2010 and 2015. However, during 2016–2019 and 2020–2024, both increasing agricultural loans and promoting farmers' income growth were more effective in driving integration.

Table 5 Stage-wise Sample Test Results of Land Transfer on Rural Industry Integration

Variable	2010-2015	2016-2019	2020-2024
Land Transfer	0.0014*	0.0043***	0.0035**
Rural Human Capital	0.0130	-0.0044	0.0140
Urbanization	-0.2601	-0.1246	0.9844**
Agricultural Fiscal Support	-0.0302**	-0.1907***	0.0226
Agricultural Loans	0.0253***	0.3088***	0.1525**
Economic Growth	-0.0139	0.0716	0.0028
Farmers' Income	0.0069	0.1606***	0.2340**
Constant	1.3647**	-2.7311***	-6.8576***
R2	0.4083	0.8337	0.7052
Sample Size	150	150	150

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

5. Further Mechanism Testing

5.1 Full Sample Mechanism Testing

Based on the results, this paper explores the mechanism by which land transfer promotes rural industry integration by adding variables such as human capital, rural information, and agricultural loans. The findings (Table 6) indicate that land transfer positively and significantly affects these variables at the 1% significance level, suggesting it can attract talent, technology, and funds to rural areas. Specifically, a 1% increase in land transfer scale can directly boost rural human capital, information, and agricultural loans by 0.0060, 0.0141, and 0.0375, respectively. The reasons include the need for agricultural mechanization to support large-scale land operations and the return of migrant workers who apply modern information technologies to agriculture.

Table 6 Mechanism Test Results of Land Transfer on Rural Industry Integration

Variable	Human Capital	Rural Information	Agricultural Loans
Land Transfer	0.0060***	0.0141***	0.0375***
Rural Human Capital		0.6067***	0.6722***
Rural Information	0.1430***		0.2276***
Agricultural Loans	0.2188***	0.3142***	
Constant	9.5522***	-1.0422***	1.9684***
R2	0.6974	0.7270	0.8394
Sample Size	450	450	450

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

5.2 Regional Mechanism Testing

This paper examines how land transfer promotes rural industry integration through human capital, rural information, and agricultural loans, noting regional differences. Using the benchmark model on samples divided into eastern, central, and western regions, it finds that in the eastern region, land transfer positively impacts human capital and agricultural loans at the 1% significance level, indicating it attracts talent and funds. In the central region, it significantly affects rural information and agricultural loans, suggesting it draws information technology and funds. In the western region, land transfer positively influences human capital, rural information, and agricultural loans, showing it attracts talent, technology, and funds. Overall, land transfer promotes rural industrial integration in each region through these factors, but the specific mechanisms vary. Notably, land transfer increases agricultural loans across all regions. The land - transfer - based mortgage loan model expands agricultural credit support, meets the financial needs of new agricultural entities, enhances rural industrial development effectiveness, and injects new vitality into rural industry integration.

Table 7 Regional Mechanism Test Results of Land Transfer on Rural Industry Integration

Region	Variable	Human Capital	Rural Information	Agricultural Loans
Eastern	Land Transfer	0.0110***	0.0043	0.0356***
	Human Capital	--	0.8778***	0.7408***
	Rural Information	0.1437***	--	0.3240***
	Agricultural Loans	0.1164***	0.3111***	--
	Constant	-11.5344***	10.0647***	12.7485***
	R2	0.7068	0.6165	0.7265
	Sample Size	195	195	195
Central Region	**Western Region**	**Human Capital**	**Rural Information**	**Agricultural Loans**
	Land Transfer	0.0016	0.0263***	0.0453***
	Human Capital	--	0.1168	0.3897***
	Rural Information	0.0561	--	0.3075***
	Agricultural Loans	0.2914***	0.4791***	--
	Constant	-12.8721***	1.2345***	9.7570***
	R2	0.5495***	0.7538	0.8620
	Sample Size	90	90	90

Western Region	Land Transfer	Human Capital	Rural Information	Agricultural Loans
	Human Capital	0.0109**	0.0245**	0.0475***
	Rural Information	--	0.2837*	0.6401***
	Agricultural Loans	0.0702*	--	0.4072***
	Constant	0.2352***	0.6050***	--
	R2	-12.7597***	1.3622	12.1233***
	Sample Size	0.7600	0.8140	0.8837
	Land Transfer	165	165	165

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

6. Discussion

6.1 Effect of Land Transfer on Rural Industry Integration

Empirical results confirm that land transfer significantly enhances rural industry integration by optimizing land resource allocation, enabling moderate-scale operations, and boosting agricultural productivity. It also reduces production costs, improves product quality and yield, and supports the development of rural secondary and tertiary industries. Furthermore, land transfer facilitates the transfer of land contract and management rights to new agricultural business entities, driving the diversification and integration of rural industries.

6.2 Regional Disparities in Land Transfer's Impact

The effect of land transfer on rural industry integration varies regionally, with the strongest impact in central region, followed by the east, and the weakest in the west. This disparity stems from differences in economic development, policy support, and agricultural foundations. The central region benefits from stronger economic development and policy support, while western region lags due to underdevelopment and a weaker agricultural foundation.

6.3 Temporal Heterogeneity

The impact of land transfer exhibits temporal heterogeneity. Initially, land consolidation enhances agricultural productivity and attracts resources to rural areas. However, as land transfer rates rise, issues like over-concentration and increased operational risks may emerge, potentially hindering the sustainable development of rural industry integration.

6.4 Mechanism of Land Transfer in Promoting Rural Industry Integration

Land transfer drives rural industry integration by attracting talent, technology, and capital to rural areas. It enables large-scale land operations, promotes advanced agricultural technologies and management practices, and attracts talent. Additionally, it encourages capital flow to rural areas, supports rural industry development financially, and spurs innovation in agricultural production and management through the application of information technology.

7. Conclusions and Policy Suggestions

7.1 Conclusions

Land transfer significantly promotes rural industry integration in China. Urbanization increased fiscal support, and agricultural loans also have positive impacts. Promoting effect of land transfer is strongest in central region, followed by eastern region, and weakest in western region, showing regional heterogeneity and temporal heterogeneity. Land transfer promotes rural industry integration by attracting talent, technology, and funds, but the mechanisms differ across regions.

7.2 Policy Suggestions

7.2.1 Promote Land Transfer

Promote orderly land transfer based on rural land certification. Set up land transfer service platforms at municipal, county, and township levels, as well as policy promotion and information exchange platforms. Serve new agricultural business entities and monitor land transfer's economic benefits locally.

7.2.2 Focus on Rural Industrial Circular Development

Village collectives should guide new agricultural business entities to carry out intensive production and operation, explore the potential value of waste from planting and breeding industries, and promote the circular development of rural industries.

7.2.3 Adopt Region-specific Policies

East and central regions should pilot rural-urban housing exchange and homestead land market entry. Guide industrial capital to villages orderly and promote land-for-equity transfer. The west should use its strengths, improve infrastructure, develop specialty agriculture, and create branded farm products and rural tourism spots.

7.2.4 Coordinate Development

Coordinate economic, social development, rural labor transfer and urbanization. Improve urban public facilities, abolish segmented household registration, lower the threshold for it, and guide rural population into cities.

7.2.5 Provide Financial Guarantees

Government should provide agricultural project investment and services for new rural business entities and guide financial institutions to offer convenient agricultural loans to meet the funding needs of rural industries integration.

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Determinants Influencing Mobile Money Customers' Choice of Financial Service Providers: An Empirical Study in Bamako, Mali

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Abstract. This study investigates the key factors influencing the choice of mobile money service providers in Bamako, Mali, a country where digital financial services are rapidly expanding yet unevenly adopted. Employing a mixed-method approach that combines Descriptive statistics, Correlation analysis, and multiple Regression analysis implemented in Stata, the research draws on data from a sample of 300 mobile money users in Mali. The study is theoretically grounded in the Theory of Planned Behavior (TPB) and the Technology Acceptance Model (TAM), which frame the analysis of consumer behavior in digital contexts. Findings reveal that Orange Money dominates the market, with accessibility of service points, transaction speed, and ease of platform use emerging as the most influential factors across all providers. Regression analysis provides deeper insights by isolating statistically significant predictors: for Orange Money, accessibility is the key driver, while for Moov Money, ease of platform use and variety of services offered significantly influence user preference. Other factors such as trust, affordability, customer service quality, and social influence though important in earlier stages of analysis, did not show statistical significance in the final regression models. The study offers actionable insights for service providers, policymakers, and development stakeholders aiming to expand financial inclusion. It recommends enhancing service accessibility, platform usability, customer support, and pricing strategies to meet diverse consumer needs. For regulators, the findings suggest the need to promote fair competition, interoperability, and digital literacy to reduce adoption barriers. Future research should consider longitudinal and qualitative approaches to further explore cultural, regional, and psychological influences on mobile money adoption. This study contributes to the growing body of literature on digital finance in Sub-Saharan Africa by identifying both functional and behavioral drivers of mobile money use in Bamako's rapidly transforming financial landscape.

Keywords. Mobile Money, Consumer behavior, Financial Inclusion, Digital Payment services, Bamako-Mali

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1 Introduction

Mobile money is reshaping financial services in developing economies by offering accessible, real-time, and low-cost alternatives to traditional banking. In Bamako, Mali, while mobile money registration has increased significantly in recent years, active usage remains relatively low, with many accounts classified as dormant[1]. Unlike countries such as Kenya where mobile money transactions are deeply embedded in daily life Mali's mobile money ecosystem is still developing. For example, by 2021, although there were 935 mobile money accounts per 1,000 adults, cash transactions continued to dominate. Only 38% of Malian adults reported receiving a digital payment in 2021, compared to 79% in Kenya and 49.5% in Ghana [2]. Orange Money was the first mobile money operator in Mali, followed by others such as Moov Money, Sama Money, Wave, Wizall, Zelia, and Coris Money. According to GSMA Intelligence [3], there were 23.4 million mobile cellular connections in Mali at the start of the year 2022. Across the broader West African Economic and Monetary Union (WAEMU), over 110 million mobile money accounts were opened between 2018 and 2022, with 60 million added since 2021, increasing financial inclusion in the region from 56% in 2018 to 71% in 2022[4]. These trends underline the increasing importance of mobile money as a tool for economic empowerment, especially in regions with limited access to traditional banking.

This study explores the key determinants influencing consumer choices of mobile money service providers in Bamako, Mali. Prior research [5, 6] identifies several factors that shape usage, including convenience, trust, security, transaction speed, and service reliability. For instance, in a study conducted on North Indian consumers, Singh et al. [7] demonstrated that age and gender significantly shaped user preferences and satisfaction toward mobile wallets, echoing similar demographic trends observed in mobile money adoption in West Africa. In Kenya, Suri and Jack [8] found that mobile money lifted millions out of poverty, particularly benefiting women and small businesses. Similarly, an international study, Tounekti et al. found that users with access to multiple mobile payment systems tend to prefer platforms based on security, transaction fees, perceived usefulness, and ease of use [9]. These platforms have supported government-to-person transfers and remittances during crises such as the COVID-19 pandemic [10]. According to Choi et al., assurance policies and loyalty programs (e.g., mileage) are among the most important features influencing consumer preferences f or mobile payment services [11]. Extending the Theory of Consumption Values, Omigie et al. found that perceived value across various dimensions including design appeal and novelty plays a crucial role in users' decisions to adopt services like M-PESA [12]. In a study conducted in Bangladesh, user satisfaction with mobile network operators was notably high, with 90% of Grameenphone customers reporting extreme satisfaction, outperforming other competitors in the market [13]. To frame this research, we draw on theoretical models such as the Technology Acceptance Model (TAM) [14], the Unified Theory of Acceptance, and the Theory of Planned Behavior (TPB) [15], which emphasize the roles of perceived usefulness, ease of use, social influence, and behavioral control in shaping user behavior. Consumer behavior research further helps to understand how demographic and psychological factors drive provider choices. For example, Azam [16] highlights the importance of understanding attitudes and decision-making for designing effective mobile service strategies. Studying consumer behavior involves analyzing not only what people buy, but also why, how often, and under what influences [17, 18]. In Bamako's context, this study investigates how variables such as age, gender,

education, income, and social class influence preferences for services like Orange Money, Moov, and Wave. Specifically, the study aims to identify the key factors such as trust, convenience, and social influence affecting provider choice, and to assess consumer satisfaction. These insights will inform strategies to expand mobile money adoption and support broader financial inclusion goals.

2 Theorical Framework & Hypothesis Analysis

2.1 Theorical Framework

This study is grounded in two well-established theoretical models that explain the adoption and use of mobile money services: the Technology Acceptance Model (TAM) and the Theory of Planned Behavior (TPB**)**. The Technology Acceptance Model (TAM), developed by Davis in 1989 [14], provides a framework for understanding how individuals come to accept and use technology. According to TAM, two primary factors perceived usefulness and perceived ease of use shape user attitudes and intentions toward adopting a technological solution. In the context of mobile money in Bamako, Mali, this model is relevant for analyzing how service-related attributes such as the speed of transactions, the ease of using the platform or application, the variety of services offered, accessibility of agents or service points, low transaction fees, and the availability of agents during convenient hours influence consumer choices. These variables reflect users' judgments regarding how mobile money services enhance convenience and improve financial efficiency, ultimately affecting their selection of a provider.

The Theory of Planned Behavior (TPB), proposed by Ajzen in 1991 [15], explains how behavioral intentions are shaped by attitudes, subjective norms, and perceived behavioral control. This framework is particularly useful in examining behavioral and social drivers behind mobile money usage in Bamako, Mali. Attitudes toward the service can be influenced by the quality of customer support and the perceived reliability of the provider. Social influence, or subjective norms, is reflected through recommendations from family and friends, as well as the general popularity and public perception of the provider. Perceived behavioral control, which concerns the user's belief in their ability to access and use the service, can be shaped by the distance to agents, the professionalism of service personnel, and the nature of relationships with distributor agents. Together, TAM and TPB provide a comprehensive lens through which both technological factors and socio-psychological determinants of consumer behavior can be understood. Applying these theories enables a deeper analysis of the elements guiding customer preferences in choosing between mobile money service providers in Bamako, Mali.

2.2 Hypothesis Analysis

Grounded in the Technology Acceptance Model (TAM) and the Theory of Planned Behavior (TPB), this study proposes and tests several hypotheses to explain the determinants of mobile money customers' choice of financial service providers in Bamako, Mali. Drawing from both theoretical constructs and insights from previous empirical literature, the following hypotheses are formulated:

1) H1: *Accessibility and ease of use significantly influence mobile money users' choice of service providers.*

This hypothesis is rooted in the TAM construct of perceived ease of use. It posits that users are more likely to choose platforms that are simple to navigate, with readily available service points and quick transaction capabilities.

2) H2: *Trust and perceived security of mobile money platforms significantly impact users' preferences.*
   Aligned with TPB's component of attitude toward behavior, this hypothesis suggests that users are more inclined to choose providers they perceive as reliable and secure, especially in contexts where digital fraud and data protection are ongoing concerns.
3) H3: *Cost-related factors, such as low transaction fees and promotional offers, play a key role in determining user choice.* This reflects the importance of economic value in technology adoption decisions. Users often compare service charges and are attracted to providers offering lower costs or added financial incentives.
4) H4: *The variety of services offered by a mobile money provider significantly influences users' choice of that provider.* This hypothesis is based on the idea that users are more likely to choose platforms that offer a broad range of financial services (e.g., transfers, bill payments, loans, savings), as it enhances perceived usefulness, an essential construct in the Technology Acceptance Model (TAM).

These hypotheses are tested using Descriptive Analysis, Correlation Analysis, and Multiple Regression Analysis to determine the most influential factors shaping user preferences. The analysis provides empirical validation of the theoretical models by identifying key attributes ease of use, trust, and affordability as the strongest predictors of mobile money provider selection.

3 Methodology

The study employed a simple random sampling technique due to its convenience, simplicity, and statistical efficiency. Data was collected through an online survey distributed via Microsoft Forms, with links shared through personal email and social media platforms such as WhatsApp, WeChat, and Facebook. The data collection spanned three months, from February to April 2024. A pre-test of the questionnaire was conducted with four academic researchers and thirty (30) mobile money users to ensure that the items were clear, comprehensible, and user-friendly. Feedback from a focus group contributed to refining the questions, enhancing clarity and usability. Ambiguous terms or unclear phrasing identified during the pre-test were revised before finalizing the survey. The final version was distributed to 300 voluntary respondents in Bamako, all active mobile money users. Participation was entirely voluntary, and the sampling aimed to capture diversity across relevant demographic characteristics.

To assess the adequacy of the sample size (N = 300), a post-hoc power analysis was conducted for multiple linear regression using an F-test to evaluate the significance of the overall model (H_0: $R^2 = 0$ vs. H_a: $R^2 \neq 0$). The observed R^2 was 0.0509. With an alpha level of 0.05 and a desired power of 0.80, the analysis indicated that a minimum sample size of 149 respondents would be required to detect this effect size ($\delta = 0.0536$). Given that the study includes 300 respondents, the sample size is statistically adequate and ensures sufficient power to detect meaningful relationships between variables.

In addition to ensure the reliability and validity of the questionnaire, Cronbach's alpha was computed for multi-item constructs such as trust, ease of use, and satisfaction. The scale reliability coefficient was 0.9594, indicating excellent internal consistency and confirming the robustness of the instrument for measuring the study's key variables. The research employed a combination of statistical methods, including Descriptive Statistics, Correlation Analysis, and Multiple Regression Analysis, to explore the determinants influencing consumers' choice of mobile money service providers. The questionnaire focused on three (03) main sections:

1) Demographic Information
2) Distribution of Mobile Money Providers Among Users
3) Determinants Influencing the Choice of Mobile Money Service Providers

Table 1. Demographic Profile of Mobile Money Users

Characteristic	Number	Percentage
Gender		
Male	221	74%
Female	79	26%
Age Group		
18-25	95	32%
26-35	153	51%
36-45	35	12%
46-55	8	3%
56 & Above	9	3%
Education Attainment		
Master and Above	131	44%
Bachelor	74	25%
Undergraduate level	16	5%
Baccalaureate level	40	13%
Secondary level	23	8%
Primary level	5	2%
Undergone Basic level	3	1%
No Formel Education	1	0.33%
Others	7	2%
Employment status		
Employed Full Time	79	26.33%
Employed Semi Time	31	10.33%
Entrepreneur/Self employed	59	19.67%
Unemployed	27	9%
Student	98	32.67%
Retired	6	2%
Marital Status		
Married	143	48%
Single	148	49%
Separated	6	2%
Widowed	3	1%
Formel Institution choice (Some customers used more than 1)		
Mobile Money Account	283	94%
Bank Account	168	56%
Micro-finance Account	26	9%
Mobile Money Providers choice (Some customers used more than 1)		
Orange Money	288	96%
Moov Money	81	27%
Sama Money	42	14%
Wave Money	34	11%
Wizal Money	1	0.33
0thers	3	1%

4 Results & Discussion

4.1 Descriptive Analysis

The descriptive analysis highlights that Orange Money (Y1) is the most widely used mobile money service in Bamako, Mali, with a mean value of 0.96, followed by Moov Money (Y2) (0.27), Sama Money (Y3) (0.14), Wave Money (Y4) (0.11), Wizall Money

(Y5) (0.003), and other electronic money services (Y6) (0.01). Among the independent variables influencing mobile money provider choice, accessibility of service points (X1) (0.55), transaction speed (X2) (0.36), and ease of platform use (X3) (0.34) are the most frequently reported factors, while elements such as agent professionalism (X11) (0.12), service provider reputation (X9) (0.13), and promotions/bonuses (X7) (0.15) have lower means, indicating relatively lesser influence on customer preferences. These insights underscore the significance of service accessibility, efficiency, and user-friendliness in driving mobile money adoption in Bamako, Mali.

Table 2. Descriptive Analysis

Variable	Obs	Mean	Std. dev.	Min	Max
Orange Money (Y1)	300	.96	.1962866	0	1
Moov Money (Y2)	300	.27	.4447012	0	1
Sama Money (Y3)	300	.14	.3475668	0	1
Wave Money (Y4)	300	.1133333	.3175295	0	1
Wizall Money (Y5)	300	.0033333	.057735	0	1
Others EMS (Y6)	300	.01	.099665	0	1
Accessibility of points/offices/Agencies(X1)	300	.55	.498325	0	1
Speed of transactions(X2)	300	.3633333	.4817633	0	1
Easy use of their platform/Application(X3)	300	.34	.4745003	0	1
Variety of services offered(X4)	300	.2333333	.4236593	0	1
Quality of customer service (X5)	300	.2233333	.4171758	0	1
Low transaction fees (X6)	300	.2166667	.4126619	0	1
Promotions and bonuses (X7)	300	.1566667	.3640935	0	1
Proximity to mobile money agents (X8)	300	.1533333	.3609105	0	1
Reputation as a reliable service provider (X9)	300	.1333333	.3405026	0	1
Brand awareness (X10)	300	.1233333	.3293688	0	1
The professionalism of the Mobile money agent(X11)	300	.12	.3255045	0	1
Mobile money agent opening hours(X12)	300	.0933333	.291385	0	1
Recommendations from friends/family(X13)	300	.0866667	.2818161	0	1
Relationship with Agent distributor (X14)	300	.0733333	.2611184	0	1
Others Factors (X15)	300	.0133333	.1148893	0	1

4.2 Correlation Analysis

The correlation analysis reveals key factors influencing customers' choice of mobile money service providers in Bamako, Mali. Transaction speed (X2) shows a strong correlation with Moov Money (Y2) (0.8051), Sama Money (Y3) (0.5341), and Wave Money (Y4) (0.4733), indicating that faster transactions significantly impact consumer preferences. Similarly, ease of use of the platform/application (X3) is highly correlated with Moov Money (Y2) (0.8473), Sama Money (Y3) (0.5621), and Wave Money (Y4) (0.4981), emphasizing the role of user-friendly platforms in adoption decisions. Reputation as a reliable service provider (X9) and brand awareness (X10) also exhibit strong associations with Wave Money (Y4) (0.9115 and 0.9532, respectively), suggesting that trust and brand image significantly influence customer choice. Variety of services offered (X4) is moderately correlated with Sama Money (Y3) (0.7314) and Wave Money (Y4) (0.6481), indicating that service diversification plays a role in mobile money selection. While low transaction fees (X6) show moderate correlations with Sama Money (Y3) (0.7672) and Wave Money (Y4) (0.6798), the correlation with Moov Money (Y2) (0.8648) is stronger, reinforcing the importance of cost-effectiveness. Customer service quality (X5) is positively correlated with Moov Money (Y2) (0.8817) and Sama Money (Y3) (0.7524), suggesting that efficient support services drive adoption. Promotional offers and bonuses (X7) also influence customer choice, particularly for Sama Money (Y3) (0.9361) and Wave Money (Y4) (0.8295). Meanwhile, recommendations from friends and family

(X13) are positively correlated with Wave Money (Y4) (0.8616), highlighting the role of word-of-mouth in adoption. Notably, Wizall Money (Y5) and other mobile money services (Y6) display weaker correlations with most determinants, suggesting that these services are less influenced by conventional adoption factors. Overall, the findings indicate that trust (X9, X10), ease of use (X3), affordability (X6), and accessibility (X1, X4) are the primary drivers of mobile money adoption in Bamako, Mali. These insights provide a basis for further regression analysis to establish causal relationships between these factors and customer preferences.

Table 3. Correlation Analysis

	Y1	**Y2**	**Y3**	**Y4**	**Y5**	**Y6**	**X1**
Y1	1.0000						
Y2	0.1241	1.0000					
Y3	0.0824	0.6634	1.0000				
Y4	0.0730	0.5879	0.8861	1.0000			
Y5	0.0118	0.0951	0.1433	0.1618	1.0000		
Y6	0.0205	0.1653	0.2491	0.2811	0.5754	1.0000	
X1	0.2257	0.5501	0.3650	0.3234	0.0523	0.0909	1.0000
X2	0.1542	0.8051	0.5341	0.4733	0.0766	0.1330	0.6833
X3	0.1465	0.8473	0.5621	0.4981	0.0806	0.1400	0.6492
X4	0.1126	0.9071	0.7314	0.6481	0.1048	0.1822	0.4990
X5	0.1095	0.8817	0.7524	0.6667	0.1078	0.1874	0.4850
X6	0.1074	0.8648	0.7672	0.6798	0.1100	0.1911	0.4757
X7	0.0880	0.7087	0.9361	0.8295	0.1342	0.2332	0.3899
X8	0.0869	0.6997	0.9481	0.8401	0.1359	0.2362	0.3849
X9	0.0801	0.6449	0.9721	0.9115	0.1474	0.2562	0.3548
X10	0.0766	0.6167	0.9296	0.9532	0.1542	0.2680	0.3393
X11	0.0754	0.6072	0.9152	0.9682	0.1566	0.2722	0.3340
X12	0.0655	0.5276	0.7952	0.8974	0.1802	0.3132	0.2902
X13	0.0629	0.5065	0.7635	0.8616	0.1877	0.3263	0.2786
X14	0.0574	0.4626	0.6972	0.7868	0.2056	0.3573	0.2545
X15	0.0237	0.1911	0.2881	0.3252	0.4975	0.8646	0.1051
	X2	**X3**	**X4**	**X5**	**X6**	**X7**	**X8**
X2	1.0000						
X3	0.9501	1.0000					
X4	0.7303	0.7686	1.0000				
X5	0.7098	0.7471	0.9720	1.0000			
X6	0.6962	0.7327	0.9533	0.9808	1.0000		
X7	0.5705	0.6005	0.7813	0.8038	0.8195	1.0000	
X8	0.5633	0.5929	0.7714	0.7936	0.8092	0.9874	1.0000
X9	0.5192	0.5465	0.7110	0.7314	0.7458	0.9100	0.9217
X10	0.4965	0.5226	0.6799	0.6995	0.7132	0.8702	0.8814
X11	0.4888	0.5145	0.6694	0.6886	0.7021	0.8568	0.8677
X12	0.4247	0.4470	0.5816	0.5983	0.6101	0.7444	0.7539
X13	0.4078	0.4292	0.5584	0.5744	0.5857	0.7147	0.7239
X14	0.3724	0.3919	0.5099	0.5246	0.5349	0.6527	0.6610
X15	0.1539	0.1620	0.2107	0.2168	0.2210	0.2697	0.2732
	X9	**X10**	**X11**	**X12**	**X13**	**X14**	**X15**
X9	1.0000						
X10	0.9563	1.0000					
X11	0.9415	0.9845	1.0000				
X12	0.8180	0.8554	0.8689	1.0000			
X13	0.7854	0.8213	0.8342	0.9601	1.0000		
X14	0.7172	0.7500	0.7618	0.8768	0.9132	1.0000	
X15	0.2964	0.3099	0.3148	0.3623	0.3774	0.4132	1.0000

4.3 Regression Analysis

Among the various providers available, Orange Money and Moov Money were selected as the focus of the analysis due to their prominence and widespread use among Bamako Malians, as revealed through earlier descriptive statistics and correlation analysis. These two providers stood out as the most important and commonly used platforms, warranting a deeper examination of the determinants of their adoption. To identify the factors influencing users' preferences for these providers, two separate regression models were estimated one for Orange Money and another for Moov Money. The selection of explanatory variables in the models was based on prior statistical testing. Specifically, only variables that showed a statistically significant relationship with the dependent variables were retained. Variables that were not significant in earlier regression models or in preliminary analyses were excluded to enhance the robustness and clarity of the final models.

In the first model, where Orange Money serves as the dependent variable (Y1), the regression results reveal that the model is statistically significant ($F = 3.96$, $p = 0.0038$), with an R-squared of 0.0509, indicating that approximately 5.1% of the variance in Orange Money usage is explained by the model. Among the independent variables, only the accessibility of service points or agencies (X1) was found to have a statistically significant effect on the use of Orange Money. The coefficient of 0.0889 ($p = 0.004$) suggests that users are more likely to choose Orange Money when they have greater physical access to its agents or service points. The other variables, speed of transactions (X2), ease of use of the application (X3), and the variety of services offered (X4), did not show statistically significant effects and had coefficients very close to zero, suggesting they do not meaningfully influence user preference for Orange Money.

In the second model, where Moov Money is the dependent variable (Y2), the results show a much stronger model fit, with an R-squared of 0.8779 and an F-statistic of 530.35 ($p < 0.0001$), indicating that nearly 88% of the variance in Moov Money usage is explained by the independent variables. In contrast to Orange Money, Moov Money adoption is significantly influenced by the variety of services offered (X4), with a coefficient of 0.6563 ($p < 0.001$), and the ease of using the platform (X3), with a coefficient of 0.3438 ($p < 0.001$). These results suggest that users are more inclined to choose Moov Money when the platform provides a broad range of services and is easy to navigate. As in the Orange Money model, the variables for accessibility (X1) and speed of transactions (X2) were not significant in predicting Moov Money use.

Overall, these findings demonstrate that user preferences for mobile money services in Bamako, Mali are shaped by provider-specific factors. Orange Money users prioritize accessibility, while Moov Money users value service variety and user-friendliness. The exclusion of other mobile money providers and non-significant variables ensured the focus remained on the most relevant factors, providing a clearer understanding of what drives user decisions in the Bamako Malian mobile money landscape.

Table 4. Regression analysis of factors influencing Orange Money usage (Y1) and Moov Money usage (Y2)

Equation	Obs	F(4, 295)	Prob > F	R-squared	Adj R-squared	Root MSE
Y1	300	3.96	0.0038	0.0509	0.0381	.19252
Y2	300	530.35	0.0000	0.8779	0.8763	.15643

	Coefficient	Std. err.	t	P>t	[95% conf.	interval]
Y1						
X1	0.0889	0.0306	2.90	0.004	0.0287	0.1491
X2	-2.21e-15	0.0772	-0.00	1.000	-0.1519	0.1519
X3	2.16e-15	0.0803	0.000	1.000	-0.1581	0.1581
X4	2.16e-17	0.0411	0.000	1.000	-0.0808	0.0808
_cons	0.9111	0.0166	54.99	0.000	0.8785	0.9437
Y2						
X1	-6.04e-15	0.0249	-0.00	1.000	-0.0489	0.0489
X2	1.92e-14	0.0627	0.00	1.000	-0.1234	0.1234
X3	.34375	0.0653	5.27	0.000	0.2152	0.4722
X4	.65625	0.0333	19.66	0.000	0.5906	0.7219
_cons	1.05e-15	0.0135	0.00	1.000	-0.0265	0.0265

5 Conclusions

This study provides a comprehensive empirical analysis of the determinants influencing consumer choice of mobile money service providers in Bamako, Mali. Drawing on Descriptive analysis and correlation analysis, the research reveals a nuanced landscape of consumer preferences shaped by both technological and psychosocial factors. Anchored in the Theory of Planned Behavior and the Technology Acceptance Model, the findings highlight how perceived ease of use, usefulness, and social influence underpin decision-making in the adoption and continued use of mobile money services. These results empirically validate the study's hypotheses.

The analyses consistently indicate that accessibility, transaction speed, and ease of platform use are the strongest determinants of provider choice. These are closely followed by trust-related factors, cost-effectiveness, and customer support quality. Social influence variables, such as promotional offers and peer recommendations, also shape user preferences, particularly for emerging providers like Sama and Wave Money. The regression analysis further enhances these insights by focusing on the two most prominent mobile money providers in Bamako, Orange Money and Moov Money selected based on their dominant usage in the earlier stages of analysis. For Orange Money, regression results show that accessibility of agents and offices is the only statistically significant factor influencing consumer preference, suggesting that the widespread presence and reach of this provider strongly drive its adoption. In contrast, the regression model for Moov Money reveals that ease of use of the platform and the variety of services offered are both highly significant determinants. This suggests that users are drawn to Moov Money not just for functionality but for a broader and more

personalized service experience. Variables such as speed and accessibility were not significant in the Moov model, highlighting distinct strategic positioning among providers. These findings validate the importance of perceived behavioral control (e.g., accessibility), perceived usefulness (e.g., service variety), and user satisfaction (e.g., ease of use) in shaping provider preference. From a practical standpoint, mobile money service providers should expand their agent networks to improve accessibility, especially in rural and peri-urban areas. Simplifying mobile platforms and interfaces can help attract less tech-savvy users. It is essential to invest in brand trust through reliable, secure platforms and transparent communication. Offering competitive transaction fees and loyalty programs could further attract and retain customers. Additionally, mobile money agents should be trained in professionalism and customer service, as these factors, while reported less frequently, still influence customer decisions. For policymakers and regulators, there is a need to encourage interoperability and fair competition among providers. Digital literacy campaigns can support adoption among underserved populations. Furthermore, reinforcing consumer protection frameworks will help build trust and reduce risks associated with fraud and misuse. Despite the robustness of the study, it is important to recognize certain limitations. The research is based on a cross-sectional survey of 300 respondents in Bamako, Mali, which may not fully capture regional or behavioral variations. The analysis also relies on observable variables and self-reported data, which could involve response bias. Future research could address these limitations by:

- Using longitudinal data to observe behavioral trends over time.
- Expanding the sample to include a broader and more geographically diverse population.
- Incorporating qualitative methods to explore cultural and psychological influences.
- Investigating the roles of financial literacy, cyber security awareness, and gender-based differences.
- Exploring how mobile money interacts with other digital financial services such as microcredit, insurance, and digital savings platforms.

In conclusion, this research advances the understanding of mobile money consumer behavior in Bamako, Mali by identifying both technical and psychosocial factors that drive adoption. It offers concrete guidance to stakeholders aiming to improve digital financial inclusion and opens new directions for inquiry in a rapidly evolving financial technology environment.

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Overview of SDN-Based Traffic Engineering

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Abstract. This paper reviews the research on Traffic Engineering (TE) based on Software-Defined Networking (SDN). Firstly, the shortcomings of traditional network architectures in managing complex traffic are introduced, and it is pointed out that SDN provides a new solution for traffic engineering through the features of separation of control and data planes, centralized control, and programmability, but at the same time, it faces many challenges. Then the three-layer architecture of SDN and its role in traffic engineering are described, and the goals, research directions and application scenarios of traffic engineering are outlined. The application of machine learning (ML) methods in SDN traffic engineering is then discussed in detail, including the advantages of deep learning (DL) in traffic prediction and classification, and the potential of reinforcement learning (RL) in routing optimization and resource scheduling. In addition, four mechanisms for optimization algorithms to merge with ML are analyzed. The integration of SDN with new architectures such as edge computing and network slicing, as well as the prospects for the application of intent-driven networking are then explored. Finally, the opportunities and challenges of SDN traffic engineering are summarized, including the advantages of flexible traffic management and cross-domain optimization, as well as the problems of network scale, security, real-time and multi-tenant management, which provide directions for future research.

Keywords. SDN, Traffic Engineering, Optimization Algorithms, Machine Learning

1.Introduction

The rapid development of information technology, especially the wide application of IoT, cloud computing, big data and 5G, has driven the dramatic increase in global network traffic. Under the increasingly complex network environment, traditional network architectures and traffic management tools have gradually exposed their limitations. Traditional equipment relies on static configuration and lacks flexibility, making it difficult to cope with traffic fluctuations, meet diversified quality of service (QoS) demands, and adapt to rapid changes in network status. Therefore, optimizing traffic

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management, improving resource utilization, and guaranteeing quality of service for multiple types of service traffic have become the core tasks of network management [1].

As a new network architecture, SDN provides a powerful solution to these problems by virtue of the separation of the control plane and the data plane, centralized control, and a high degree of programmability. SDN achieves flexible, real-time resource scheduling through a centralized control platform, which dynamically adjusts paths according to different network demands and significantly optimizes network performance [2]. Its policy-driven traffic management mechanism lays the foundation for building a flexible and efficient traffic engineering system [3].

In SDN architecture, OpenFlow, as the earliest and most widely used southbound interface protocol, is responsible for realizing the communication between controllers and network devices. Through OpenFlow, the controller can directly issue flow table rules, accurately control the data forwarding behavior, and dynamically collect network state information, combined with real-time topology and link load to make the global optimal decision, which greatly improves the automation and intelligence of network management.

Traffic engineering, as the core goal of network optimization, aims to improve the overall network performance through reasonable resource allocation and traffic scheduling. Traditional traffic engineering methods rely on static configuration, which is difficult to cope with dynamic changes in the network state, and the introduction of SDN has achieved a fundamental change in traffic engineering management: with centralized control and programmable interfaces, the network can adjust the flow path based on the real-time state, thus improving bandwidth utilization and reducing latency and packet loss [4].

In recent years, the convergence of ML algorithms has further advanced the development of traffic engineering. By learning traffic patterns from historical data, ML methods can optimize traffic prediction and scheduling strategies and enhance the automation and intelligence of traffic engineering systems. It makes traffic engineering more accurate and efficient in complex network environments [5]. Nevertheless, the application of SDN and ML in traffic engineering still faces challenges, such as dynamic topology changes, QoS guarantee, and coordination of multiple service demands. How to achieve efficient scheduling and ensure QoS guarantee for differentiated traffic is still an urgent issue that needs in-depth research [6].

In this paper, we will systematically introduce SDN-based traffic engineering methods, discuss their research progress and application practices, analyze the advantages and shortcomings of existing technologies, and look forward to their future development direction. The next section will first outline the SDN architecture and its application in traffic engineering, followed by a discussion of the main objectives and key challenges of traffic engineering.

1.1. Overview of SDN Architecture

SDN is an innovative network architecture whose core concept is to separate the control plane from the data plane to achieve flexible management and dynamic optimization of the network. In traditional networks, the control plane and the data plane are usually coupled together, and network equipment is responsible for both data forwarding and complex tasks such as traffic control and routing. This architecture is often difficult to meet the demand for real-time optimization and flexible configuration in the face of large-scale, dynamically changing network environments[7].

SDN centralizes network control by extracting control functions from individual network devices and deploying them centrally in one or more controllers. These controllers control the global network state and manage tasks such as traffic scheduling, path selection, and resource allocation in a unified manner, while the data plane devices (e.g., switches, routers) are only responsible for forwarding packets based on the instructions issued by the controllers. Through this decoupled design, SDN dramatically improves the flexibility and programmability of the network, which is especially suitable for complex QoS requirements and large-scale network environments.

The SDN architecture typically consists of three layers:

a) Application layer: It includes various network applications such as traffic monitoring, load balancing, network optimization, security management, and so on. The application layer interacts with the control layer to propose business requirements and guide network behavior to achieve functions such as dynamic bandwidth adjustment, path optimization, and fault recovery. This layer is highly abstracted to facilitate on-demand customization and deployment of network services [8].

b) Control Layer: Known as the "brain" of SDN, this layer consists of one or more controllers responsible for policy formulation, resource allocation, and traffic scheduling. The controllers collect real-time topology and network state information, and make global optimization decisions based on business requirements, including path computation, security policy formulation, and load dynamic adjustment. Compared with traditional decentralized control, centralized control brings higher flexibility, visibility and programmability [9][10].

c) Data Layer: consists of physical or virtualized switches, routers, etc., which are responsible for executing forwarding rules issued by the controller. Devices at this layer are focused on efficient execution of forwarding operations without complex control logic, resulting in more simplified, lower cost, and faster processing, which improves overall network performance [9].

As shown in Fig. 1, with this architecture, SDN provides a high degree of flexibility and programmability, enabling precise control and real-time adjustments at the network level. The centralized control and data-driven nature of SDN makes it an ideal framework for optimizing traffic engineering.

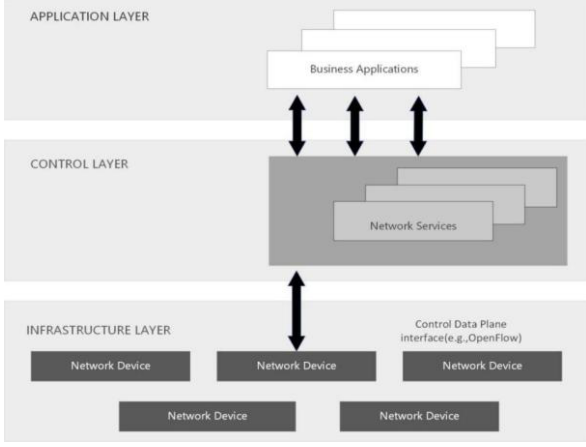


Fig. 1 SDN three-layer architecture

1.2. Overview of Traffic Engineering

Traffic engineering aims to optimize network performance, improve bandwidth utilization, reduce latency, and ensure QoS for different traffic types by scheduling network traffic and allocating network resources. it is the core function of routing and bandwidth allocation in the control plane [9][11], and its goal is to effectively manage network traffic, avoid congestion, improve throughput, and ensure efficient network operation in multiple application scenarios. With the expansion of network scale and diversification of application requirements, traffic engineering has become a key issue in network management. the introduction of SDN brings greater flexibility and precision to traffic engineering, providing new technical paths to address complex network challenges [12][13]As shown in Fig. 2, an example of traffic engineering-based route optimization is demonstrated. In Fig. 2(a), the shortest path protocol (e.g., OSPF) transmits traffic from node A to node C, resulting in link AC congestion. In contrast, in Fig. 2(b), some of the traffic is forwarded through paths AB and BC, effectively relieving the load on the AC link. This shows that traffic engineering can significantly improve network performance through dynamic path selection and intelligent scheduling.

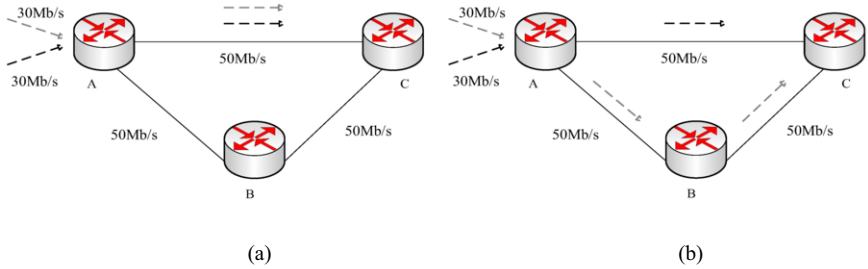


Fig. 2 Example of flow engineering for route optimization

Traffic engineering in traditional network architectures relies on static routing and fixed path configurations, which is applicable when the network structure and traffic are relatively stable. However, in the face of frequent changes in network topology and diverse QoS requirements, its limitations become more and more obvious. SDN, on the other hand, realizes dynamic adjustment of traffic paths and intelligent allocation of resources through centralized control and flexible programming interfaces, significantly improving network performance and management efficiency [14][15].

As shown in Figure 3, traffic engineering research focuses on optimized scheduling and resource allocation, covering multiple directions such as traffic prediction, path selection, QoS guarantee and load balancing. These studies usually leverage the centralized management and programmability of SDN controllers, combined with the intelligent features of ML algorithms, to achieve dynamic sensing and accurate optimization of network traffic [16][17] Among them, traffic prediction and path selection optimization help network managers to grasp traffic patterns and make reasonable scheduling, while QoS optimization and load balancing guarantee network efficiency, stability and reliability under different service demands [18][19].

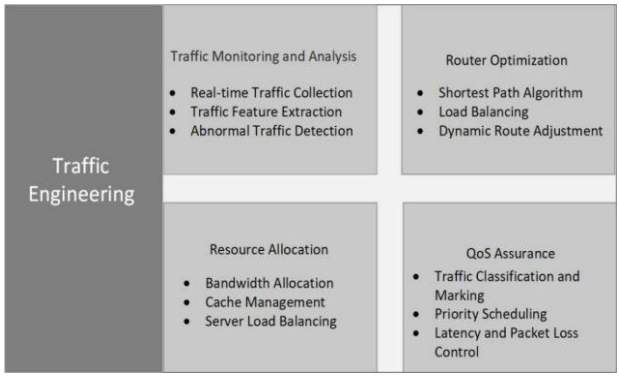


Fig. 3 Main research contents of traffic engineering

2.ML-based Methods

The constant changes in network architectures and application scenarios make it increasingly difficult for traditional traffic scheduling and routing methods to meet the requirements of modern SDN for flexibility, dynamism, and efficiency. In particular, ML-based approaches show great potential in the face of increasing traffic demands, complex network topologies, and variable network environments. DL and RL approaches can significantly improve the efficiency and adaptability of traffic engineering through intelligent decision making and self-learning.

2.1.DL-based Methods

DL has been widely used in traffic engineering, especially in tasks such as network traffic prediction, traffic classification and identification, and routing optimization and resource allocation. DNN is able to deal with more complex nonlinear relationships and has strong generalization ability compared to traditional rule- or model-based optimization methods by automatically learning complex features and patterns in data [20].

2.1.1. Traffic Forecasts

Under SDN architecture, accurate prediction of network traffic is of key significance for resource preallocation, congestion control and QoS guarantee. Leinonen et al [21] proposed a traffic prediction method based on Long-Short-Term Memory (LSTM) network, which deeply exploits the temporal characteristics of traffic, and demonstrates good generalization ability and prediction accuracy in multi-source heterogeneous data environment, and is more robust than the traditional autoregressive model in Zhang et al. [22] further proposed the Hierarchical-Attention-LSTM model, which enhances the modeling ability of LSTM on multi-timescale dependencies through the hierarchical attention mechanism, and achieves excellent performance on real network datasets such as GÉANT and Abilene, significantly improving the ability to recognize anomalous traffic patterns. traffic pattern recognition.

He et al [23] combined causal inference with graph neural networks (GNN) to construct a causal graph-based network state modeling framework, which effectively captures the traffic evolution patterns under different topologies and improves the

modeling ability of complex spatio-temporal dependencies. Kablaoui et al [24] proposed a prediction method of image-based time series, which transforms the traffic sequences into images, and exploits them through convolutional neural network (CNN) to mine the spatial features implied in them and significantly improve the prediction performance.

The above studies show that deep learning methods have significant advantages in capturing network spatio-temporal features, improving prediction accuracy and adapting to dynamic environments, which provides an effective path for realizing intelligent traffic engineering.

2.1.2.Traffic Classification and Identification

Traffic classification and identification are key aspects of policy issuance and access control implemented by SDN controllers. Although there are relatively few related researches, there are still several noteworthy results. Long et al [25] proposed a deep learning-based NetFlow flow classification framework, which uses multi-layer feed-forward neural networks to model the original fields, and achieves high-accuracy recognition in a variety of typical application scenarios, suitable for large-scale real-time processing and resource-constrained environments. Salau et al [26] constructed a machine-based learning framework for SDN traffic classification, which utilizes the flow table data collected by the controller to extract multi-dimensional features such as statistical features, protocol fields and flow duration, and systematically evaluates the classification performance of algorithms such as KNN, decision tree, random forest, SVM, and plain Bayes. The experimental results show that Random Forest and SVM perform the best in terms of accuracy and robustness, with classification accuracy exceeding 96%. In addition, the study analyzes the applicability of each algorithm in identifying different attack types (e.g., DoS, Probe, R2L, etc.), and verifies the utility of ML-based classification mechanisms in SDN security management.

Part of the research also combines RL with deep classification models to improve the ability to recognize encrypted traffic and covert communications, enhance the system's response to new types of threats, and provide technical support for the deployment of SDN in security scenarios.

2.2.RL-based Methods

RL is another ML method widely used in SDN traffic engineering, mainly in routing optimization, resource scheduling and load balancing, etc. RL learns how to select the optimal action based on the current state by interacting with the environment to maximize the long-term rewards. In SDN, RL is able to adaptively adjust the traffic allocation strategy in the network, especially in the case of frequent changes in network topology, traffic load and fault conditions, RL shows significant advantages.

2.2.1.Route Optimization

Traditional SDN routing schemes such as OSPF and ECMP often rely on static path computation, which is difficult to adapt to the dynamic changes in network topology and traffic load. For this reason, researchers have tried to introduce RL models to autonomously find optimal routing paths through interactive learning mechanisms.

Guo et al [27] designed a Collaborative Multi-Intelligent Reinforcement Learning (CMRL) framework, which employs multiple intelligences to control sub-network areas separately and reduces the conflict of the globally optimal policy by introducing a

differential reward mechanism, which effectively improves the efficiency and robustness of path selection in large-scale hybrid SDN environments. Zhang et al [28] constructed a distributed routing architecture that integrates multi-path selection and DRL distributed routing architecture that significantly improves the network throughput and reduces the frequency of congestion in multiple controller cooperative scenarios. In addition, this study also employs state hierarchies and priority queuing mechanisms to further enhance the DRL algorithm's ability to respond to bursty traffic. wang et al [29] further propose a reusable reinforcement learning routing algorithm (RLSR-Routing), which divorces the training and exploration process of routing paths, allowing controllers to be quickly deployed in multiple different network environments after training. The method introduces path constraints based on Segment Routing (SR), effectively avoids routing loops, and reduces the communication cost between the control and data planes.

These works show that RL-based routing algorithms can learn and adapt to optimal path strategies in changing network states, with good generalization ability and practical deployment value.

2.2.2.Resource Scheduling and Load Balancing

SDN has the advantages of global visibility and centralized control, which provides more space for resource scheduling algorithms. RL can dynamically adjust the allocation strategy of computing and bandwidth resources through trial-and-error mechanism to satisfy the traffic demand while taking into account the performance and energy efficiency.

Sun et al [30] proposed a joint resource allocation framework based on DRL, which solves the problem of coordinated allocation of spectrum and computational resources in cellular networks, effectively reduces the average task completion time and enhances user fairness. Anoushee et al [31] proposed an intelligent resource management mechanism for edge computing environments, which allocates computational tasks among multiple SDN edge nodes via RL, achieving low latency and high performance. computation tasks, achieving the joint optimization of low latency and high throughput, which is particularly suitable for application deployment in industrial IoT and HD video scenarios. Xie et al [32] proposed a dynamic resource allocation method for SDN based on the Deep Deterministic Policy Gradient (DDPG) algorithm, which is designed to improve the network performance and quality of service. The method is able to respond to network state changes in real time and automatically adjust the resource allocation strategy, thus improving network throughput and resource utilization. Experimental results show that the DDPG algorithm maintains up to 95 Mbps throughput and 95% resource utilization under different network loads, demonstrating superior performance and flexible resource management capabilities.

These studies show that RL can effectively improve the resource adaptation and QoS guarantee capability of network systems under high load, dynamic demand and multi-user scenarios, which is an important direction for the intelligent evolution of SDN.

2.3. DRL-based Methods

Combining DL with RL, the method aims to combine the advantages of DL and RL: DL is good at automatic extraction of complex features, RL is good at dynamic decision making and strategy optimization. Under the SDN architecture, the controller has global

view and centralized control capability, which is naturally suitable for acting as an "agent" in RL for context awareness and policy adjustment.

Farhan et al.[33] pointed out that many existing SDN traffic engineering models based on GNN ignore the impact of link reliability on network performance. For this reason, they proposed RDG-TE model integrating DRL and GNN, introducing link reliability factor into training process and reward function, so as to enhance robustness and adaptability of system under link failure scenario. We compare the results with the existing models, and the experimental results have shown that the proposed method is superior to the existing models in terms of reducing the number of hops and improving routing accuracy.

In addition, Lin et al.[34] introduced Transformer into the DRL framework to address the convergence of routing policy learning in a hybrid SDN environment. By using multi-feature embedding and position coding, the model can better model the temporal characteristics of the network, so that the model can generate a more stable optimal policy in a dynamic traffic environment.

In terms of QoS awareness, Guo et al.[35] proposed a QoS-aware routing method for SDN-IoT scenario by integrating DL for network state modeling and RL optimization routing decision, which effectively improved the scheduling capability of high-throughput and low-delay services.

From a broader research perspective, in recent years, a large number of literatures have focused on the application of DRL to traffic engineering and QoS optimization in SDN. These studies have gradually reached a consensus on the model architecture, learning objectives and application scenarios. As shown in Table 1, DQN, DDPG, Actor-Critic and other mainstream RL methods are often combined with DNN, GNN, RNN and other models, and are widely used in key tasks such as link weight adjustment, path selection, bandwidth allocation, etc., and have achieved significant optimization effects in delay, throughput, reliability and other indicators.

Table 1 Examples of DRL Partial Methods

Paper	Description	Learning Approach	Action	Performance
[36]	Uses deep learning for WAN traffic engineering optimization, significantly improving performance and speed	DRL (Q-learning, GNN)	Flow allocation	Speedup, traffic demand satisfaction, network performance
[37]	DRL with spatio-temporal features for SDN routing	DRL (DDPG + CNN + LSTM + TAM)	Dynamic routing	Lower delay, better convergence
[38]	DRL for efficient task offloading in edge IoT	DRL (DQN variant)	Task offloading	Less energy, higher task success
[39]	Utilizes DRL to optimize traffic engineering based on network experience	DRL (DDPG)	Traffic engineering	End-to-end delay, network utility
[40]	A multi-agent DRL approach to optimize routing for diverse QoS requirements in real-time	DRL (Actor-Critic with Graph Neural Networks)	Routing decision (next hop)	Latency, throughput, packet loss, network scalability

[41]	Time-aware DRL for optimizing routing strategies in SDN	DRL (DDPG, RNN)	Link weight adjustment	Delay, load balancing, QoS improvement, dynamic traffic
[42]	A DRL-based approach to improve routing efficiency for traffic engineering in SDN	DRL (DQN)	Next-hop	Delay, throughput, network usage

Combining the advantages of DL and RL enables such methods to provide more accurate prediction and faster adaptation when dealing with complex traffic engineering problems. DL is responsible for the automatic learning of features while RL continuously optimizes the decision-making strategy through a rewarding mechanism, which is especially suitable for large-scale and dynamically changing network environments. However, the combined approach also faces the drawbacks of DL and RL, such as high computational resource consumption and long training time. Therefore, how to efficiently combine these two methods to achieve faster and more accurate traffic scheduling is an important direction for future research [43].

3.ML Enhancement Mechanisms in Optimization Algorithms

In traffic engineering for SDN, optimization algorithms are widely used for tasks such as path computation, resource allocation, and queue scheduling. However, in the face of challenges such as highly dynamic network states and complex and changing traffic patterns, traditional static or rule-driven optimization methods often lack sufficient responsiveness and generalization capabilities. In recent years, the integration of ML with optimization algorithms has become a research hotspot, aiming to improve the foresight, adaptivity and overall efficiency of optimization through a learning mechanism. The mechanism can be embedded into the optimization process at different levels, which are mainly classified into four categories: prediction enhancement, heuristic guidance, parameter tuning and joint modeling.

3.1.Predictive Enhanced Optimization

This method significantly improves the timeliness and global nature of traditional optimization algorithms by using ML models to predict the future state of the network and provide input information for the optimization process in advance. The prediction targets often include traffic matrix, link congestion status, service request patterns, etc.

The Teal system trains DNNs with historical network state data to predict future link loads and potential bottleneck locations. The prediction results are then combined with heuristic path planning policies to achieve fast and robust path deployment in WAN environments. Teal's prediction-assisted mechanism not only improves path stability, but also reduces the control overhead caused by frequent policy updates [44]. In addition, the GRU-based network prediction model captures the periodicity and burstiness of traffic in a time-series context. The prediction results are fed back to the link weight calculation module in real time, which in turn dynamically adjusts the OSPF or ECMP routing cost to achieve more flexible load balancing [45].

The advantage of such methods is that they can apply the learned timing laws to optimization problem solving, breaking through the limitation of traditional optimizers' dependence on the current state. However, the risk of propagation of prediction errors needs to be concerned, especially in unpredictable situations such as sudden

abnormalities in links and equipment failures, the system needs to introduce an anomaly detection mechanism or a fallback mechanism to safeguard it.

3.2.Heuristic Learning Guides

Heuristic algorithms are widely used in the field of network optimization, but their search efficiency and the quality of the solution heavily depend on the design of the heuristic strategy. Introducing ML into the heuristic search process enables automatic learning of better local selection rules from empirical data.

Structure learning methods, represented by GNN, are able to capture the higher-order semantic information of network topology. In transportation network optimization, GNN combined with DRL can learn efficient node selection strategies that guide genetic algorithms or particle swarm algorithms to prioritize the exploration of high-quality solution domains [46].The CFR-RL framework further proposes to embed an RL policy network into a path reconfiguration module, which dynamically reroutes the critical flows while maintaining the QoS, through continuous learning of mapping relationships between network state and link utilization [47]. In addition, path optimization models that combine attention mechanisms with deep network structures have shown superior performance, such as the neural-heuristic path finder proposed by Wu et al [48], which efficiently learns high-quality candidate path combinations in traveler and capacity-constrained path problems.

This approach is especially suitable for scenarios where the network environment changes frequently and the rules are difficult to design manually, which helps to improve the search efficiency and solution quality in large-scale network optimization.

4.New Architecture-based Methods

The rapid development of network technology has driven the combination of SDN with other emerging architectures, especially the convergence of SDN with edge computing, SDN with network slicing, and other technologies, which has become an important way to enhance network performance, optimize resource management, and improve QoS. The combination of these new architectures not only enhances the flexibility and scalability of the network, but also promotes the process of network intelligence and meets the growing business demands [49].

4.1.Combination of SDN and Network Slicing

Network slicing technology provides customized services for different applications by dividing the physical network into multiple virtual “slices”, which is especially important in 5G. When combined with SDN, network slicing can be managed and optimized more flexibly, significantly improving the efficiency of resource allocation and traffic scheduling.

Chang et al [50] pointed out that current data centers often ignore the availability of the control plane when pursuing efficient traffic engineering. To this end, a strategy to optimize controller deployment is proposed to enhance traffic engineering efficiency while guaranteeing high availability of the control plane in case of controller failure.

Experimental results show that this strategy outperforms existing schemes in terms of network performance.

In addition, SDN and network slicing are also applied in SD-WAN: SDN provides flexible traffic control, and network slicing achieves service customization guarantee, which improves the performance and manageability of SD-WAN [51].

Overall, the convergence of SDN and network slicing brings innovative paths for network optimization and resource management, improves the flexibility, scalability and intelligence of the network, and lays the technical foundation for the construction of next-generation networks.

4.2.Intent-Driven Networking

Intent-Driven Networking (IDN) is a self-driven network architecture that integrates the flexibility and automation capability of SDN, and realizes the automatic execution of application intents by decoupling the control logic and closed-loop orchestration, so as to enhance the intelligence and automation level of network management.

Liu et al [52] proposed a generic IDN paradigm, constructed a multi-level policy abstraction and resolution mechanism, and designed an intent orchestrator and a policy translation engine to support the automatic mapping of high-level business goals into configuration commands recognizable by the SDN controller. This method reduces the complexity of manual intervention, improves configuration efficiency and adaptability, and is especially suitable for dynamic tuning of policies in heterogeneous environments such as cloud computing and edge computing, etc. Jeong et al. [53] applied IDN to 5G network management, constructed an intent-based automation framework, realized closed-loop control of resources and traffic, and effectively met diversified QoS requirements.

IDN has significant advantages in enhancing network automation and flexibility, but still faces challenges such as user intent expression, accurate parsing and optimization of execution mechanism in complex environments, which is an important direction for current research.

5.Opportunities and Challenges in SDN Traffic Engineering

The widespread use of SDN in modern networks has made traffic engineering an important component in ensuring network performance, reliability, and efficiency. SDN greatly enhances traffic scheduling, optimization, and network resource provisioning by providing a flexible network management and control platform. However, while SDN offers many opportunities in traffic engineering, it also poses many challenges, especially in the face of complex network environments, dynamic traffic patterns, and changing business requirements [54][57].

5.1.Opportunities

a) Flexible traffic management. one of the biggest advantages of SDN is its centralized control architecture, which allows network administrators to control and adjust traffic paths in real time. In traditional networks, traffic engineering is often limited by the configuration of network hardware and devices, while SDN offers greater flexibility and programmability through hardware and software decoupling. With SDN

controllers, network administrators can formulate traffic policies and schedule and optimize traffic on the network in real time from a centralized control platform. This flexibility allows traffic engineering to better adapt to network topology changes and different service requirements [56].

b) Policy-based traffic optimization. SDN supports more granular traffic optimization policies through its programmable features. For example, dynamic traffic management can be performed based on various factors such as application type, traffic demand, and network state. Traffic engineering policies can be written and adjusted on the SDN controller, enabling the network to adaptively adjust to the real-time state. This policy-based traffic optimization not only improves the utilization of network resources, but also ensures that different service types (e.g., video streaming, real-time communication, etc.) can receive customized QoS [57][58].

c) Cross-domain traffic optimization. With the rise of technologies such as 5G and edge computing, the management of cross-domain traffic has become particularly important. SDN makes traffic optimization between different network domains more efficient through its centralized control platform [59]. With SDN controllers, network administrators can perform traffic scheduling and resource allocation across different network domains (e.g., data centers, carrier networks, edge networks, etc.) to optimize overall network performance. The ability to optimize cross-domain traffic is particularly important for globalized and distributed network architectures.

5.2.Challenges

a) Network size and complexity increase. Although SDN brings many advantages for traffic engineering, SDN controllers may face performance bottlenecks as the network scale increases and the topology becomes more complex. In large-scale SDN networks, controllers need to handle a large amount of traffic and dynamic network state information, which puts forward higher requirements on their computation and processing capabilities. Meanwhile, in the face of frequently changing network environments, controllers need to respond quickly and adjust paths to prevent congestion and performance degradation [60][61]. Therefore, improving the scalability and processing efficiency of SDN controllers in large-scale environments is still a key issue that needs to be addressed.

b) Security and Privacy Protection Issues. although the centralized architecture of SDN controllers improves network controllability and flexibility, it also brings security risks. Once the controller is attacked or invaded, it may lead to the paralysis of the entire network or leakage of sensitive data. Therefore, strengthening the controller's security protection, attack resistance and integrity verification of critical data are important prerequisites to guarantee the stable operation of traffic engineering [62]. Meanwhile, with the increasing emphasis on user privacy protection, how to avoid user data leakage while achieving traffic optimization has also become an important challenge.

c) Real-time and Decision Delay. Traffic engineering requires the network to have a fast response capability to cope with sudden traffic changes or failures. SDN controllers need to complete complex operations in the process of receiving data in real time, calculating the network state, formulating optimization strategies, and issuing control commands. Especially in high-load environments, the decision delay may affect the optimization effect and even cause performance degradation. Therefore, how to reduce the computational complexity and improve the response speed under the premise of ensuring the optimization effect is one of the focuses of current research.

In summary, SDN brings new opportunities for traffic engineering such as flexible traffic management, policy-driven optimization and cross-domain scheduling, but still faces many challenges in terms of network scale, complexity, real-time and security. In the future, SDN architecture and algorithm design need to be continuously optimized to enhance its scalability, reliability and security in large-scale networks. With the continuous development of related technologies, SDN will play a more critical role in traffic engineering, and how to effectively deal with the above challenges will also be an important direction of research [62].

6.Research Contributions of this Paper

This paper systematically reviews and summarizes traffic engineering on the basis of SDN, and provides in-depth analysis around reinforcement learning, deep learning and its integrated DRL method, and machine learning enhancement mechanism in optimization algorithms. The specific contributions are as follows:

Proposing a multi-dimensional technology integration perspective: this paper starts from three dimensions of DL, RL, and DRL, systematically combs through the existing research results and core algorithms, and highlights the advantages and applicability of each method in different scenarios, which provides a comprehensive reference of technical routes for the subsequent research.

Constructing a framework for combining optimization mechanisms and new architectures: Combining machine learning enhancement mechanisms with traditional optimization algorithms, we propose four fusion strategies, such as prediction enhancement, heuristic guidance, parameter adjustment, and joint modeling, which further promotes the modeling and engineering development of intelligent traffic engineering.

Explore the convergence trend of SDN and emerging network architectures: We analyze the convergence approach and latest progress of SDN with edge computing, network slicing, and IDN, demonstrate the expansion potential of SDN as the next-generation network infrastructure, and provide theoretical support for network optimization and service orchestration in multi-domain and multi-tenant scenarios.

Clarifying future research directions: Based on the overview of existing approaches, we systematically analyze the challenges of scale, latency, security, and multi-tenant QoS faced by SDN traffic engineering, and indicate key research paths such as model efficiency, heterogeneous environment adaptability, and deployment feasibility, which will help to promote further breakthroughs between academia and industry in this field.

7.Summary and Conclusions

With the continuous evolution of the network environment and the continuous growth of data traffic, SDN-based traffic engineering has become a key technical path to realize intelligent and dynamic network management. This paper reviews the SDN architecture and its application in traffic engineering, deeply analyzes the typical methods of machine learning (including DL, RL, and DRL) in path optimization, resource scheduling, and load balancing, and their convergence mechanisms, and explicitly demonstrates the important role of ML-enhanced optimization algorithms in improving network adaptability and efficiency.

Meanwhile, the article discusses the convergence trend of SDN with emerging architectures such as network slicing and intent-driven networking, and analyzes the challenges of QoS guarantee, controller scalability, and real-time decision-making capability in the future multi-domain and multi-tenant environment. It is foreseeable that with the development of intelligent algorithms and the continuous improvement of SDN control mechanisms, traffic engineering will play an even more critical role in network performance optimization, quality of service assurance and network autonomy management.

Future research can further start from the following aspects: first, to improve the real-time and generalization ability of ML models under large-scale networks; second, to strengthen the exploration of multi-policy cooperative scheduling mechanism; and third, to promote the transformation of theoretical models to the engineering deployment landing, in order to achieve a wider range of intelligent network control goals.

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CEO's Overconfidence and Firm Performance: Case in Vietnam

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Abstract. This research examines some new measurements of CEO overconfidence behavior: (1) Excessive operating cash flow surplus (cause) combined with overinvestment (manifestation) (Over1); (2) Earnings per share exceeding the same industry (Over2); (3) Overinvestment (cause) leading to Revenue Management behavior (manifestation) (Over3). In addition, the study also examines financial indicators, in which the growth of the stock index is a sign of encouragement for the overconfident behavior of CEOs, affecting efficiency. The author also considers the ownership structure that can increase or restrain the overconfident behavior of CEOs, thereby affecting the efficiency and risk of the enterprise. The results show that CEO overconfidence increases firm performance. Both state and foreign ownership have an impact on increasing performance. Stock market growth also increases performance, but especially in the context of overconfidence, it reduces performance. From the results, the author also proposes recommendations on how to control CEO overconfidence to help stabilize and increase business performance for listed companies.

Keywords. CEO's overconfidence; firm performance and companies listed in Vietnam

1. Introduction

Synthesizing studies to date shows that there are three popular methods of measuring CEO overconfidence behavior: Option-based method [1], income forecast-based method (Otto, 2014) [2], and press-based approach [3]. The press-based approach is also difficult to implement because it requires collecting personal information of each CEO on the media, in addition, there have been many recent price manipulation cases, information transparency on the Vietnamese stock market is only rated at a low average level [4]. Or the measurement method through the form of mergers and acquisitions according to Ahmad Ismail and Christos P. Mavis [5] is also difficult to measure in Vietnam because the M&A market is almost not public, and legal procedures are complicated [6]. From the above comments and summaries, it can be seen that the income method is the most effective and especially, domestic studies have not yet used this measure to consider measuring the overconfident behavior of CEOs. Therefore, the

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author will use the income-based forecasting method as a representative measure of CEO overconfidence. Using the income method to measure the overconfidence behavior of CEOs, there are currently studies in the world in two main directions: (i) Using the EPS variable, by comparing the difference between the announced plan EPS and the actual EPS such as [7]; (ii) Using earnings management behavior to measure the overconfidence behavior of CEOs, this research direction has been widespread in all three methods including: accrual-based earnings management [8].

Malmendier and Tate [1] or Sumiyana [8] argue that the source of CEO overconfidence is overinvestment. While overinvestment behavior comes from the main cause when the business has outstanding cash flow. In this study, the author uses a different method of measuring CEOs' overconfidence behavior, which represents a difference from previous studies. First, the author uses the income method based on the difference between the expected EPS and the actual EPS achieved by the company, this method is also used by previous authors such as (Sumiyana Sumiyana et al., 2023) [8] but the difference in this study is that the author calculates the value of outstanding EPS based on the sub-sector, calculated by year. The second measure the author uses in the study is based on the postulate of (Malmendier and Tate, 2005) [1] that excess cash flow is the source of overinvestment behavior, while overinvestment is a manifestation of overconfident CEOs. To reinforce the issue of whether overconfidence behavior exists or not, the author uses a combination of these two factors at the same time, meaning that a company i in year t, if it has excess cash flow accompanied by overinvestment, is considered to have an overconfident CEO behavior, in addition, the calculation by industry and by year is also different. The third measure author uses is based on the assumption and concept of CEO overconfidence behavior when he is willing to make decisions that are riskier than his ability [9]. From here, authors such as Sumiyana Sumiyana [8] have used the measure of earnings management behavior to examine CEO overconfidence behavior. But if we only consider earnings management to assign CEO overconfidence behavior or not, it is not really convincing in terms of risk, because if the company is in a good business period, the industry is in the growth stage, then earnings management is sometimes good for the company [10]. While there are also many studies that suggest that overinvestment and earnings management behavior have a close relationship [11], in this study, the author uses a combination of both earnings management and overinvestment factors, meaning that in any year t, if a business in a certain industry j simultaneously overinvests and exhibits earnings management behavior, then it is considered that there is overconfidence behavior of the CEO. Previous measures of CEO self-confidence behavior only considered indirectly through the results. In this study, the author considers both the cause and the result aspects, thus ensuring more reliability and certainty.

2. Literature Reviews

Zaludin et al [12] also showed that managers' overconfidence, internal financial resources, and corporate governance have positive effects on investment. In this study, the author used the difference between the average real earnings and the declared earnings of CEOs to measure overconfidence. Hossein Alidadi [13] studied one hundred years of companies listed on the TSE. The results showed a positive effect of the CEO's overconfidence on overinvestment. Recently, many studies have also concluded that overinvestment is a reliable indicator of CEO's overconfidence, because

when CEOs are highly confident, their behavior will orient future investment policies to maximize output [1]. Researchers have since used capital expenditure [14] and overinvestment [8] to measure CEO confidence. Mueller and Brettel [15] used a sample of German CEOs over a 10-year period to examine how CEO's overconfidence effects firm performance. Mueller et al. findings suggest that CEO's overconfidence has a negative impact on firm performance in recession. However, the authors also found that CEO's overconfidence has a positive impact on profitability in the early stages of a firm. Research by Bilicka [16] also found that managerial overconfidence (measured through the variable of overinvestment) has a positive impact on the internal financial situation and thereby improves firm performance. Vitanova [17] developed a model to explore CEO management decisions and its impact on internal governance. Vitanova presents theoretically that CEO overconfidence is also seen as a way of corporate governance that creates greater consensus among shareholders and management interests. Based on existing empirical studies (Zaludin et al [12]; Hossein Alidadi [13]), the author puts forward the research hypothesis **H1**: There is a positive correlation between CEO overconfidence and firm performance.

3. Data and Methodology

The author uses three measures of CEO's overconfidence. First, the author regresses equation (1) [18] to find firms with superior cash flow as following model:

$$\mathbf{OCF_{it} = a_0 + a_1 OCF_{it-1} + a_2 AR_{it-1} + a_3 AP_{it-1} + a_4 INV_{it-1} + a_5 DEP_{it-1} + a_6 Other_{it-1} + e_{1it}} \quad \mathbf{(1)}$$

Where:

OCF is the operating cash flow (OCF = (EBIT + Depreciation - Tax); AR is the change in receivables; AP is the change in payables; INV is the change in inventories; DEP is the depreciation; Other represents the accrual (Other = Earning – (OCF + AR + INV – AP – DEP).

Model 1 is regressed by year and industry; a company has excess cash flow when the residual e>0 and vice versa.

Next, the author calculates the overinvestment behavior of the enterprise based on the method of (Tam P.H. et al., 2024) [19]. Through regression equation (2) as follows:

$$\mathbf{Inv_{it} = b_0 + b_1 Inv_{i,t-1} + b_2 Dar_{i,t-1} + b_3 Cash_{i,t-1} + b_4 Growth_{i,t-1} + b_5 Size_{i,t-1} + b_6 Age_{i,t-1} + b_7 Ret_{i,t-1} + e_{2it}} \quad \mathbf{(2)}$$

Where:

Inv is the new investment of company i in year t, divided by total assets; Dar is the debt ratio measured as total debt to total assets; Cash is the cash holding ratio; Growth is the revenue growth rate; Size is measured as the logarithm of total assets; Age is the age of the company's listing; Ret is the dividend distribution ratio.

To strengthen the measure of overconfidence behavior, in this study, a company whose CEO has overconfidence behavior must satisfy both conditions: (i) has overinvestment and (ii) has surplus cash flow. The author assigns a value of 1. If a company satisfies both conditions, it means that the CEO at that company has overconfidence behavior. On the contrary, the CEO who does not have overconfident

behavior is assigned a value of 0. With this measurement is called the variable OC1 (**Over1**).

The second measure, author uses the regression model through the origin (RTO) according to Adelman and Watkins [20] to measure the difference between planned EPS and actual EPS achieved as follows model:

$$\mathbf{EPS_{it}} = \overline{\boldsymbol{EPS_{it}}} + \mathbf{e_{3it}} \quad \textbf{(3)}$$

The author also regresses equation (3) by industry group and year. Any enterprise with residual e3>0 shows that the income expectation exceeds others, it is assumed that the overconfident behavior of CEOs when they expected to be "better-than-average" [1]. This measure is called the **Over2** in this paper.

In addition, authors such as Sumiyana Sumiyana et al. [8] argue that CEO's overconfident will attempt to manage earnings upward. To inflate earnings, CEO's overconfident tend to increase operating cash flow and reduce production costs. This result is similar to the result of Sumiyana Sumiyana et al. [8]. Therefore, some authors also measure CEO overconfidence through earnings management behavior [8]. However, according to accounting standards and corporate law, earnings management is a legal deviation from reported economic profits. Therefore, in this study, to solidify the measure of overconfidence behavior when using pure earnings management behavior, the author uses a combination of two conditions to confirm the CEO's overconfidence behavior: both overinvestment and earnings management behavior, especially revenue management. First, the author estimates the normal cash flow from business activities by assuming the normal OCF is a linear function of revenue and change in revenue, as follows:

$$OCF_{it}/Asset_{it-1} = k_1(1/Asset_{it-1}) + k_2(Sales_{it}/Asset_{it-1}) + k_3(\Delta Sales_{it}/Asset_{it-1}) + e_{4it} \quad \textbf{(4)}$$

In there: OCF = cash flow (CF) from operating activities; Asset = Total assets; Sales = Revenue; ΔSales change in revenue this year and last year.

Abnormal CF from operations (R-OCF) = actual OCF minus normal OCF calculated from regression equation (4). In case of abnormal cash flow >0, it is coded = 1 and vice versa =0 (no earnings management). After determining whether the business has earnings management, the author combines with the enterprise with overinvestment according to equation (2), if the enterprise has both revenue management and overinvestment, it will be assigned a value of 1 (the CEO enterprise has overconfidence behavior) and vice versa, it is assigned a value of 0 (the CEO enterprise does not have overconfidence behavior). By this measurement is called the variable OC3 (Over3).

Model for assessing the impact of overconfidence on firm performance:

Model 1: $\mathbf{ROA}_{it} = \beta_0 + \beta_1 Over1_{it} + \beta_2 FO_{it} + \beta_3 SO_{it} + \beta_4 D\text{-}income_{it} + \beta_5 Stock\text{-}growth_{it} + \beta_6 CEO\text{-}Ownership_{it} + \beta_7 Size_{it} + \beta_8 Age_{it} + \beta_9 Growth_{it} + \beta_{10} Lev_{it} + \beta_{11} Liq_{it} + \beta_j \sum_{j=1}^{7} Indus_j + u_{it}$ **(5)**

Model 2: $\mathbf{ROA}_{it} = \beta_0 + \beta_1 Over2_{it} + \beta_2 FO_{it} + \beta_3 SO_{it} + \beta_4 D\text{-}income_{it} + \beta_5 Stock\text{-}growth_{it} + \beta_6 CEO\text{-}Ownership_{it} + \beta_7 Size_{it} + \beta_8 Age_{it} + \beta_9 Growth_{it} + \beta_{10} Lev_{it} + \beta_{11} Liq_{it} + \beta_j \sum_{j=1}^{7} Indus_j + u_{it}$ **(6)**

Model 3: $\mathbf{ROA}_{it} = \beta_0 + \beta_1 Over3_{it} + \beta_2 FO_{it} + \beta_3 SO_{it} + \beta_4 D\text{-}income_{it} + \beta_5 Stock\text{-}growth_{it} + \beta_6 CEO\text{-}Ownership_{it} + \beta_7 Size_{it} + \beta_8 Age_{it} + \beta_9 Growth_{it} + \beta_{10} Lev_{it} + \beta_{11} Liq_{it} + \beta_j \sum_{j=1}^{7} Indus_j + u_{it}$ **(7)**

Performance variables are used in the model; the author uses measures by ROA. The industries selected for this study include: (1) IT (industry-benchmark), (2) industrial production (CN), (3) medical & pharmaceutical (YD), (4) consumer (HHDV), (5) materials (NVL), (6) real estate (BĐS) (7) information and communication (TT). Data collected from non-financial listed companies from 2012-2022.

4. Results and Discussion

Table 1. Descriptive results of variables

Variables	Obs	Min	Medium	Max	Std	Max
ROA	5,543	-0.62	0.06	0.84	0.08	0.84
SO	5,543	0.00	0.23	0.99	0.25	0.99
FO	5,543	0.00	0.09	0.95	0.14	0.95
D_income	5,543	0.00	0.09	0.49	0.14	0.49
Stockgrowth	5,543	-0.33	0.11	0.48	0.21	0.48
CEO_Owner	5,543	0.000	1.67	56.48	4.74	56.48
Size	5,543	23.33	27.39	33.99	1.59	33.99
Age	5,543	5.00	9.26	23.00	3.97	23.00
Growth	5,543	-1.00	0.31	244.45	4.27	244.45
Lev	5,543	0.001	0.48	1.37	0.22	1.38
Liq	5,543	0.03	2.66	146.92	4.66	146.92

Source: Author's calculation

Table 1 presents the results describing the variables (excluding variables with binary values 0 and 1). The ROA variable has an average value of 5.89%. Regarding ownership structure, it shows that state ownership accounts for an average of 22.58%, foreign ownership averages 9.88%, a fairly low rate even though Vietnam has allowed an increase in the ownership rate of foreign investors. The level of income diversification is still quite low, reaching only 0.09 (this value is calculated according to DINC = 1- HHI Index). The average market growth index is 10.86%, while in the decline period it is -33.24%, showing that this index has strong fluctuations. Regarding the ownership ratio of the CEO, the average holding ratio of the CEO is 1.67%, especially in enterprises where the CEO does not hold shares (0%), the highest ratio is 56.48% belonging to major shareholders with controlling rights. The control variables such as age, size, revenue growth, leverage and liquidity have mean values of 9.26; 27.38; 31.43%; 0.47 and 2.65 respectively.

Table 2. Quantitative results of the impact of overconfidence on firm performance

Variables	Model1		Model2		Model3	
	Pool-OLS	GMM	Pool-OLS	GMM	Pool-OLS	GMM
Over1	0.012*	0.012*				
Over2			0.042*	0.042*		
Over3					0.001	0.0006
SO	0.037*	0.035*	0.041*	0.039*	0.038*	0.035*
FO	0.062*	0.059*	0.042*	0.04*	0.062*	0.06*
D_Income	-0.007	-0.01	-0.006	-0.008	-0.007	-0.01
Stockgrowth	0.006	0.005	0.009**	0.008**	0.006	0.005
CEO_Owner	0.001*	0.0006**	0.0005*	0.0006*	0.0005*	0.0006**
Size	0.005*	0.005*	0.005*	0.004*	0.005*	0.005*
Age	-0.001*	-0.001*	-0.001*	-0.001*	-0.001*	-0.001*
Growth	0.001***	0.001**	0.0005	0.0005	0.001**	0.001**
Lev	-0.1398*	-0.121*	-0.1468*	-0.129*	-0.14*	-0.122*
Liq	-0.0003	-0.0001	-0.0003	-0.0001	-0.0003	-0.0001
BDS	-0.016**	-0.018*	-0.017*	-0.02*	-0.017**	-0.019*
CN	0.006	0.002	0.004	0.0001	0.005	0.002
YD	0,014	0.014	0.01	0.009	0.013	0.014
HHDV	0.013**	0.011**	0.01***	0.007	0.013**	0.011***
NVL	0.009	0.007	0.007	0.005	0.009	0.007
TT	0.013***	0.011	0.006	0.003	0.013**	0.01
Const	-0.033	-0.023	-0.035***	-0.025	-0.036***	-0.026

Source: Author's calculation (*); (**); (***) corresponding to significant levels of 1%; 5% and 10%

Table 2 shows the quantitative results of the impact of CEO overconfidence behaviors with other variables on book performance (ROA). The results of the three measures of CEO overconfidence behavior (Over1, Over2 and Over3) all show a positive impact on performance, in addition, both Pool-OLS and GMM methods show high agreement in research results. These results are consistent with the stated hypothesis H1. These results demonstrate the consistency and robustness of the measured variables and the research model. First, CEO overconfidence behavior measured by overinvestment (Overinvest) combined with cash flow (Over1) and excess earnings (Over2) all have positive impacts on book and market performance when considering statistically significant variables in both cases without considering interactions and considering interaction effects. This result is also consistent with the heuristic theory of Kahneman and Tversky [21] when it is assumed that the judgment of results based on patterns that have occurred in the past is highly representative, and past data has a great influence on decisions. This result is also consistent with the research results of Sumiyana Sumiyana

et al [8]. However, if CEO overconfidence caused by earnings management behavior through revenue management combined with overinvestment measured by (Over3) also has a positive effect on firm performance. When listed companies are public companies, they are subject to the control of many stakeholders, requiring transparency of information and other related reports. Therefore, confident behavior to create biased values beyond normal regulations or standards is easily recognized and will be monitored by more stakeholders or when the company is in a good business period, the industry is growing, then earnings management behavior is sometimes good for the company (Deepak Verma et al) [22].

The stock index growth variable has a positive and statistically significant effect. When the market grows, it shows a good economic situation, good prospects for business and industry development, investors expect higher growth and business valuation, so it has a positive effect on efficiency, especially market efficiency [23]. On the other hand, when the stock market is growing, the possibility of falling prices creating high returns will stimulate CEOs to make investment decisions but will cause poor performance [24]. The positive impact of state-owned enterprises on firm performance is due to the "helping hand" and "monitoring role" of the government. Foreign ownership variables both have positive and significant effects on book return (ROA) and market return. The reason why foreign ownership has a positive impact on efficiency is because of the contribution of foreign investors in many aspects such as management experience, investment experience, etc. Overconfident behavior under the regulation and control of foreign investors in this case has a positive impact on efficiency, thanks to their valuable contributions, thereby helping to improve business efficiency for enterprises. Income diversification variable exists inversely with efficiency. In addition, this result also holds when considering the interaction effect of diversification on overconfidence behavior. This result also supports the research results of Lim CY et al [25]. The results support the theory of economies of scale, when the impact of company size is positive and statistically significant, meaning that increasing scale will reduce cost issues, increasing efficiency. Revenue growth variable has a positive and statistically significant effect on performance [26]. This helps the company develop production and business activities, accumulate reinvestment capital and increase business efficiency. Regarding the impact of industry on book value added (ROA), the results show that real estate enterprises are less efficient than the standard industry (IT) and even other industries. Real estate is a special industry; it is not only an investment for profit but also a scarce investment asset. In addition, the results also show that businesses operating in the fields of pharmaceuticals, healthcare, industrial production; consumer goods and services are more effective than other industries.

5. Conclusion and Recommendation

Regarding the impact of Over variables on efficiency, the results are consistent in showing that the measures of overconfidence due to excess cash flow combined with overinvestment conditions (Over1), excess earnings compared to the industry (Over2) and overinvestment combined with revenue management have a positive (+) impact on efficiency measured by ROA. The surplus cash flow estimation equation (equation 1) shows that the calculation model is based on the time lag from the business results of the previous year, so when a business has surplus cash flow, it not only happens in the current year but also the good operating results of previous years. Therefore, although

surplus cash flow creates a confident mentality and also stimulates overinvestment, if this behavior is defended by the cash flow from business activities considered stable in previous years, it will contribute to increasing efficiency. Therefore, if a business has a continuous surplus operating cash flow, and decides to overinvest, causing the CEO to be overconfident also creates a positive signal in improving efficiency. These results show that when a CEO has overconfident behavior, it is necessary to check whether the cash flow is surplus or whether the income is reliably superior or not. If the causal conditions are not satisfied, the CEO's overconfident behavior not only does not increase efficiency but can also create risks for the business.

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Estimating Electromagnetic Wave Velocity for GPR Based on Velocity Scanning and Migration Imaging Techniques

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Abstract. Ground penetrating radar (GPR) is an important geophysical technique used in near-surface exploration to map subsurface features based on their dielectric properties. Accurate estimation of electromagnetic wave velocity plays a critical role in GPR data processing and result interpretation. This paper presents an electromagnetic wave velocity estimating method based on velocity scanning and migration imaging techniques. A velocity scanning range is set based on the initial electromagnetic wave velocity calculated from the hyperbolic geometry of the GPR image. This method performs the migration and binarization imaging for each velocity in the scanning range, and obtains the energy focusing index (EFI) that measures the imaging effect. The velocity that minimizes the EFI in the scanning range is the optimal one.

Keywords. GPR detection, Velocity estimation, Velocity scanning, Migration imaging, Binarization imaging.

1. Introduction

Ground penetrating radar (GPR), characterized by high efficiency, convenience, high resolution and non-destructiveness, has been extensively utilized in near-surface geological investigations [1-3].

Electromagnetic wave velocity estimation plays a critical role in GPR synthetic aperture imaging and subsurface anomaly localization. Electromagnetic wave velocities are usually calculated based on empirical permittivity constants, which leads to low accuracy in localizing anomalies. In scenarios requiring enhanced detection precision, electromagnetic wave velocity can be determined based on hyperbolic reflection signatures present in GPR image data [4-7]. However, this method requires high-quality data and is highly susceptible to operator bias. Nagashima et al. (1993) developed an image edge detection-based methodology for automated extraction and fitting of hyperbolic radar echoes, reducing operator bias in velocity estimation [8]. Toru (1991)

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pioneered the application of Hough transforms to GPR image for electromagnetic wave velocity estimation in early studies, but the method exhibits low computational efficiency and limited noise robustness [9]. The data processing methods for GPR exhibit substantial similarities to those used in seismic exploration. Several well-established techniques from seismic exploration—including migration imaging and velocity estimation methods—can be effectively adapted for GPR data processing [10-12]. Velocity spectrum analysis method is commonly used in seismic data processing to estimate the velocity of seismic waves, which can be used in seismic exploration and GPR common midpoint (CMP) data processing analysis, can also be applied to the common offset (CO) data processing [13]. The principle involves postulating a series of trial velocities and calculating the coherence of signals at different offsets or channels using hyperbolas determined by these trial velocities. The coherence values are then stacked and plotted in a velocity versus two-way vertical travel-time diagram, forming a velocity spectrum. Velocity spectra are imaged for a series of trial velocities in a process called velocity scanning. When a trial velocity approximates the true velocity, the stacked energy exhibits a peak in the velocity spectrum. Consequently, both the hyperbolic reflection velocity and two-way vertical travel-time can be extracted from the velocity spectrum [14-16]. However, field-acquired data often contain noise and errors, which can lead to mispositioning of energy peaks in velocity spectra during velocity scanning, thereby reducing the accuracy of velocity analysis. To mitigate this issue, this study introduces an improved approach: during velocity scanning, the migrated image is further converted into a binarized image, and an energy focusing index (EFI) is defined to measure the imaging quality. Instead of directly detecting energy peaks (maximum value) in the velocity spectrum, the method locates the troughs (minimum value) of the EFI, significantly enhancing the accuracy of velocity scanning results.

In the proposed method, we firstly obtain an initial electromagnetic wave velocity based on hyperbolic geometry analysis of the GPR image. Subsequently, a velocity scanning range is established using this initial estimated velocity. For each velocity within the scanning range, the following steps are performed: (1) migration imaging, (2) binarization imaging, and (3) EFI calculation. The velocity corresponding to the minimum EFI is ultimately determined as the final result of this method.

This study utilizes the finite-difference time-domain (FDTD) method to simulate GPR data [17-18]. In the synthetic example, the processing workflow is clearly demonstrated, and the velocity calculated by the method closely approximates the preset velocity. In field-acquired data application, the detected depth of the anomaly shows high agreement with the actual measured depth, confirming the method's validity for practical applications.

2. Methodologies

2.1 Hyperbolic geometry analysis

A region with distinct hyperbolic characteristics is selected in a typical GPR image (Fig. 1), where the horizontal axis represents the antenna position along the survey line and the vertical axis represents the two-way travel time. Point (x_0, t_0) represents the coordinates of the hyperbola's vertex, while points (x_1, t_1) and (x_2, t_2) represent the coordinates of the reflection points. The burial depth of the reflector is *h*, the

electromagnetic wave velocity is v_0, and the time error between the picked time and the true travel time, arising from system latency and vacuum propagation delay, is denoted as t_s.

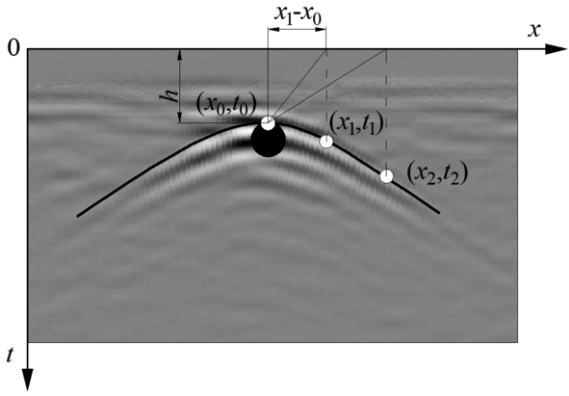


Fig. 1. Schematic diagram of electromagnetic wave velocity determination based on geometric characteristics of GPR reflections.

When the GPR device is positioned directly over the reflector, the following condition is satisfied:

$$h = v_0 * (t_0 - t_s) / 2 \tag{1}$$

The geometric relationship between points (x_0, t_0), (x_1, t_1) and (x_2, t_2) satisfies the following conditions:

$$h^2 + (x_1 - x_0)^2 = (v_0 * (t_1 - t_s) / 2)^2 \tag{2}$$

$$h^2 + (x_2 - x_0)^2 = (v_0 * (t_2 - t_s) / 2)^2 \tag{3}$$

By substituting Eq. (1) into Eq. (2) and Eq. (3), and then rearranging the terms, the following relationships are derived:

$$\frac{4(x_1 - x_0)^2}{v_0^2 (t_1 - t_0)} = t_1 + t_0 - 2t_s \tag{4}$$

$$\frac{4(x_2 - x_0)^2}{v_0^2 (t_2 - t_0)} = t_2 + t_0 - 2t_s \tag{5}$$

By subtracting Eq. (5) from Eq. (4), the variable t_s is eliminated, and the resulting equation can be rearranged to express v_0 as follow:

$$v_0 = 2 \left| \frac{(x_1 - x_0)^2}{(t_1 - t_0)(t_1 - t_2)} - \frac{(x_2 - x_0)^2}{(t_2 - t_0)(t_1 - t_2)} \right|^{1/2} \tag{6}$$

2.2 Migration imaging

The GPR waveform data is denoted as $u(x, z=0, t)$ in this study, where x is the antenna position, t is the two-way travel time, and z is the depth below the ground surface (z is fixed to zero, since the antenna is moved on the ground). This paper employs the F-K (frequency-wavenumber) transform for migration imaging [19], with the primary steps outlined as follows:

(1) Perform a two-dimensional fast Fourier transform (2D FFT) on $u(x, z=0, t)$ along the spatial (x) and temporal (t) axes, yielding the transformed result $U(k_x, z=0, \omega)$.

$$U(k_x, z=0, \omega) = \iint u(x, z=0, t) e^{-jk_x x} e^{-j\omega t} dx dt \tag{7}$$

$$\omega = \frac{v}{2}\sqrt{k_x^{\,2} + k_z^{\,2}} \tag{8}$$

where ω represents the angular frequency, v represents the electromagnetic wave velocity, k_x and k_z represent the wavenumber along the x-direction and z-direction, respectively.

(2) Perform z-direction extrapolation on $U(k_x, z=0, \omega)$, yielding the transformed result $U(k_x, z, \omega)$.

$$U(k_x, z, \omega) = U(k_x, z=0, \omega) e^{jk_z z} \tag{9}$$

(3) Perform a 2D inverse fast Fourier transform (IFFT) on $U(k_x, z, \omega)$, yielding the transformed result $u(x, z, t)$.

$$u(x, z, t) = \frac{1}{(2\pi)^2} \iint U(k_x, z, \omega) e^{j(k_x x + \omega t)} dk_x d\omega \tag{10}$$

(4) Substitute Eq. (8) into Eq. (10), set the time variable t to zero, and solve for the migrated result $u(x, z, t=0)$.

$$u(x, z, t=0) = \frac{1}{(2\pi)^2} \iint \frac{v}{2} \frac{k_z}{\sqrt{k_x^{\,2} + k_z^{\,2}}} U(k_z, z=0, \frac{v}{2}\sqrt{k_x^{\,2} + k_z^{\,2}}) e^{jk_z z} e^{jk_x x} dk_x dk_z \tag{11}$$

2.3 Binarization imaging

The preset velocity has a significant impact on migration imaging results. To intuitively evaluate the imaging quality, this study applies binarization imaging to the migrated images, obtaining binarized images [20-21]. The main steps are as follows:

(1) Compute the mean energy $\overline{u}$ of the migrated image.

$$\overline{u}(x, z, t=0) = \sum_{x,z}^{M,N} u(x, z, t=0) / (M * N) \tag{12}$$

where M and N denote the number of points in the x-direction and z-direction, respectively.

(2) Compare the image energy values with a predefined threshold to obtain a binarized image u', where values are classified as 1 (foreground) if their energy exceeds the threshold, and 0 (background) otherwise.

$$u'(x,z,t=0)=\begin{cases}1, u(x,z,t=0)\geq \alpha * \overline{u}\\ 0, u(x,z,t=0)<\alpha * \overline{u}\end{cases} \tag{13}$$

where α denotes the threshold factor, typically selected within the range [0.6, 0.9], and is set to 0.8 in this paper.

(3) Compute the energy focusing index (EFI, f) for a binarized image to evaluate its migration imaging quality.

$$f=\sum_{x,z}^{M,N} u'(x,z,t=0)/(M*N) \tag{14}$$

2.4 Velocity scanning

This study utilizes the electromagnetic wave velocities derived from hyperbolic geometry analysis as a reference to define a velocity scanning range, and the main steps are defined as follows:

(1) Compute the initial relative permittivity (ε_r^0) via the initial velocity (v_0) and the vacuum light velocity (c).

$$\varepsilon_r^0=(\frac{c}{v_0})^2 \tag{15}$$

(2) Compute the relative permittivity scanning range.

$$\varepsilon_r \in [\varepsilon_r^0-\beta, d\varepsilon, \varepsilon_r^0+\beta] \tag{16}$$

where β denotes the half-scan length, typically selected within the range [3, 5]; $d\varepsilon$ denotes the scan step, typically selected within the range [0.1, 0.5].

(3) Compute the scanning velocities.

$$v=\frac{c}{\sqrt{\varepsilon_r}} \tag{17}$$

For each trial velocity within this range, migration imaging, binarization imaging and EFI calculation will be performed, and the velocity with the minimum EFI will be the optimal velocity solved by this method.

3. Synthetic example

To present the processing procedure of the proposed method in detail, this study established a forward model, and obtained the forward GPR waveform data through the FDTD method [17-18]. The geoelectrical model is shown in Fig. 2, the main parameters

of the numerical simulation are shown in Table 1, and the corresponding GPR forward modeling image is shown in Fig. 3.

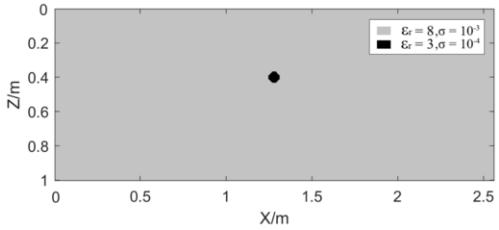


Fig. 2. Geoelectrical model for GPR forward modeling. The relative permittivity (ε_r) of the background medium is 8, and that of the anomaly is 3. The conductivity (σ) of the background medium is 10^{-3}, and that of the anomaly is 10^{-4}.

Table 1. Parameters of the numerical simulation.

Parameter	Value	Unit
Main frequency	9×10^{8}	Hz
Spatical grids	nx = 512, nz = 200	-
Space step	dx = dz = 0.005	m
Time number	nt = 1024	-
Time step	$dt = 2\times10^{-11}$	s
Absorbing layer	Lx = 10×dx, Lz = 10×dz	-
Relative permittivity	background: 8, anomaly: 3	-
Conductivity	background: 10^{-3}, anomaly: 10^{-4}	S/m
Permeability	$4\pi\times10^{-7}$	H/m

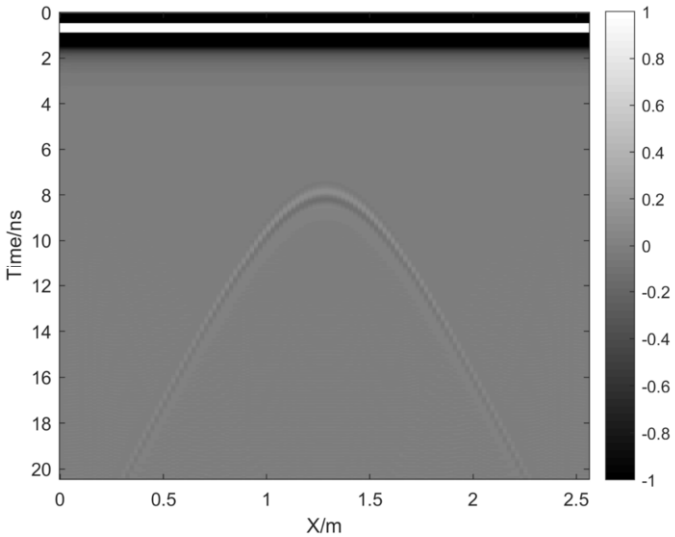


Fig. 3. Original GPR image. Gray-scale image converted from forward modeling waveform data.

As can be seen from Fig. 3, the surface air-wave reflections exhibit notably strong energy (with travel times less than 1.8 ns), thereby attenuating the energy of reflections from deep-seated anomalies. To enhance the visibility of deep-seated anomaly reflections, this study applied a surface-wave suppression procedure to eliminate dominant near-surface reflections, and the processed GPR image after suppression is illustrated in Fig. 4.

In addition, three additional reflection points were introduced in Fig. 4 following the methodology outlined in Section 2.1. The coordinates of the three introduced points are as follows: $P_0(1.28, 7.79)$, $P_1(0.82, 11.65)$ and $P_2(1.78, 12.22)$. The electromagnetic wave velocity (v_0) calculated using Eq. (6) is 0.1065 m/ns. The vacuum light velocity (c) is 0.3 m/ns, and the theoretical relative permittivity (ε_r) is 8. Therefore, the theoretical electromagnetic wave velocity calculated using Eq. (17) is 0.1061 m/ns. The close agreement between the theoretical electromagnetic wave velocity and the hyperbolic-geometry-derived velocity demonstrates the robustness of the proposed method.

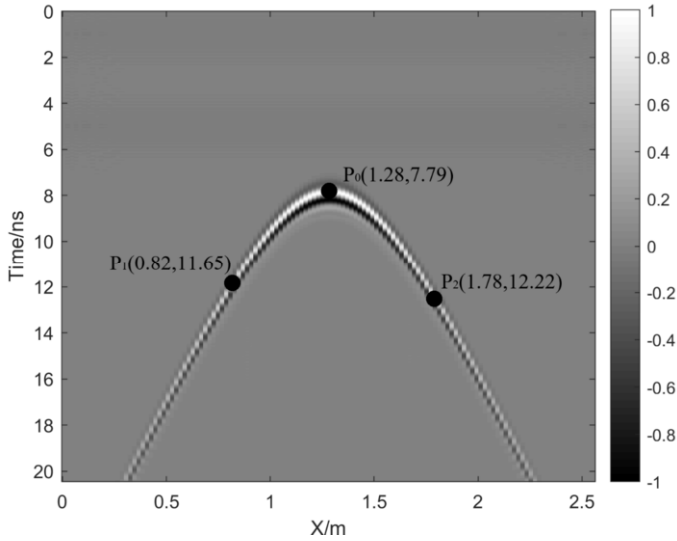


Fig. 4. Three typical reflection points selected from the original GPR image with surface reflection waves suppressed.

This study subsequently established a scanning range of [4, 13] and a step increment of 0.25 for relative permittivity (ε_r), sequentially testing each value within the range. For each trial value (applied to velocity calculation), we executed migration imaging, binarization imaging, and EFI computation, yielding the EFI variation curve shown in Fig. 5. The relative permittivity (ε_r) corresponding to the minimum EFI in Fig. 5 is 8, which matches the theoretical value, thereby validating the accuracy of the proposed method.

When the trial velocity is equal to the true velocity ($\varepsilon_r = 8$), the migrated image concentrates energy primarily at the true reflector position, yielding a well-focused binarized image and a low EFI ($f = 0.00052$), as demonstrated in Fig. 6.

When the trial velocity is lower than the true velocity ($\varepsilon_r = 10$), the migrated image's energy diverges downward from the true reflector position, resulting in a downward-diverging binarized image and an elevated EFI ($f = 0.00168$), as demonstrated in Fig. 7.

When the trial velocity is higher than the true velocity ($\varepsilon_r = 6$), the migrated image's energy diverges upward from the true reflector position, resulting in an upward-diverging binarized image and an elevated EFI ($f = 0.00334$), as demonstrated in Fig. 8.

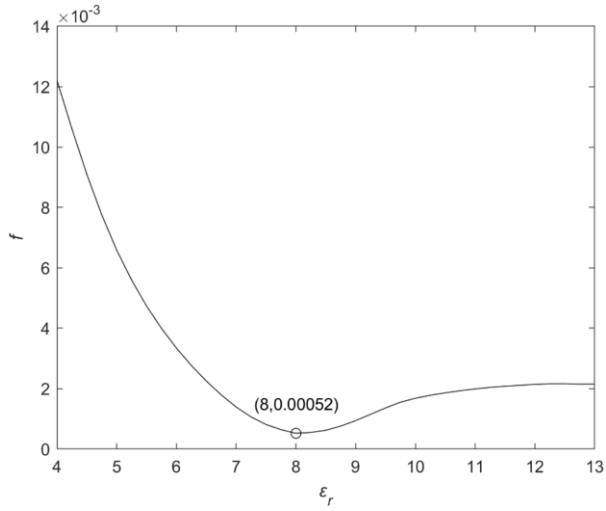


Fig. 5. Curve of EFI variation with relative permittivity for velocity scanning. The minimum EFI (f) is 0.00052, and the corresponding relative permittivity (ε_r) is 8.

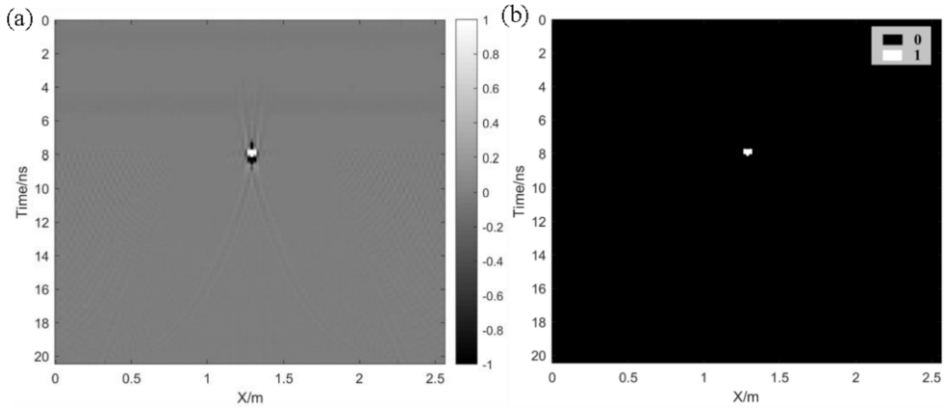


Fig. 6. Migrated and binarized images when the trial velocity is equal to the true velocity. (a) is the migrated image, (b) is the corresponding binarized image.

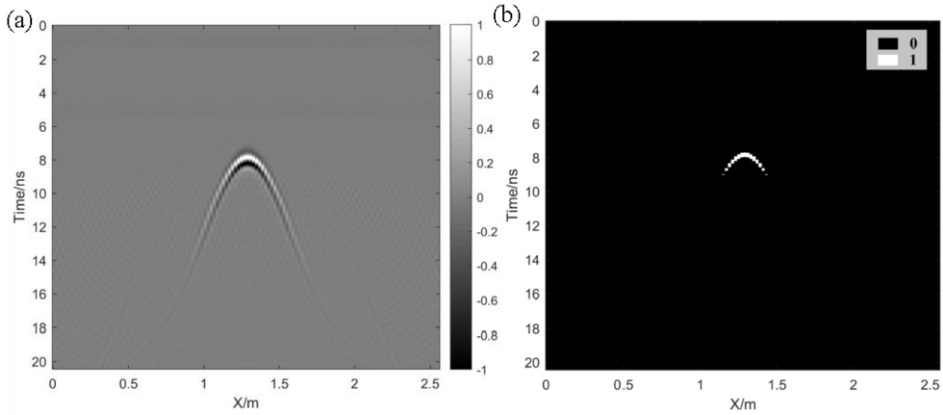


Fig. 7. Migrated and binarized images when the trial velocity is lower than the true velocity.

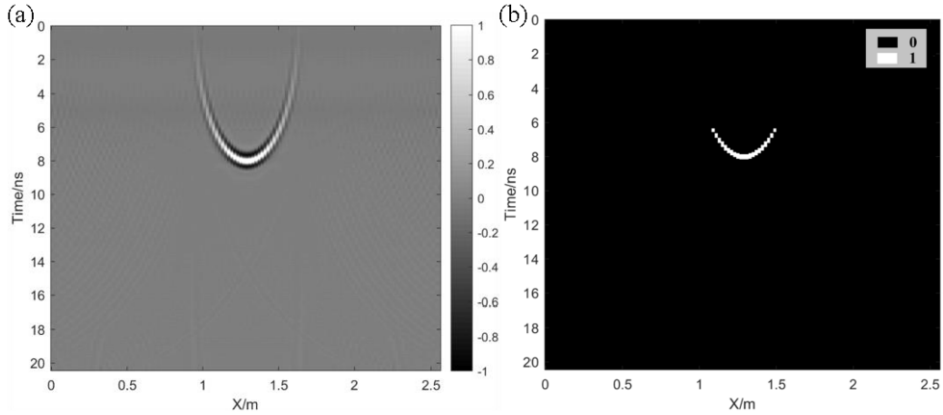


Fig. 8. Migrated and binarized images when the trial velocity is higher than the true velocity.

4. Field example

To further test the applicability of this method with actual measured data, this study conducted GPR data collection and processing in a field setting. The survey area consisted of a homogeneous clay formation, with a buried 0.1-meter diameter polyethylene water pipe at a depth of approximately 0.7 meters. This study employed a GPR system with a center frequency of 400 MHz, and the antenna was dragged perpendicular to the water pipe orientation during data acquisition.

The GPR image with removed air-wave reflections is presented in Fig. 9(a). The variation curve of EFI over the relative permittivity scanning range of [6, 16] is depicted in Fig. 9(b). The migrated and binarized images corresponding to the minimum EFI are presented in Fig. 9(c) and (d), respectively.

In Fig. 9(b), the relative permittivity corresponding to the minimum EFI is 12.25, and the electromagnetic wave velocity calculated based on Eq. (6) is 0.0857 m/ns. The two-way travel time of the anomaly in Fig. 9(d) is 16.91 ns, yielding a water pipe burial depth

of 0.72 m. This result closely matches field measurements, demonstrating the accuracy and effectiveness of the proposed method.

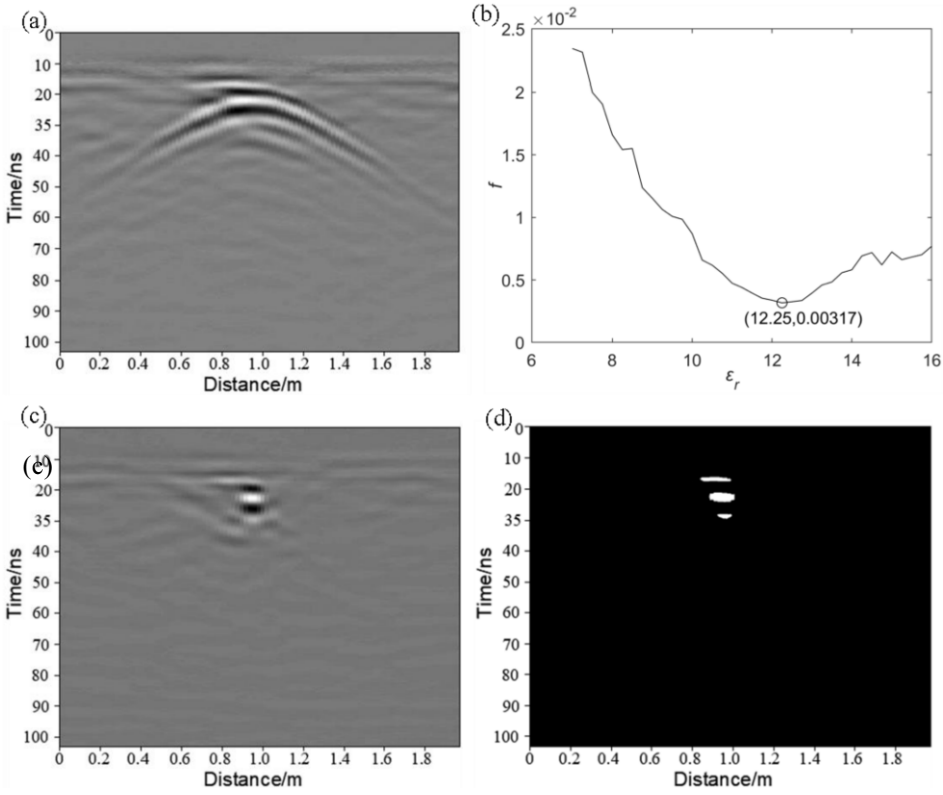


Fig. 9. Velocity estimation results of the field GPR data. (a) is the raw image of the field data, (b) is the EFI curve of velocity scanning, (c) and (d) are the migrated and binarized images, respectively.

5. Conclusions

This study proposes a GPR electromagnetic wave velocity estimation method based on migration imaging and velocity scanning. The primary steps include: (1) estimating an initial velocity from hyperbolic geometry of the raw GPR image, (2) defining a velocity scanning range and performing migration imaging, binarized imaging, and EFI calculation for each trial velocity, and (3) identifying the trial velocity corresponding to the minimum EFI as the estimated electromagnetic wave velocity. To elucidate the procedural details of the proposed method, this study simulated GPR data using the FDTD method, and visualized the evolution of the EFI during velocity scanning. This study demonstrated the migrated and binarized images for trial velocities that were approximate, underestimated, and overestimated relative to the true velocity. These examples collectively illustrate the method's sensitivity to velocity perturbations and its capability to converge toward the optimal solution. This method accurately retrieved the true electromagnetic wave velocity in the synthetic and field examples, validating its effectiveness and practicability in practical engineering implementations.

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The Impact of Climate Risks on Corporate Mergers and Acquisitions in Heavy-Pollution Industries

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Abstract. This study examines the impact of climate risk on corporate merger and acquisition (M&A) decisions, using a sample of A-share listed firms in heavily polluting industries in China from 2016 to 2023. The findings reveal two key insights: First, climate risk significantly increases the likelihood of firms undertaking M&As, and this result holds after robustness checks. Second, government environmental subsidies strengthen the positive effect of climate risk on M&A activity. We therefore propose two policy actions. Firms should recognise the positive link and use acquisitions as a key response when climate risk rises. Governments should adopt rule-based environmental subsidies that allocate funds according to measurable climate performance to deter symbolic acquisitions. The study provides empirical evidence for corporate strategy and targeted environmental regulation under climate transition.

Keywords. Climate Risk Corporate; Mergers and Acquisitions; Government Environmental Subsidies

1. Introduction

With the rapid development of the global economy, rising temperatures and the increasing frequency of extreme weather events caused by human activities have become undeniable facts. Over the past four decades, the occurrence of disasters such as floods and droughts has quadrupled, with insured losses from extreme weather in 2024 alone reaching a record high. To address this systemic challenge, governments worldwide have introduced mandatory ESG disclosure regulations—for instance, the ISSB's IFRS S1/S2 standards in 2023, which identify climate risk as a core disclosure requirement. Heavily polluting industries, characterized by high emissions and energy consumption, are particularly vulnerable. The power sector, responsible for nearly 40% of global carbon emissions, faces direct threats from extreme weather, which can damage raw materials, equipment, and infrastructure. Meanwhile, corporate development in Western economies has undergone four major waves of mergers and acquisitions (M&As) since the late 19th century, reflecting strategic adaptations in modern business. Recently, Chinese firms have also shown rising M&A activity in Belt and Road Initiative (BRI) regions and emerging markets. Lu et al. (2021) found that polluting firms significantly increase environmental investments through green M&As

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[1]. M&As enable firms to consolidate resources, optimize supply chains, and achieve economies of scale, making them a key strategy for mitigating climate risks. However, existing research has paid limited attention to how climate risk influences M&A decisions in heavily polluting industries. This study fills this gap by examining the impact of climate risk on corporate M&As in China's high-pollution sectors. Our findings provide critical insights for both managerial strategy and environmental policy, justifying the significance of this research.

2. Related works

Climate risk significantly impacts corporate management. Liu (2025) demonstrated that increased climate risk awareness substantially improves corporate ESG performance [2]. Guo et al. (2025) examined the impact of climate change on Chinese firms' performance, revealing that meteorological disasters significantly reduce corporate performance [3]. Regarding M&A research, Linan et al. (2023) investigated how CEO narcissism affects acquisition decisions, finding that executive personality traits and equity incentives influence M&A behavior [4]. Yang et al. (2024) showed that when firms in an industry face environmental penalties, their peers tend to increase green M&A activities [5]. Guangrui et al. (2023) found that polluting firms are more likely to pursue (or avoid) green M&As when investors assign higher (lower) premiums to such deals [6]. Current research remains limited in examining M&A behavior and its implications for heavily polluting industries facing climate risks. This study addresses this gap and provides empirical evidence to inform policy-making.

3. Research Design

3.1 Sample Selection and Data Sources

This study examines 1,027 A-share listed companies in heavily polluting industries on the Shanghai and Shenzhen stock exchanges from 2016 to 2023. After excluding ST/*ST firms and observations with missing key variables, the final dataset comprises 6,320 valid firm-year observations. We measure climate risk using a text-based analysis of corporate annual reports. Firm-level financial and governance data are sourced from the CSMAR database.

3.2 Variable Definitions

Independent Variable: Climate Risk. Following Jian et al. (2020), we construct a climate risk dictionary containing 98 keywords (e.g., "earthquake," "typhoon," "rainfall," "water level," "solar energy") [7]. We calculate the frequency of these terms in annual reports and normalize them by the total word count to derive our climate risk index. A higher value indicates greater climate risk exposure.

Dependent Variable: Corporate M&A. If a sample firm engaged in M&A during the year, it was assigned a value of 1; otherwise, it was assigned a value of 0.

Control Variables: Control variables were divided into two categories: board-level and financial-level variables. Details are shown in Table 1.

Table 1. Variable Definition Table

Category	Variable	Measurement methods
dependent variable	MAD	Binary dummy variable: Take 1 if a merger occurs in the current year and 0 if no merger occurs
independent variable	CR	Climate risk CR keyword frequency/total number of MA&D sections
Moderating variables	GES1	Government environmental subsidy plus one, taking the natural logarithm
Control variables	SIZE	The natural logarithm of a company's total assets at the end of the year
	LEV	Total liabilities/total assets of the enterprise at the end of the year
	ROE	The ratio of a company's net profit at the end of the year to its average net assets
	Growth	(Current period revenue - previous period revenue)/ previous period revenue
	Cashflow	Net cash flows from operating activities/total assets
	Top10	The combined shareholding ratio of the top ten shareholders
	Board	Total number of board members

4. Empirical Results

4.1 Descriptive Statistics

As shown in Table 2, the mean value of climate risk (CR) is 0.233 with a standard deviation of 0.237, indicating significant cross-firm variation in climate risk exposure. The maximum value reaches 1.186, suggesting some firms face risk levels five times higher than the average. For merger and acquisition decisions (MAD), the mean is 0.216 (SD = 0.411), reflecting an asymmetric distribution consistent with the infrequent and heterogeneous nature of industry M&A events. Only selected control variables are reported.

Table 2. Descriptive Statistical Results

Variables	N	Mean	Sd	Min	Max
CR	6320	.233	.237	0	1.186
MAD	6320	.216	.411	0	1
SIZE	6320	22.493	1.414	18.127	26.366

4.2 Baseline Regression Results

Table 3 presents the baseline regression results. The coefficient of CR is positive and statistically significant at the 5% level, indicating that climate risk has a significantly positive effect on corporate M&A decisions. Specifically, higher climate risk exposure increases the likelihood of firms engaging in M&A activities. This occurs because climate risk erodes competitive advantage, intensifies financing constraints and tightens environmental regulation, thereby compelling high-polluting firms to acquire green resources rapidly, circumvent regulatory penalties and restore market confidence through mergers and acquisitions, generating a positive feedback loop in which higher

risk strengthens acquisition incentives. This paper only reports selected control variables' regression coefficients.

Table 3. Benchmark regression results of climate risk on corporate mergers and acquisitions

Explanatory variables	MAD
CR	0.410 * *
	(2.194)
SIZE	0.069*
	(1.725)
ROE	0.015***
	(3.914)
Growth	0.003**
	(2.245)
Constant	1.727 * *
	(-2.014)
Observations	6320
R2	0.012

Note: The t-statistics are in parentheses, ***p<0.01, **p<0.05, *p<0.10

4.3 Robustness Tests

(1) Alternative Dependent Variable

We replace the dependent variable with M&A deal value (MAamount). As shown in Column (1) of Table 4, the coefficient of climate risk (CR) remains positive and statistically significant at the 5% level, indicating a significant positive impact on M&A deal values. These findings indicate that climate risk significantly influences both the decision to undertake M&A and the amount invested, thereby enhancing the reliability and persuasiveness of our results.

(2) Exclusion of Pandemic Period

After excluding data from the COVID-19 pandemic period (2020-2022), the results presented in Column (2) of Table 4 show that climate risk maintains its positive and statistically significant (at 5% level) effect on M&A decisions. This further strengthens the reliability of our findings, confirming that the results are not driven by the COVID-19 period.

Table 4. Robustness Test Results

Explanatory variables	(1)Alternative Dependent Variable	(2)Exclusion of Pandemic Period
	MAamount	MAD
CR	1.68e+08**	0.547**
	(2.117)	(2.279)
Controls	Yes	Yes
Constant	7.34e+08	-0.348
	(0.769)	(-0.314)
Observations	6320	3722
R2	0.011	0.009

Note: The t-statistics are in parentheses, ***p<0.01, **p<0.05, *p<0.10

4.4 Moderating effect analysis

In the moderation test, we use government environmental subsidies (GES1) as the moderator and create the interaction term after mean-centering. Table 5 shows that the coefficient on c_CR × c_GES1 is positive and significant at the 5% level. This indicates that higher subsidies strengthen the positive effect of climate risk on acquisition decisions. Subsidies lower the cost and resistance of acquisitions under climate risk by providing capital, signalling policy endorsement, and incentivising green innovation.

Table 5. Regression results of the moderating effect of government environmental subsidies

Explanatory variables	MAD
c_CR	0.363 *
	(1.925)
c_GES1	0.004
	(0.667)
c_CR*c_GES1	0.045 * *
	(1.985)
Controls	Yes
Constant	1.574 *
	(-1.812)
Observations	6320
R2	0.012

5. Conclusion and Discussion

Prior work shows that acquisition decisions depend on executive traits and equity incentives [4], industry regulation [5], and investor preferences [6]. We extend this literature by introducing climate risk. Using data on Chinese heavy-polluting listed firms, we find: (1) climate risk (CR) significantly increases the probability of making an acquisition (MAD); (2) government environmental subsidies strengthen this effect by lowering green-transition costs and raising expected acquisition returns.

Our findings show that firms can use climate-risk indicators to anticipate when acquisitions are necessary to protect long-term value. The results also inform China's dual-carbon regulation for heavy-polluting industries. Firms should recognise the positive link between climate risk and acquisitions, treat acquisitions as a key response when climate risk rises, and run pre-deal climate assessments. Policymakers should strengthen this incentive with targeted environmental subsidies: widen coverage, allocate funds on clear climate metrics, and set up an evaluation system to block symbolic acquisitions.

Limitations and future research. The study uses only Chinese heavy-polluting listed firms. Cross-country data are needed to test whether the findings hold in other institutional settings.

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The Impact of Virtual Integration Under Differential Strategic Positioning

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Abstract: This study aims to explore the impact of digital technology-enabled virtual integration on corporate performance in a technologically turbulent environment, revealing the mechanism of virtual cooperation. Drew upon the perspective of demand-side virtual integration and employing structural equation modeling with Partial Least Squares Regression on a sample of 701 Chinese manufacturing enterprises, the research found that: 1) Technological turbulence promotes inter-firm virtual integration among enterprises; 2) Virtual integration has a positive impact on operational efficiency, but only deep-level virtual integration has a positive effect on operational effectiveness; 3) Virtual integration partially mediates the relationship between technological turbulence and operational performance; 4) Image differentiation positioning has a positive moderating effect on the relationship between technological turbulence and virtual integration. The findings help to deeply understand virtual integration strategies in modern business, and provide a theoretical supplement to the research on digital technology-driven inter-organizational collaboration and coordination.

Keywords: Digital technology; Virtual integration; Big data application; Technological turbulence; Differentiated positioning

1. Introduction

With the empowerment and integration of digitization, big data has become a key force in promoting industrial transformation and reshaping competitive advantages. By applying big data, enterprises can not only access fixed and structured information but also gain more impactful dynamic and unstructured information. Diverse data and information enable enterprises to quickly perceive market demands and opportunities and convert them into actual products and services using existing resources and capabilities, as well as allow them to collect and analyze competitor data, and adjust business models and strategies. Similarly, applying big data also provides robust support for inter-firm collaboration. It not only enables information and data sharing but also helps organizations optimize internal and partner business processes by identifying and improving ineffective processes, reducing redundant ones and resource wastage. However, evidence of the collaborative effects supported by digitization still needs to be enriched.

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Along with the transformation and upgrade of digitization, virtual integration supported by digital technology as an emerging quasi-vertical integration is widespread in supply chain collaboration practices. Virtual integration is different from vertical integration. Virtual integration is a hierarchical governance mechanism. Vertical integration means incorporating upstream and downstream creation activities within the enterprise's boundaries, transforming market transactions into internal organizational coordination. It can offer many benefits, including reducing transaction costs, enhancing control over critical resources and capabilities in the value chain, increasing the enterprise's market power, and preventing the leakage of technology and critical information. Unlike vertical integration, virtual integration is a relationship governance[1], an important strategic choice for supply chain cooperation in digital transformation.

Virtual integration, supported by digital technology, integrates internal functions with external collaborating enterprises, crossing organizational boundaries to achieve operational efficiency and customer responsiveness[2]. In contrast to the internalization of external functions in vertical integration, virtual integration strategies often emphasize the "deconstruction" of organizational structures - eliminating non-core functional units (such as distribution channels) but obtaining these services through virtual integration with partners who provide these functions (such as distribution, marketing, and advertising)[2]. Tight inter-organizational coordination, flexible organizational structures (systems), and a focus on core competencies are the three basic characteristics of virtual integration.

Research on this quasi-integrated inter-firm cooperation can be traced back to the 1980s and has been continuously deepened with the development of information and communication technologies (ICT). Early literature exploratively discussed the fundamental concepts and frameworks[3], as well as practical cases[4] of inter-organizational information systems, and their role in creating competitive advantages[5]. In the 1990s, researchers paid significantly more attention to this research theme, with the number of related literatures increasing sharply. The virtual cooperation at this stage was mainly based on the Electronic Data Interchange (EDI) system, with "Electronic integration" emerging as a widely adopted term, while widely employed empirical analysis methodologies. At the end of the 1990s, Michael Dell explicitly introduced the concept of "virtual integration" when expounding on the business model of Dell Computer Corporation[6]. Since then, this term has gradually become a representative theoretical expression in this field.

Over the past few decades, scholars have explored various aspects of virtual integration, including the operation of virtual integration in SMEs, factors influencing virtual integration[2, 7]; partners selection in virtual integration[8], costs and limitations of virtual integration, and factors influencing enterprises' adoption of virtual integration strategies[2], and so on. Studies have found that the profitability of virtually integrated enterprises is better than that of physical integration with virtual integration enterprises, suggesting that virtually integrated enterprises have higher turnover rates, thereby improving operational efficiency. However, previous research has mainly focused on the supply-side virtual integration, with relatively insufficient attention paid to the demand-side ones. The inherent mechanism by which digitally enabled virtual integration affects enterprise performance under the key dynamic context of technological turbulence remains to be further clarified. Furthermore, there is a lack of systematic discussion on the boundary conditions (such as image differentiation positioning) among technological turbulence, virtual integration, and enterprise performance. Therefore, clarifying how

technological turbulence affects enterprise performance through virtual cooperation can not only enrich the theoretical framework of inter-organizational virtual cooperation but also provide important practical insights to respond to technological changes and optimize virtual integration strategies.

The paradigm of "Environment-Strategy-Performance(E-S-P)" has been adopted in numerous research (e.g. Mokhtarzadeh et al., 2022; Fernandes,2017)[9, 10]. Enterprises are just a subsystem of the environment in which they operate. Changes in the external environment often lead to alterations in an enterprise's internal structures, organizational behaviors, etc. An organization can maintain and enhance its performance only by adapting to the environment and avoiding the impacts of environmental uncertainty[11, 12]. Following the E-S-P research paradigm, this study aimed to explore the relationship between technological turbulence, virtual integration, and enterprise performance under a differentiation strategic positioning, hoping to enrich the theory of virtual integration and be beneficial to practice.

2. Theoretical background and hypothesis

Some companies carry out value chain activities with a high vertical integration structure, while others do so by stretching their functions to outside partners based on digital technology support[13]. There are various modes of cooperation arrangements available for companies, such as buyer-producer alliances, strategic supplier relationships, outsourcing, joint ventures, franchising, joint R&D activities, and joint marketing arrangements[14]. With the rapid development of digital technologies and the prominent drawbacks of highly vertical integration, many companies are adopting the virtual integration model in practice as an alternative to the Vertical Integration strategy.

Virtual integration involves core companies and partners leveraging digital technology to conduct cross-organizational activities such as information sharing, process collaboration, knowledge integration, and coordinated innovation, ultimately achieving value co-creation. So far, researchers have explained virtual integration differently. Angeles et al.(2001)[15] described virtual integration as supply chain manufacturers achieving further integration of information, operations, and decision-making based on cross-organizational information systems support. Sha et al.(2005) [8]view virtual integration as a collaborative network of production and distribution that brings together several independent business partners to efficiently and effectively collaborate in planning, execution, and control. Abebe (2007) [2] considers virtual integration as an organizational strategy that integrates internal functions with suppliers and distributors, crossing organizational boundaries to coordinate for effective operation and rapid customers response. In this study, virtual integration refers to a quasi-integration model in which focal manufacturing enterprises, supported by digital technologies, replace traditional market or hierarchical governance through data sharing and dynamic collaboration. Its characteristics include: 1) Virtual integration strategies are based on digital technology; 2) Virtual integration strategies represent an extension of organizational structures, linking core internal functions with external related functions through digital technology to achieve related function services; 3) The core of virtual integration lies in cross-organizational coordination, where companies achieve virtual integration goals through inter-organizational collaborative planning, execution, and control. Through digital technology support, enterprises can effectively integrate and control their activities with upstream and downstream partners.

Inter-firm cooperation is an intermediate structure in the institutional continuum between market and hierarchical governance. It extends beyond fundamental resource sharing to involve deep multidimensional collaboration, such as R&D, market strategies, and customer services. Within the research framework of virtual integration, this study defines information sharing in core business processes (e.g., order processing, logistics tracking) as basic integration, characterized by relatively loose collaboration. Whereas collaboration enabling full-chain data interoperability (e.g., collaborative production planning, joint R&D) is defined as deep integration, which requires establishing a long-term and dynamically adjustable collaboration mechanism. Core companies and their partners can effectively improve supply chain performance[16], reduce collaboration costs[17], and realize value creation by sharing information. Deep integration, as cross-organizational process re-engineering, not only can address the interface issues of cross-organizational business processes, and streamline processes for standardization and efficiency, but also, with the support of digital technology, can redefine the tasks and roles of member enterprises in the process, effectively eliminating non-value-added activities.

Referencing Kim et al. (2018) [18]and Tang et al. (2022)[19], this study divides virtual integration into two dimensions: electronic coordination and collaboration. Electronic coordination involves the execution and control of virtual integration, while electronic collaboration involves channel activity, cooperation, and collaboration.

2.1. Technological Turbulence and Inter-enterprise Virtual Integration

Environmental Uncertainty refers to sources of events or trends that bring opportunities and challenges to enterprises. Technological uncertainty, particularly the continual emergence and rapid iteration of emerging technologies, profoundly impacts enterprises' strategies, organizational structures, and behavior. It is an undeniable source of uncertainty in the contemporary economy.

As a subsystem of a larger environmental system, organizations are often influenced by environment changes. According to organizational adaptation theory, as an adaptive system, organizations can adjust their characteristics in response to environmental changes to achieve optimal or at least acceptable functionality[20, 21]. Facing intense technological turbulence, cooperation in the supply chain can address information asymmetry, and reduce the difficulty of market forecasting, thereby enhancing enterprises' adaptability. As an adaptive system, it would be wise for virtually integrated enterprises to increase the degree of virtual integration in response to the technological environment changes to enhance adaptability and match with uncertain environments (Schilling et al., 2001). Therefore, we can hypothesize:

H1: The higher the technological turbulence, the higher the extent of virtual integration between enterprises and their partners. Specifically:

H1a: The higher the technological turbulence, the higher the extent of electronic coordination between enterprises and their partners.

H1b: The higher the technological turbulence, the higher the extent of electronic collaboration between enterprises and their partners.

2.2. Virtual Integration and Enterprise Performance

Virtual integration enterprises can engage in information and data sharing, process collaboration, knowledge integration, and collaborative innovation with upstream and downstream partners based on digital technology support. It can not only improve enterprises' control over processes, reduce or eliminate waste, and optimize inventory and transportation, thereby significantly enhancing manufacturers' production performance and supply chain operations[22], but also enhance the ability to manage demand fluctuations , and reduce the bullwhip effect. Additionally, virtual integration among supply chain partners can improve feedback speed and error-correcting ability, enhance supply chain flexibility, improve supply chain agility, strengthen cooperation relationships, and enhance resource utilization, which are beneficial to yield cost advantages [7]. Therefore, it is reasonable to believe:

H2: Inter-firm virtual integration enhances enterprise operational efficiency. Specifically:

H2a: Inter-firm electronic coordination enhances enterprise operational efficiency.

H2b: Inter-firm electronic collaboration enhances enterprise operational efficiency.

H3: Inter-firm virtual integration enhances enterprise operational effectiveness. Specifically:

H3a: Inter-firm electronic coordination enhances enterprise operational effectiveness.

H3b: Inter-firm electronic collaboration enhances enterprise operational effectiveness.

2.3. Moderating Effect of Differentiated Strategic Positioning

Differentiation strategy is fundamental to building and maintaining competitive advantages. The differentiation can originate from: (1) Product differentiation, manifested by providing unique products and features; (2) Service differentiation, i.e., providing unique, superior service beyond the norm to customers, such as offering 24-hour fast service channels, product consultation, or after-sales services; and (3) image differentiation, which creates a unique corporate image or brand personality distinct from competitors.

Product differentiation depends on the products' or its users' characteristics. Generally, product differentiation can manifest as exceptional quality[23], which involves product performance, durability, reliability, and consistent specifications. Excellent product quality is a crucial competitive factor. Product differentiation can also be characterized by innovative features, directly reflected in the product itself, such as novelty or continuous product updates.

Image differentiation involves creating and conveying a unique corporate image or brand personality, enabling consumers to distinguish the organization from its competitors. It is a fundamental strategy for firms to gain a competitive advantage. Corporate social responsibility (CSR) is a powerful means of shaping image differentiation, which refers to corporations' accountability towards society, the environment, and stakeholders while pursuing economic objectives[24]. This responsibility includes compliance with laws, ethical norms, environmental protection, public welfare, employee welfare, and other aspects. By engaging in CSR, enterprises can more easily build a good reputation and shape a unique brand image in the minds of

consumers. This differentiated image is difficult to imitate, as it involves the enterprise's values, culture, and sense of social responsibility, which are a unique competitive advantage.

In a multifaceted system, corporations can enhance their virtual integration with supply chain entities, thereby efficiently mitigating unforeseen occurrences and augmenting their resilience in addressing the uncertainties engendered by technological fluctuations. In order to promote strategic alignment, entities that have achieved virtual integration will engage in collaborative orchestration with partners who are more facilitative of achieving strategic goals, guided by their prevailing strategic orientation. This strategic orientation will likely elicit more advantageous organizational behaviors to fulfill the concomitant strategic objectives. A differentiated strategic orientation enables virtually integrated enterprises to undertake preemptive strategies in response to the uncertainties deriving from technological instability. Thus, it can be hypothesized:

H4: The clearer the product differentiation positioning, the stronger the impact of technological turbulence on inter-enterprise virtual integration. Specifically:

H4a: The clearer the product differentiation positioning, the stronger the impact of technological turbulence on inter-enterprise electronic coordination.

H4b: The clearer the product differentiation positioning, the stronger the impact of technological turbulence on inter-enterprise electronic collaboration.

H5: The clearer the image differentiation positioning, the stronger the impact of technological turbulence on inter-enterprise virtual integration. Specifically:

H5a: The clearer the image differentiation positioning, the stronger the impact of technological turbulence on inter-enterprise electronic coordination.

H5b: The clearer the image differentiation positioning, the stronger the impact of technological turbulence on inter-enterprise electronic collaboration.

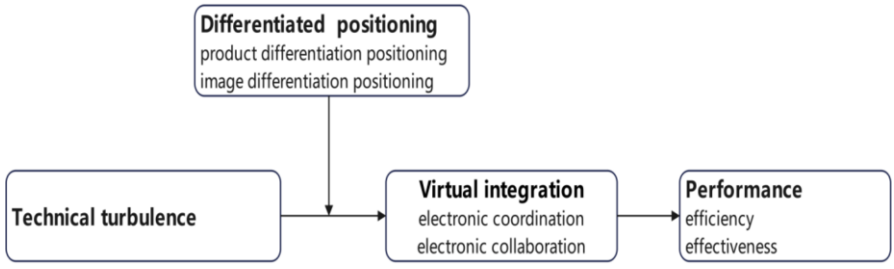


Figure 1. Conceptual framework

3. Methodology

This study focused on manufacturing firms on the Chinese mainland, using the Likert 5-point scale as the analytical instrument. Through a questionnaire survey, 701 valid samples were collected, with a response rate of nearly 15%. The scale items are revised from previous research to reflect the concrete circumstances. During modifying scales, input from several corporate executives was actively sought.

3.1. Technological Turbulence

Technology changes involve not only product technologies but also logistics technology, etc. The results of such changes are reflected in new products, the optimized

manufacturing processes and distribution channels. Accordingly, this study measured the extent of technological turbulence in terms of the change of product and logistics process technology, with three items: a. Speed of changes in logistic processes; b. Speed of changes in core production processes; c. the speed at which products become obsolete.

3.2. Virtual Integration

Previous research has focused on virtual integration in operation execution, process planning, and control. The item's content includes aspects such as order tracking, market information sharing, production coordination, inventory coordination, support for material or component design, and support for quality control[7, 15]. Based on these, this study adopted Kim et al. (2018)[18] and Tang et al. (2022) [19]and divided it into two dimensions. One is electronic collaboration, measured with three items: 1) vendor-managed inventory or consignment stock; 2) plan, forecast and replenish collaboratively; and 3)time replenishment. The other is electronic coordination, measured with items such as 1) inventory information sharing; 2) production planning and demand forecasting information sharing; and 3) order tracking.

3.3. Operational Performance

Operational Performance is a multidimensional concept often measured in efficiency and effectiveness[25]. Efficiency is the degree to which an enterprise uses internal resources economically, and effectiveness is the degree to which it achieves its goals. This study also used efficiency and effectiveness to estimate firms' operational Performance. Efficiency was measured with 1) Labor productivity, 2) Inventory turnover rate, 3) Capacity utilization rate, and effectiveness with: 1) Unit production costs, 2) Procurement costs, and 3) Manufacturing cost[26].

3.4. Differentiation Strategy Positioning

There are two ways to measure product innovation: one is by R&D investment, as seen in Boehe et al.(2010)[23], using "product-related R&D investment, process-related R&D investment, and launching new products" to measure product differentiation. The other is by the innovative features the product presented, which this study adopted, and measures it with items as (1) a broader product range, (2) more frequently introducing new products, and (3) the products provided are more novel.

Corporate social responsibility (CSR) is a powerful means to shape a unique image. Therefore, this study operationalizes image differentiation positioning as a CSR. CSR entails a firm's responsibility towards stakeholders, the environment, and society while conducting business operations. Boehe et al. (2010)[23] measured it with four indicators -"social or environmental certification, input certification, environmental protection, and social responsibility reputation". According to Boehe and Cruz (2010) [23], this study measured it with items such as (1) employee satisfaction, (2) Environmental protection effect, and (3) Social reputation.

4. Methodology, Measurement Model and Reliability, Validity, and Common Method Bias

The analysis unit in this study is the digital collaboration relationships between Chinese manufacturing enterprises and their channel partners. Data were collected through a questionnaire survey using Convenience Sampling, with the respondents being middle or senior managers of enterprises (e.g., department directors and deputy general managers). Finally, A total of 701 valid questionnaires was obtained. The samples mainly cover four major manufacturing industries: electronics and information industry (30.16%), chemical industry (27.42%), machinery manufacturing industry (15.00%), and biology & pharmaceuticals (17.74%), with other sectors accounting for 9.68% in total. Notably, high-tech manufacturing (electronics and information + biology & pharmaceuticals) and chemicals account for more than 70%. In terms of enterprise scale, small and medium-sized enterprises are the mainstay (accounting for 85.8%), with large enterprises (over 1,000 employees) accounting for about 14%, and enterprises (under 500 employees) accounting for more than 60%. Geographically, samples were mainly concentrated in China's three major economic circles (≈30% each), with other regions accounting for about 10% of the total.

Table 1. Factors, Items, Loadings, CR, and AVE

variable	items	std. loading	CR	AVE
Technical turbulence	The speed of new products becomes obsolete	0.508	0.648	0.384
	The speed of core production processes changes.	0.695		
	The speed of logistics processes changes.	0.641		
electronic coordination	Sharing inventory information. Electronically.	0.771	0.797	0.567
	Sharing production planning and demand forecasting information electronically.	0.783		
	Order tracking electronically.	0.702		
electronic collaboration	Vendor-managed inventory or consignment stock electronically.	0.723	0.784	0.549
	Plan, forecast, and replenish collaboratively electronically.	0.782		
	Complete timely replenishment through the support of electronic technology.	0.715		
efficiency	Labor productivity compared to competitors	0.712	0.755	0.507
	Inventory turnover compared to competitors	0.688		
	Capacity utilization compared to competitors	0.736		
effectiveness	The unit manufacturing cost compared to competitors	0.751	0.756	0.508
	The procurement costs compared to competitors	0.661		
	The manufacturing overhead costs compared to those of competitors	0.724		
product differentiation positioning	a broader product range	0.609	0.794	0.57
	more frequently introduce new products	0.92		
	Products more innovative	0.702		
image differentiation positioning	The employee satisfaction	0.619	0.812	0.595
	Environmental protection effect	0.816		
	Social Reputation	0.858		

The study conducted a confirmatory factor analysis (CFA) using AMOS 23 to analyze the measurement model. The model converged smoothly, and the fit indices were satisfactory: $\chi 2/df=2.088$, less than 3; GFI=.947, CFI=.958, IFI=.958, TLI=.948, all above 0.9; RMSEA=.039, less than 0.08.

Composite Reliability (CR) reflects the internal consistency of factor indicators. A higher CR value indicates greater internal consistency of the factors. Hair (1997) [27]suggested that 0.7 was satisfactory and implied that internal consistency was good.

Fornell and Larcker (1981) [28]recommended that the CR value should be greater than 0.6. and all factor loadings were acceptable[27], indicating good internal consistency. Convergent validity tests whether the indicators focus on the measurement factors. The average Variance Extracted (AVE) value is usually used to estimate the Convergent Validity. The higher the AVE value is, the more the indicators can represent the measured factor. When the AVE value is above 0.5, the Convergent Validity is satisfactory. The convergent validity is acceptable if the value is between 0.36 and 0.5 [28]. In this study, all AVE values were above the acceptable threshold. Discriminant validity tests the extent to which a construct is genuinely different from another. High Discriminant Validity indicates that the construct is unique, the other constructs cannot represent the object it represents. If the correlations of a factor with all other factors are lower than its square root of AVE, it is considered that the factors have better Discriminant Validity. Tables 1 and 2 show that the discriminant validity of the factors is satisfactory. Specific factor loadings, CR, and AVE values can be found in Table 2.

Measurement errors can be considered based on the latent variable technique. . At the same time, the main effects are being estimated to assess whether such errors would undermine any statistical relationships within the results. Additionally, it allows for testing of potential common method variance (CMV) issues at a confidence level, determining whether CMV would inflate or weaken the effects obtained. Harman's single-factor test is a common method to detect common method bias. If CMV is severe, a single latent factor can explain all variables[29], while a poor fit in single-factor analysis indicates that CMV does not pose a serious threat to the estimation results[30]. In this study, a single-factor CFA analysis was conducted on all items, and the model fit was as follows: $\chi 2/df=14.417$ GFI=.649, AGFI=.582, CFI=.419, IFI=.422, TLI=.364, RMSEA=.138. The poorer fit of the single-factor CFA model suggests that the CMV is not a significant threat to the estimation results.

Table 2. Means, Standard Deviations, and Correlations

variable	Mean	std.	1	2	3	4	5	6	7
Technical turbulence	3.115	0.837	**.620**						
Electronic coordination	3.338	1.008	.115**	**.753**					
Electronic collaboration	2.604	1.043	.226**	.423**	**.741**				
Efficiency	3.288	0.570	.168**	.180**	.193**	**.712**			
Effectiveness	3.123	0.564	.139**	.148**	.210**	.650**	**.713**		
Image differentiation positioning	3.286	0.925	.423**	.110**	.202**	.154**	.206**	**.755**	
Product differentiation positioning	3.393	0.586	.147**	.207**	.179**	.576**	.485**	.184**	**.771**

Note: N=701 two-tailed test. ** P<.01, * p<.05. The values in the lower triangle represent correlations, and the values on the triangular lines represent the square roots of AVE.

As shown in Tables 1 and 2, the discriminatory validity of the factors is satisfactory.

5. Hypothesis Testing and Discussion

In this study, we employed structural equation modeling (SEM) to test the indirect effects and Partial Least Squares Regression (PLS) to examine the moderating effects of differentiated strategic positioning. The structural equation model converged normally, and the model fit was satisfactory with $\chi 2/df=2.37$, less than 3; GFI=.957, AGFI=.940, CFI=.955, IFI=.956, TLI=.945, all greater than 0.9; RMSEA=.044, less than 0.08. The results are presented in Figure 2.

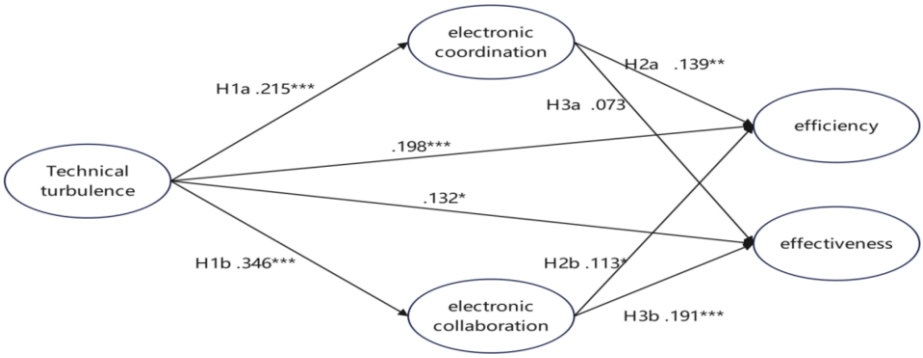


Figure 2. SEM Estimation Results

5.1. Path Coefficient Estimation

From the path coefficients shown in Figure 2, hypotheses H1 and H2 both received support, with path coefficients (two-tailed test) as follows: H1a: .215 ($p<0.001$); H1b: .346 ($p<0.001$); H2a: .139 ($p<0.01$); H2b: .113 ($p<0.05$). Hypothesis H3 received partial support.

Hypothesis H1 proposed that in the face of technological turbulence, firms will strengthen inter-organizational virtual integration to enhance adaptability. The test supports this hypothesis. The study shows that the uncertainty brought by technological turbulence significantly affects electronic coordination and collaboration. In enterprise operations, product and logistics technology changes would trigger changes in a firm's practices and possibly its business models, leading to adjustments and optimizations in inter-organizational coordination and collaboration. The test results for hypothesis H1 provide theoretical evidence for the relationship between technological turbulence and inter-organizational virtual integration.

Hypotheses H2 and H3 assumed that virtual integration benefits firm operational efficiency and effectiveness. Hypothesis H2 received support, while hypothesis 3 received partial support. The results show that both electronic coordination and collaboration have a significant positive impact on a firm's operational efficiency. However, electronic collaboration has a significant impact on operational effectiveness, while electronic coordination does not. The reason may be that information and data sharing increase transparency, enhancing operational efficiency. However, information transparency itself cannot directly bring about operational benefits and needs to go through other transformation mechanisms. Therefore, in the practice of demand-side virtual integration, we not only need to pay attention to information and data sharing but also need to emphasize collaboration in channel activities.

Wang et al. (2006) Previous studies found that supply-side virtual integration helps manufacturers achieve greater operational benefits and efficiency[7]. This study, starting from demand-side virtual integration, empirically demonstrates that demand-side virtual integration also helps improve a firm's operational performance.

5.2. Mediating Effects

There are many methods to test mediation effects, with the most widely used being the causal steps approach proposed by Baron and Kenny (1986)[31]. However, the causal

steps method has two main drawbacks: low testing power[32-34] and it does not base the quantification of the mediation effect, but is inferred from a set of testing results. The coefficient product method is another commonly used method for mediation testing. The Sobel test is the most famous method in this category. However, it has a significant flaw: it requires the sample distribution of the indirect effect to be normal. However, the distribution of a*b is often asymmetric, with skewness and kurtosis [35]. Conversely, the BOOTSTRAP test has stronger testing power [36, 37] and avoids the limitations in the causal steps approach and the Sobel test[33]. It is currently a superior method for estimating indirect effects. This study also adopted this method for the mediation effects.

As shown in Table 3, the Z-values of indirect, direct, and total effects of both paths, "Technical Turbulence-Virtual Integration-Effectiveness" and "Technical Turbulence-Virtual Integration-Efficiency" are all above 1.96. At a 95% confidence level, both the Bias-Corrected and Percentile estimates have confidence intervals that do not include 0. All these indicate that virtual integration plays a partial mediating role between technological turbulence and operational performance.

Table 3. Mediator effect report

Effect	Point estimate			Bootstrapping			
				Bias-Corrected 95% CI		Percentile 95% CI	
	β	SE	Z	Lower	Upper	Lower	Upper
Technical turbulence -Virtual integration-effectiveness							
Total effects	.149	.042	3.548	.070	.231	.074	.237
Indirect Effects	.057	.023	2.478	.026	.108	.022	.101
Direct Effects	.092	.046	2.000	.010	.169	.014	.174
Technical turbulence -Virtual integration-effectiveness							
Total effects	.161	.040	4.025	.085	.238	.091	.243
Indirect Effects	.042	.018	2.333	.015	.079	.012	.074
Direct Effects	.119	.042	2.833	.049	.195	.053	.201

5.3. Moderating Effects

A moderating variable affects the relationship between two or more variables[38]. Ordinary Least Squares (OLS) regression is the most common method for estimating moderating effects. This study also employed this method to examine the moderating effect. Before conducting the regression analysis, the independent variables of technological turbulence and the moderating variables of product differentiation positioning and image differentiation positioning were centered[38, 39]. The analysis results, as shown in Table 4, except for Model 4, the coefficients of the interaction terms in Models 2, 6, and 8 are significant, and the ΔR2 and ΔR2 adjusted values are significant. The results suggest that product differentiation positioning moderates the relationship between technological turbulence and electronic coordination. In contrast, image differentiation moderates the relationship between technological turbulence and both electronic coordination and collaboration. Therefore, Hypotheses H4a, H5a, and H5b are supported, while Hypothesis H4b is not.

Table 4. Report on Regression Analysis Results

	E-coor	E-coor	E-colb	E-colb		E-coor	E-coor	E-colb	E-colb
	Model 1	model 2	Model 3	Model 4		Model 5	model 6	Model 7	Model 8
constant	3.338***	3.308***	2.966***	2.965***	constant	3.338***	3.322***	2.966***	2.956***
TT	0.101*	0.097	0.244***	0.244***	TT	0.105 *	0.096*	0.255 ***	0.250 ***

PDP	0.081	0.085	0.061	0.062	IDP	0.334***	0.278***	0.170*	0.140 *
TT*PDP		0.092*		0.003	TT*IDP		0.232***		0.148*
R^2	0.018	0.024	0.049	0.049	R^2	0.050	0.065	0.056	0.061
Adjusted R^2	0.015	0.020	0.047	0.045	Adjusted R^2	0.047	0.061	0.053	0.057
Adjusted $\triangle R^2$	0.018	0.006	0.049	0.004	Adjusted $\triangle R^2$	0.050	0.015	0.056	0.006
F Change	6.337**	4.265*	18.073***	0.004	F Change	18.390***	11.081***	20.540***	4.126*

Note: two-tailed test. *** p<.001; *p<.01; *p< .05; TT –Technical turbulence; PDP – product differentiation positioning; IDP - image differentiation positioning; E-coor –electronic coordination; E-colb –electronic collaboration

To more intuitively capture the moderating effect of differentiated positioning, this study, based on the simple slopes method, used one standard deviation above and below the mean of the moderating variable to represent high and low values[39, 40], and plotted moderation diagrams illustrating these moderating effects: the effect of product differentiation positioning on technological turbulence and electronic coordination, as well as the effect of image differentiation positioning on electronic coordination and collaboration, as shown in Figures 3, 4, and 5.

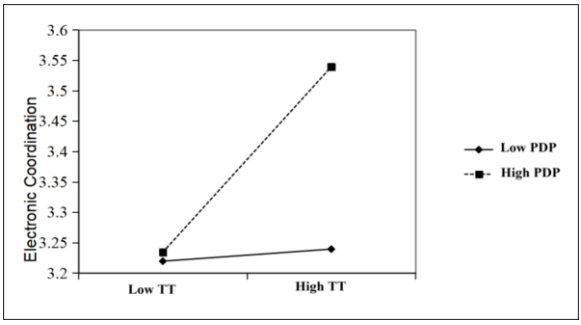


Figure 3. product differentiation positioning (PDP) on Technical Turbulence (TT)and Electronic Coordination (E-coor)

The diagram in Figure 3 shows that the two curves representing the high and low groups intersect, indicating that product differentiation positioning positively moderates the relationship between technological turbulence and electronic coordination. The more pronounced a firm's product innovation differentiation strategy is, the more virtual integrated enterprises are likely to enhance inter-firm electronic coordination, to improve their adaptability to environments characterized by technological turbulence.

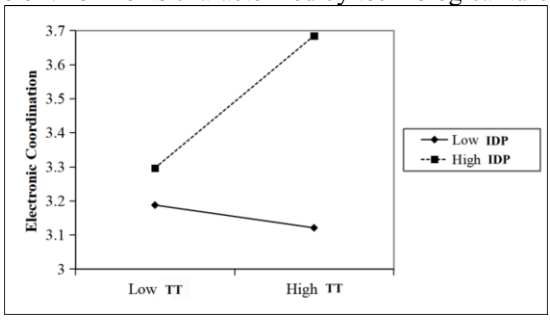


Figure 4. Image Differentiation Positioning (IDP)on Technical Turbulence (TT)to Electronic Coordination (E-coor)

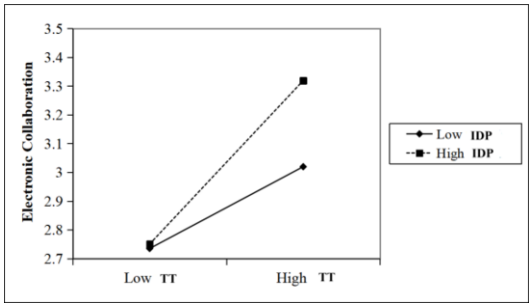


Figure 5. Image Differentiation Positioning (IDP) on Technical Turbulence (TT) and Electronic Collaboration (E-colb)

Figures 4 and 5 demonstrate that image differentiation positioning positively moderates the relationship between technological turbulence and virtual integration. They indicate that the more pronounced a firm's image differentiation positioning is, the more beneficial it is to enhance the inter-firm virtual integration to improve adaptability.

The results of the regression analysis partially support the hypothesis that a firm's differentiated strategic positioning moderates the relationship between technological turbulence and inter-firm virtual integration. Specifically, the moderating effect of product differentiation positioning on the relationship between technological turbulence and inter-firm electronic collaboration is not significant. The reason may stem from the differential adaptability of "soft differentiation capabilities" (image differentiation) versus "hard differentiation attributes" (product differentiation) to distinct cooperation modes under technological turbulence. Image differentiation positioning, with its global influence and trust-signaling capacity, can meet the core needs of electronic coordination (e.g., data sharing) and electronic collaboration (e.g., resource co-creation). In contrast, product differentiation positioning, which focuses on the tangible attributes of products with limited impact (e.g., confined to R&D), can only adapt well to e-coordination needs (process alignment, information synchronization), but cannot meet the e-collaboration's demand (e.g., cross-enterprise strategic synergy). The results show that in virtual cooperation, "soft power" is more compatible than "hard power", offering a new direction for alliance strategies in a turbulent environment.

6. Conclusions and Future Research Directions

Virtual integration has become one of the emerging research focuses in recent years. In contrast to previous studies that mainly focused on the supply side of virtual integration, this study emphasizes the demand side. Using the "Environment- Strategy- Performance" framework, we explored the relationships among technological turbulence, virtual integration, and business performance under differentiation positioning. We found:(1) inter-organizational virtual integration partially mediates technological turbulence and business performance, and (2) differentiation strategic positioning moderates the relationship between technological turbulence and virtual integration. In terms of the impact of virtual integration on business performance, inter-organizational electronic collaboration significantly affects both business efficiency and business effectiveness, while electronic coordination has a significant impact on business efficiency but not on business effectiveness.

This study is helpful to the theoretical understanding of inter-organizational virtual integration supported by digital technology. The depth of virtual integration varies, with coordination and control being the more basic levels, inter-enterprise collaboration and synergies, joint decision-making, and knowledge innovation, representing higher levels. This study found that deeper cooperation, such as process integration and collaborative decision-making, has a greater impact on business performance. Business management is a complex engineering system, and firms should strive for balance among various business strategies and focus areas. In the process of digital collaboration, given that "soft power" is more compatible than "hard power," strategic priorities should be adjusted accordingly under the constraint of limited resources.

Of course, this study also has limitations and shortcomings. Firstly, the samples have certain limitations. In distribution, though SMEs are dominant, micro-enterprise samples are relatively few. Regional distribution is concentrated in developed areas, with insufficient samples from underdeveloped regions. Thus, future research should balance sample distribution to enhance the findings' universality. Secondly, environmental uncertainty involves various sources. Besides technological changes, other sources such as market fluctuations and regulatory changes may also introduce uncertainty. Exploring how these uncertainties influence inter-organizational virtual integration is worth further attention. Additionally, as virtual integration is a new inter-organizational coordination mechanism, the role of trust between virtually integrated firms in virtual integration, and for Chinese enterprises, how guanxi impacts virtual integration within the context of Chinese culture, are important areas for further research.

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A Study on the Coordination of Recruiting Farm Volunteers Through Green Tourism: An Interview with JA Tourism & Communications

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Abstract. This study investigates the coordination of recruiting farm volunteers through green tourism in Japan, addressing the research question: What key factors are necessary to further develop the recruitment of farm volunteers through green tourism? A semi-structured interview with JA Tourism & Communications was analyzed using a matrix diagram, through which the "Promotion of Communication" emerged as a key theme. Drawing on Aoki's collaborative development theory and Kaneko's volunteer theory, the study highlights the need for farmers' willingness and volunteers' understanding to address communication barriers, offering insights for rural revitalization.

Keywords. Farm volunteers, green tourism

1. Introduction

According to the "Tourism Nation Promotion Basic Plan," green tourism is defined as a form of leisure activity that involves staying in rural areas to experience nature, culture, and engage with local communities. It is highlighted as a prime example of new tourism, distinct from traditional sightseeing trips [1]. Green tourism is anticipated to serve as an effective strategy for rural areas to attract farm volunteers from outside their communities. According to an announcement by the Ministry of Agriculture, Forestry and Fisheries, the amount of abandoned farmland in Japan will reach approximately 257,000 hectares in 2023, which is an area larger than the area of Saga prefecture (approximately 244,000 hectares) [2]. In addition, Japanese agriculture is experiencing a labor shortage caused by the declining number of agricultural workers and the rapid aging of the rural population [3]. Government statistics highlight that the number of core individuals primarily engaged in farming continues to decrease, with no signs of this trend slowing down (see Table 1 for details) [4]. Given these circumstances, farm volunteers are expected to play an increasingly important role in the effective use of farmland in the future. As Murata (2025) points out, addressing agricultural challenges in rural areas is essential for strengthening the sustainability of society as a whole [5]. Japan which has the fastest aging population in the world [6] and a significantly declining

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birthrate, faces a particularly urgent situation. Therefore, the findings of this study, which uses Japan as a case study, may offer valuable insights for tackling similar issues in other countries facing demographic and agricultural challenges.

Building on the above background and recognition of the issues outlined above, this study focused on the recruitment of farm volunteers through the framework of "green tourism" and posed the following research question: *What key factors are necessary to further develop the recruitment of farm volunteers through green tourism?* To address this question, a semi-structured interview was conducted with JA Tourism & Communications, a leading organization in this field. The interview aimed to examine the organization's current practices and challenges, and to explore the broader implications of these findings, including the identification of essential elements for future development.

Table 1. Changes in the Number of Core Persons Mainly Engaged in Farming (2000–2020).

		2000	2005	2010	2015	2020
Core persons mainly engaged in farming		2.40 million people	2.24 million people	2.05 million people	1.76 million people	1.36 million people
	Age 65 or older	1.23 million people	1.29 million people	1.26 million people	1.14 million people	0.95 million people
	(Ratio)	51.2 %	57.4 %	61.4 %	64.9 %	69.6 %
	Average age	62.2 years old	64.2 years old	66.2 years old	67.1 years old	67.8 years old

Source: Created by author from [4].

2. Materials and Methods

The survey was conducted through a semi-structured interview held on December 23, 2024, via Zoom, with JA Tourism & Communications, a leading organization in coordinating efforts to engage farm volunteers through green tourism.

2.1. Farm Volunteers and Green Tourism

Farm volunteers have gained increasing attention as a valuable labor resource for agricultural management entities facing worker shortages, with local governments and non-profit organizations (NPOs) playing a central role in recruiting participants [4]. However, challenges remain, such as the low level of public awareness about farm volunteer activities [7]. As a result, there is ongoing discussion about the need to enhance the recognition of farm volunteers and explore effective methods for recruiting them [8].

Green tourism has been promoted as a policy in Europe since the 1980s. [9]. In Japan, the term "green tourism" first appeared in government documents in 1992 and has gradually gained traction across the country since then [10]. As previously mentioned, green tourism is defined as a form of leisure activity that involves staying in rural areas to enjoy nature, experieince local culture, and engage with rural communities [1]. In this

sense, green tourism fosters urban-rural interaction, with farm volunteer activities serving as a representative example of this concept [11].

One of the key challenages in implementing farm volunteer programs through green tourism lies in matching prospective participants with suitable host farmers and coordinating events effectively. Aoki (2022), for instance, highlighted an initiative in Odawara City, Kanagawa Prefecture, which sought to cultivate agricultural workers through green tourism. This initiative was not undertaken solely by the city government but was carried out in collaboration with an outside coordinator [12]. As a result, the program achieved high levels of participant satisfaction, and attracted over 800 individuals between 2018 and 2020 [12]. In contrast, typical farm volunteer activities are often organized independently by municipalities, which issue public calls for participants. However, from the standpoint of effective matching and coordination, it may beneficial for municipalities to collaborate with external organizations that possess relevan expertise and experience, rather than managing such programs on their own.

2.2. JA Tourism & Communications

JA Tourism & Communications is a general incorporated association under Japan Agricultural Cooperatives (JA), headquartered in Tokyo [13]. This association was established with the goal of promoting public-interest tourism businesses in 1967 [13]. Its articles of incorporation outline its mission is to promote and revitalize rural areas, foster tourism, and conduct public relations, surveys, and research related to these efforts [13]. In doing so, the association aims to contribute to the creation of vibrant local communities where people can lead fulfilling lives [13].

2.3. Activities to Be Interviewed

This study focuses on issues related to the coordination of recruiting farm volunteers through green tourism. As such, the interview was conducted with JA Tourism & Communications, which carries out activities most closely aligned with the subject of this research, specifically the Nekonote Ennoutai initiative. *Nekonote Ennoutai* aims to support Japan's rural areas, which are grappling with labor shortages due to depopulation and an aging population, by recruiting volunteers to assist with agricultural work [13]. The initiative also seeks to foster a deeper understanding of food and agriculture through direct interaction with crops, soil, and farmers [13].

The 2023 *Nekonote Ennoutai* activities, which involved 21 events and 199 participants, were analyzed (see Table 2 for details). These 21 activities were categorized based on their content and the Japan Standard Industrial Classification (JSIC) published by the Ministry of Internal Affairs and Communications [14]. For each category, the interviews were conducted to explores three main topics: (1) the difficulties and challenges involved in planning and implementing these activities, (2) the satisfaction of host farmers and the potential interest among other farmers, and (3) the potential demand among participants (farm volunteers). In the analysis, the interviews were first carefully transcribed and summarized without losing their meaning. The key information from these interviews was then organized by category and topic using a matrix diagram, which served as the basis for the subsequent analysis.

As Ninomiya (2018) emphasizes, agriculture differs significantly from other industries due to its inherent uncertainty and regional specificity [15]. In other words, agriculture is characterized by the constant need to respond flexibly to unforeseen

circumstances and customize to suit regional characteristics [15]. In particular, when focusing on regional specificity, it is unlikely that a one-size-fits-all solution can be applied across the board [15]. Consenquently, this study attempts to categorize and discuss agriculture in each project as a whole, there may be some inconsistencies with this perspective. However, it remains feasible to consider agricultural support through green tourism as a form of package travel product, which allows for a general discussion while maintaining a degree of objectivity.

Table 2. Overview of the 21 Activities of *Nekonote Ennoutai*.

Categories	Abstructs of the activities	Locations	Participants	Months	Remarks
C3 Flower farming	① Picking tulip flowers	Takaoka City (Toyama Pref.)	6 people	Apr.	Stay
C2 Vegetable farming	② Cutting Shiitake mushrooms	Yamatsuri Town (Fukushima Pref.)	16 people	Apr.	Stay
C4 Rice farming	③ Planting rice	Kimino Town (Wakayama Pref.)	2 people	May	Day trip
C1 Fruit farming	④ Growing grapes	Obuse Town (Nagano Pref.)	10 people	Jun.	Stay
C3 Flower farming	⑤ Tidying up carnations	Hadano City (Kanagawa Pref.)	26 people	Jun.	Day trip
C1 Fruit farming	⑥ Picking plums	Annaka City (Gunma Pref.)	12 people	Jun.	Day trip
C1 Fruit farming	⑦ Growing Feijoas	Iwaki City (Fukushima Pref.)	6 people	Jul.	Stay
C1 Fruit farming	⑧ Picking mandarin oranges	Oi Town (Kanagawa Pref.)	9 people	Jul.	Day trip
C2 Vegetable farming	⑨ Planting cabbages	Otari Town (Nagano Pref.)	9 people	Aug.	Stay
C1 Fruit farming	⑩ Growing Chestnuts	Ena City (Gifu Pref.)	8 people	Sep.	Stay
C4 Rice farming	⑪ Harvesting rice	Kimino Town (Wakayama Pref.)	3 people	Oct.	Day trip
C2 Vegetable farming	⑫ Growing turnips	Matsumoto City (Nagano Pref.)	7 people	Oct.	Stay
C1 Fruit farming	⑬ Growing persimmons	Marumori Town (Miyagi Pref.)	7 people	Nov.	Stay
C1 Fruit farming	⑭ Harvesting yuzu fruits	Yamatsuri Town (Fukushima Pref.)	8 people	Nov.	Stay
C1 Fruit farming	⑮ Harvesting mandarin oranges	Kamogawa City (Chiba Pref.)	8 people	Dec.	Day trip
C1 Fruit farming	⑯ Harvesting mandarin oranges	Oi Town (Kanagawa Pref.)	18 people	Dec.	Day trip
C6 Aquaculture	⑰ Washing oyster shells	Iki City (Nagasaki Pref.)	6 people	Dec.	Stay
C5 Grain farming	⑱ Sorting soybeans	Hayakawa (Yamanashi Pref.)	10 people	Jan.	Stay
C2 Vegetable farming	⑲ Harvesting Chinese cabbages	Tatebayashi City (Gunma Pref.)	11 people	Jan.	Day trip
C2 Vegetable farming	⑳ Harvesting cabbages	Otari Town (Nagano Pref.)	9 people	Feb.	Stay
C2 Vegetable farming	㉑ Shiitake mushroom cutting	Yamatsuri Town (Fukushima Pref.)	8 people	Mar.	Stay

Source: Created by author from [13].

3. Results and Discussion

The results and discussion of the interview are presented below. Notably, "Promotion of Communication" emerged as a key element, providing a direct response to the research question.

3.1. Interview

The main findings from the interview are summarized in the matrix diagram (see Table 3 for details). In terms of general participant characteristics, Nekonote Ennoutai does not specify a particular target group. However, the majority of participants tend to be active seniors aged 65 and over. These participants are often financially secure, have an interest in agriculture, and seek both leisure and hands-on experiences through their invlovement. While JA Tourism & Communications aims to attract a more diverse demographic, including younger generations, it currently faces challenges in determining effective strategies to appeal to these groups.

To recruit host farmers, JA Tourism & Communications collaborates with local JA, municipal governments, and local revitalization cooperation teams. Rather than targeting all farmers in a region, the association focuses on supporting those who express a willingness to host farm volunteers, often cultivating these relationships through involvement in other community-based projects. Host farmers appear to benefit in two primary ways from accepting participants: access to a supplementary labor force and opportunities for personal interaction with volunteers. The former is typically the main motivation, and in many cases, host farmers report satisfaction with the labor support provided. The latter benefit includes opportunities for direct exchange with consumers, enabling farmers to share insights and receive feedback regarding agricultural practices, such as how products are sold and product quality. These interactions often serve as platforms for mutual learning, such as discussions on marketing methods, consumer perceptions, and the challenges of farming.

However, there are also notable challenges. Many farmers are not naturally inclined toward open communication, which sometimes necessitates mediation by the association or local coordinators to facilitate dialogue between farmers and participants. This required level of interaction can be tiring for some farmers and is recognized as a key issue. Additionally, local acceptance plays a critical role; it is important to have community members who are open to welcoming outsiders. Although it can be difficult to verbally convey the benefits of hosting volunteers, farmers often gain understanding and appreciation after experiencing it firsthand. That said, during the initial stages, some farmers hesitate to participate due to concerns about how they might be perceived by their peers, preferring to avoid potential social friction.

Table 3. Matrix diagram of interview results.

Categories	Items related to participants	Items related to planning and holding	Items related to host farms	Other items
C1 Fruit farming	- Active seniors are the primary participants, but there are also a number of individuals in their 40s and 50s.	- Participants are easy to recruit and events tend to be easy to hold.	- Host farmers, particularly those who are small-scale and facing a labor shortage, tend to report high levels of satisfaction with the program.	- To increase the number of participants, it is important to hold more day trips.
C2 Vegetable farming	- Active seniors are the primary participants. - There are many repeat participants and many women attending alone.	- Many events require overnight stays, which places a relatively heavy burden on participants.	- Because a lot of physical labor is involved, it contributes greatly to the host farmers.	- There is a high level of satisfaction in being able to witness the production of brand crops and experience the rural areas.
C3 Flower farming	- The participants are diverse (active seniors, young people, first-time participants, repeat visitors, etc.).	- Due to being delicate crops, on-site and work management is crucial. - There are some difficulties in gathering host farmers.	- Host farmers, particularly those who are small-scale and facing a labor shortage, tend to report high levels of satisfaction with the program.	- The words of gratitude from the host farmers resonate with the participants, which contributes to their satisfaction and encourages repeat participation.
C4 Rice farming	- Active seniors are the primary participants. - There seemes to be a regional difference between the east and west in the awareness of participants.	- Unlike other categories, participants need to contact the host farmers directly to apply to participate.	- Due to factors such as cost-effectiveness, the satisfaction of host farmers may not be very high.	- The key to attracting participants is to highlight the appeal of the event, such as opportunities to learn about rural areas.
C5 Grain farming	- Many of the participants are active seniors and repeat visitors.	- This activity is organized in collaboration with a tourism association, but organizing events has become increasingly difficult due to the aging local population.	- As this is a long-running activity, there seems to be a high level of satisfaction among the host farmers.	- Since it is a hot spring resort, some people are attracted to participate for this reason.
C6 Aqua-culture	- There are many repeat participants among the younger generation. - Many participants are from the Kanto region.	- Plannning and holding activities has been running smoothly. - Since travel involves a ferry, it is difficult to carry out the tour in bad weather.	- The demand for labor increases during the oyster harvesting season, leading to a high level of contribution from participants and greater satisfaction among the host farmers.	- There is high demand for visiting remote islands, and many participants are interested in the activity because it offers an experience that is difficult to have on their own.

Source: Created by author.

Of the total 21 activities, nine fall under the category of "Fruit farming (C1)", making it the most popular and in-demand activity among participants. Several factors contribute to this popularity: the tasks are relatively straightforward, focusing on

handling fruit, and participants often receive fruit as a souvenir, which adds an appealing incentive to their experience.

"Vegetable farming (C2)" is the second most popular category, accounting for six out of the 21 total activities. Similar to C1, the tasks in C2 are easy for participants to understand. What particularly attracts them, however, is the opportunity to observe the production of brand-name vegetables, which adds an educational and unique element. Additionally, since vegetable farming typically involves more physical labor than fruit farming, host farmers tend benefit more from the support provided by farm volunteers.

In contrast, the remaining activity categories were held less frequently. "Rice farming (C4)" and "Grain farming (C5)" were notably less popular compared to the other categories. Attracting participants for rice farming has been particularly challenging, pointing to the need to enhance its appeal. Grain farming, on the other hand, has faced difficulties due to the aging population within the local tourism associations, making it increasingly difficult to coordinate and host events, contributing to the decline in their frequency. Despite their limited occurrence, "Aquaculture (C6)" and "Flower farming (C3)" remain popular among participants. Both categories are highly seasonal, limiting how often they can be offered. Aquaculture activities, in particular, often involve long-distance travel and ferry rides, making them less practical to organize regularly. However, the opportunity to engage in such a unique and rare experience contributes significantly to their appeal. In the case of flower farming, while the host farms are typically small-scale and the tasks short-term, the heartfelt expressions of gratitude from the farmers left a strong impression on participants. This emotional connection appears to be a key factor in encouraging repeat participation.

Given the nature of green tourism, which involves recruiting farm volunteers, several challenges related to planning and implementation of activities has been identified. However, in the case of "Flower farming (C3)," a notable factor contributing to participant satisfaction and repeat attendance is the heartfelt expressions of gratitude from host farmers. This emotional exchange appears to resonate deeply with participants, and be particularly prominent in this category, which is an aspect worth highlighting.

3.2. Key Element: "Promotion of Communication"

In the previous section, the interview results about *Nekonote Ennoutai* were discussed. It could be surmised that the answer to the research question of this study ("*What key factors are necessary to further develop the recruitment of farm volunteers through green tourism?*") is the "Promotion of Communication." Specifically, the "Promotion of Communication" refers to encouraging farmers to share honest opinions and feedback to farm volunteers, either before or after their participation. In fact, as demonstrated in the case of "Flower farming (C3)," when words of farmers are conveyed to participating farm volunteers, it can significantly encourage repeat participation. Therefore, it is naturally desirable to expand such opportunities for communication to other agricultural support activities as well. As indicated in the interview results, the degree to which the gratitude from the host farmers resonated with the participants was particularly evident in "Flower farming (C3)." This finding suggests that there is potential room for growth in other categories, where such messages have not yet effectively reached participants.

The key to realizing the "Promotion of Communication" lies in the willingness of the farmers themselves. As revealed in the interview results, a number of farmers experience difficulty with interpersonal communication. For such farmers, it may be difficult to convey their honest feelings and opinions (not just gratitude but also other

thoughts) to the participants, and doing so may be mentally exhausting. Admittedly, there are both advantages and disadvantages to persuading farmers of the need to promote communication and encouraging them to make such efforts, especially given the anticipated difficulties some may face. Nonetheless, if society envisions a future in which farm volunteers are widely accepted and effectively contribute to addressing the labor shortages in Japanese agriculture, then fostering communication between farmers and volunteers becomes an essential endeavor. Indeed, Aoki (2004) also points out that a fundamental point for promoting green tourism is for hosts to have autonomy and openness [16]. Based on this, he develops the collaborative development theory, which argues that rural revitalization and the promotion of green tourism can be achieved through cooperative efforts between urban and rural areas, grounded in a shared awareness of common challenges [16]. Furthermore, Kaneko's theory of volunteering provides valuable insight in support of encouraging willingness and autonomy among farmers, particularly in terms of fostering openness and communication. Kaneko (1992) defines volunteering as a profoundly engaging process of relational discovery, in which the boundries between "helping" and "being helped" become increasingly blurred, rendering distinctions between giver and receiver less relevant [17]. He emphasizes that volunteers act with the expectation of receiving some form of reward, and that the true value of volunteering arises when this reward is perceived not as something earned independently, but as something given by another. According to Kaneko, volunteers find meaning in the mutuality of the relationship—when they feel they have been supported, have learned from others, or have been able to contribute meaningfully, the value lies in that shared experience [17]. From this perspective, improving opportunities for host farmers to express their honest feelings and opinions can enhance the overall value that volunteers derive from their participation. This, in turn, may lead to the expansion of farm volunteer activities. The utility of farm volunteer labor in agricultural management has been demonstrated both in the interview findings presented in this study and in Murata's (2023) research [8]. It is therefore desirable to make full use of this labor resource while simultaneously fostering an environment in which both volunteers and host farmers can engage in the kind of mutual discovery and relational depth described by Kaneko. Murata (2023) further argues that in order to sustain and expand initiatives like the one examined in this study, it is essential to develop a self-sustaining system driven by the voluntary actions of those involved [8]. Creating the kind of communicative and reciprocal environment described above could be a significant step toward realizing such a system. However, given the current context in Japan with a large amount of abandoned farmland and a declining agricultural workforce the need to promote communication may be even more pressing for farmers who have never hosted farm volunteers or who remain hesitant to do so. Ultimately, the decision to accept farm volunteers and engage in communication is left to the discretion of each individual farmer, as the business owner. Nevertheless, in light of Japan's agricultural labor shortages and the broader challenge of underutilized farmland, expanding opportunities for farm volunteer involvement appears to be a highly desirable direction—one that aligns with the long-term sustainability of both agriculture and rural communities. To move toward this goal, the promotion of communication is essential. As Kaneko suggests, volunteer relationships offer a new perspective on human interaction and represent a principle of behavior that can reveal new social values. These relationships can serve as a "window" through which to break through social stagnation and enrich society through diversity [17]. Opening this window will require active cooperation between farmers and farm volunteers, and improved communication will play a central role in achieving that.

Finally, it is important to recognize that communication is a two-way process. Farm volunteers, for their part, must also be mindful that some farmers may not be naturally comfortable with interpersonal communication. Building mutual understanding on both sides is therefore key to creating a more effective and meaningful experience for everyone involved.

4. Conclusion

In this study, the research question, "*What key factors are necessary to further develop the recruitment of farm volunteers through green tourism?"* was addressed through an interview with JA Tourism & Communications. The current practices and challenges related to the coordination of farm volunteer recruitment through green tourism were analyzed using a matrix diagram, with the aim of identifying essential elements for future development. As a result, the study concluded that the "Promotion of Communication" is one of the key factors necessary for advancing such initiatives.

In discussing this element, the study emphasized the importance of both farmer willingness and volunteer understanding. These points were examined through the lens of Aoki's collaborative development theory and Kaneko's volunteer theory, which together underscore the value of mutual engagement and relational discovery in sustaining meaningful volunteer programs.

Although this study focused on the Japanese context, its findings may offer valuable insights for addressing similar issues in other countries, particularly those facing demographic challenges such as aging populations and declining birthrates. Japan, as the fastest-aging society in the world, serves as a compelling case study, and the lessons drawn here may hold relevance for agricultural sustainability globally.

Moreover, it is desirable that the issues explored in this study not remain confined to academic discourse but be translated into practical applications within the agricultural sector. Therefore, a key task moving forward is to consider specific, actionable measures to increase the feasibility and impact of these findings.

Two future challenges are worth highlighting. First, this study examined only a single case. In the future, it will be important to investigate additional cases to validate and broaden the findings. Second, while the study identified the need to promote communication, it did not sufficiently explore effective strategies or methods for doing so. Further research is needed, drawing on insights from other academic disciplines such as sociology, psychology, and communication studies, to develop and implement practical approaches to enhancing communication between farmers and volunteers.

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The Impact of Tax Incentives on China's Automobile Manufacturing Industry ——Taking Zhejiang Province as an Example

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Abstract. From 2017 to 2019, the Chinese government continuously lowered the VAT rate to stimulate market vitality. Taking the automobile manufacturing industry as an example, combined with the case of Geely Automobile, this paper constructs a fixed effect model through the financial data of listed companies to study the impact of tax rate adjustment on corporate performance. The results show that: first, the reduction of the VAT rate is significantly positively correlated with the improvement of corporate performance, and the greater the reduction, the more obvious the effect; second, the capital structure plays a regulatory role, the debt-to-asset ratio negatively affects performance, and the scale of the enterprise has a positive effect; finally, the policy effect is heterogeneous and fluctuates due to differences in the turnover cycle of accounts receivable/payable of enterprises. The study reveals the path of the VAT policy on the automobile manufacturing industry, and provides an empirical basis for the government to optimize tax policies and promote high-quality development of the industry.

Keywords: performance, automotive manufacturing, VAT, tax rate adjustment, debt asset ratio

1. Introduction

Since the dawn of the 21st century, China's automobile industry has grown at break-neck speed, topping global production and sales charts for 16 straight years. In 2024, the country manufactured 31.282 million vehicles and sold 31.436 million, increases of 3.7 % and 4.5 % respectively—both all-time highs that testify to the sector's resilience and its shift toward higher-quality expansion.

As a strategic pillar of the national economy, the industry's fortunes are tightly linked to tax policy [1]. Between 2017 and 2019, Beijing adjusted the value-added tax

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(VAT) rate three times. The 2017 reform left manufacturing rates untouched[2]; in May 2018 the 17 % and 11 % brackets were each trimmed by 1%[3]; and in April 2019 the manufacturing rate was cut from 16 % to 13 % and the 10 % bracket to 9 %[4]. This paper zeroes in on the latter two changes (2018–2019) to gauge their effect on the auto sector and on corporate performance.

Industry data reveal a largely steady revenue trajectory after the cuts. Although the pandemic triggered a brief dip in 2019, the lower VAT rates cushioned tax burdens and hastened recovery (Figure 1). Tax incentive policies play an important role in the development of enterprises. The effective development of enterprises requires not only the encouragement and drive of national policies, but also the reasonable positioning and efforts of enterprises themselves [2]. Grasp the challenges and opportunities of development, make good use of the regulatory function of taxation on enterprise development, improve the development quality of the automobile manufacturing industry, and help the transformation and upgrading of automobile manufacturing enterprises [3].

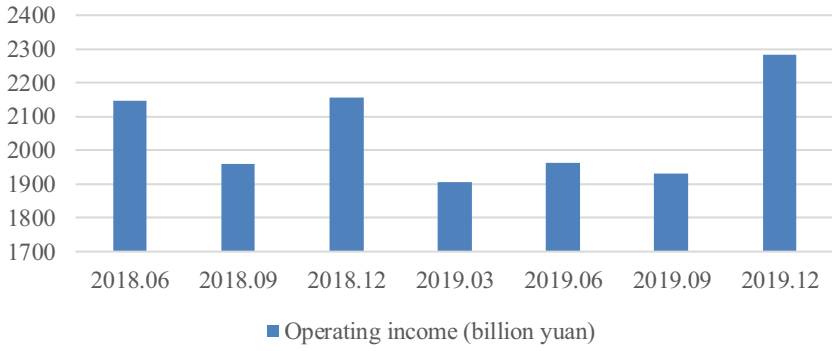


Figure 1. Changes in the operating income of the automobile manufacturing industry from 2018 to 2019.

Using firm-level data and an empirical model, we quantify how the VAT reductions translated into measurable performance gains. The results provide actionable insights for policymakers fine-tuning tax design and for automakers recalibrating strategy. By filling a gap in the micro-level VAT literature, the study offers timely guidance for both government and industry.

In Hangzhou, China, we can clearly see the chain effect of the VAT rate cut and supporting policies on the automotive industry chain. In April 2019, the manufacturing tax rate was reduced from 16% to 13%. Hangzhou Geely Automobile Co., Ltd. estimated that it could pay 75 million yuan less in VAT that year. Combined with a one-time deduction of 23 million yuan for real estate and a 20-million-yuan tax refund at the end of the period, it released more than 110 million yuan in funds throughout the year. The company then used all this "tax reduction benefit" for equipment renewal and technology upgrades, and lowered the prices of some models to pass the policy dividends directly to consumers. In the upstream of Geely's supply chain, Zhejiang Jingang Automobile Co., Ltd. added 4.46 million yuan in deductions in 2016 because the input tax on factory construction was deductible. In 2017, it continued to deduct 2.97 million yuan. After the

[2] Notice on Policies Concerning the Consolidation of VAT Tax Rates:(chinatax.gov.cn).
[3] Notice on Policies Concerning the Consolidation of VAT Tax Rates:(chinatax.gov.cn).
[4] Notice on Policies Concerning the Consolidation of VAT Tax Rates:(chinatax.gov.cn).

company's cash flow improved, it quickly expanded its fixed asset investment. What is more noteworthy is that the "bank-tax interaction" mechanism between Geely and Jingang has played an amplifying effect: relying on its A-level tax credit for three consecutive years, Jingang Automobile obtained a low-interest loan of 50 million yuan from Hangzhou Bank, with the interest rate 15% lower than the benchmark, further strengthening the virtuous cycle of tax reduction-capacity expansion-reinvestment (Figure 2).

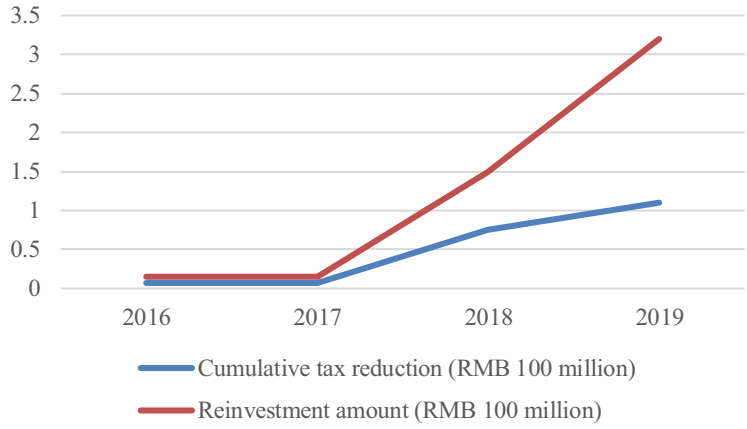


Figure 2. Tax Reduction - Reinvestment of Hangzhou Automotive Enterprises (2016–2019).

2. Literature Review

The impact of fiscal incentives on sectoral growth has long commanded scholarly attention, with a broad consensus that such measures materially enhance firm performance. Against this backdrop, this study zeroes in on the repercussions of recent VAT-rate adjustments. As China's dominant revenue instrument, VAT not only underpins fiscal stability but also functions as a lever for industrial upgrading.

Existing evidence, however, reveals marked heterogeneity. Using a difference-in-differences framework, Yulia V. Leontyeva shows that the VAT-to-VAT reform lowered effective tax burdens, yet benefits were unevenly distributed across regions [4]. B. Xia and Y. Li document that preferential VAT treatment catalyzed the expansion of China's clean-energy sector [5]. J. Z. Zhang, Q. Lu demonstrate that the same reform eliminated cascading taxation in air transport and accelerated sectoral growth [6], while Mayburov's case study illustrates how VAT concessions reduced costs and boosted efficiency for new-energy vehicle manufacturers [7].

Despite this growing literature, the specific effects of post-2018 VAT-rate cuts on the automotive industry remain under-explored. This paper therefore examines how the latest rate adjustments influence the performance of automobile manufacturers and derives actionable strategies to inform sustainable development for the sector.

3. Research Methodology

In order to examine the impact of the VAT rate cut on the performance of the automobile manufacturing industry, this paper takes 82 Shanghai and Shenzhen A-share listed

vehicle companies from the third quarter of 2017 to the first quarter of 2020 as the research sample, and constructs a multivariate linear regression model:

$$ROA_{it} = \beta_0 + \beta_1 \mathrm{Rate1}_{it} + \beta_2 \mathrm{Rate2}_{it} + \beta_3 \mathrm{DAR}_{it} + \beta_4 \mathrm{SIZE}_{it} + \beta_5 \mathrm{DSO}_{it} + \beta_6 \mathrm{DPO}_{it} + \beta_7 \mathrm{OCR}_{it} + \beta_8 \mathrm{ITR}_{it} + \beta_9 \mathrm{PPEI}_{it} + \mu_{it}$$

Among them, ROA is the ratio of net profit to average total assets, which is used to measure corporate profitability and asset efficiency; Rate1 and Rate2 correspond to the two VAT rate cuts on May 1, 2018 (17%→16%) and April 1, 2019 (16%→13%), respectively, and capture policy shocks in the form of dummy variables, taking 0 before tax reduction and 1 after tax reduction, i is the i-th enterprise, t is the t-th time, β_0 is a constant item, and μ_{it} is a random error item.

The control variable vector X includes: debt asset ratio (DAR) and enterprise scale (SIZE), days sales out-standing (DSO) and days payable outstanding (DPO), operating cost ratio (OCR), inventory turnover ratio (ITR), PPE investment (PPEI) measures capital expenditure intensity. The variable selection is comprehensively referenced to the research of S. H. Park [8], B. Ramaseshan [9], to exclude other performance interference.

The sample selection follows the following principles: companies that were listed after 2018, had been *ST or ST, had serious financial data missing, and were not vehicle manufacturers were eliminated, and 82 companies were retained. The data is mainly taken from CSMAR, and the missing quarterly values are supplemented by cumulative value differences. Given that the timing of the three VAT adjustments is clear and the policy transmission is rapid, it can be regarded as an exogenous shock to avoid estimation bias.

Based on the above analysis, the research hypothesis is put forward: the reduction of VAT tax rate has a positive impact on the corporate performance of automobile manufacturers.

4. Research results

The operating ability of an enterprise is affected by various financial indicators. Previous scholars mostly used the total profit to analyze the impact of tax rate adjustments on automobile manufacturing enterprises [10, 11], but a single profit indicator is not comprehensive enough to measure an enterprise's operating ability.

In order to measure the profitability of enterprises more reasonably, this paper adopts the comprehensive indicator of return on assets instead of the single financial indicator of total profit. Return on assets is represented by the ratio of net profit to average total assets, where net profit is the quarterly data compiled and calculated based on the CSMAR database. Figure 3 shows the average change in the return on assets of the sample automobile manufacturing enterprises before and after the adjustment of the VAT tax rate.

Through the observation of Figure 3, no obvious rules have been found in the return on assets of the automobile manufacturing industry. During the implementation of the 2018 tax rate, the return on assets of 17 enterprises increased slightly, accounting for 20.73% of the overall sample, a relatively small proportion. During the implementation of the tax rate in 2019, 26 companies had an increase in their return on assets, accounting

for 31.82% of the total sample, a relatively small proportion. Therefore, it is speculated that the reduction of the VAT tax rate has little impact on the performance of automobile manufacturers.

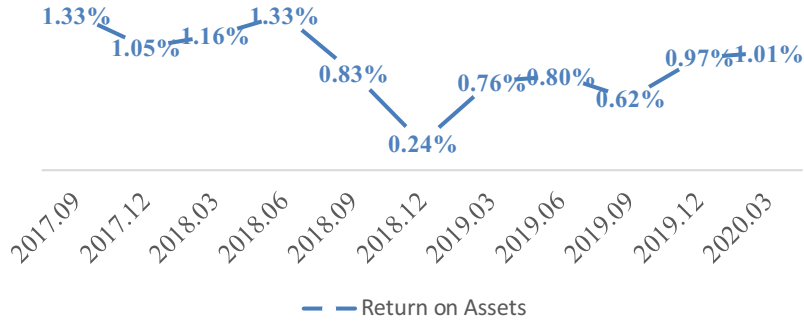


Figure 3. The average change in the return on assets of sample automobile manufacturers before and after VAT tax rate adjustment.

This paper takes the data of listed companies in the automobile manufacturing industry as variables. After analysis and sorting, the data is statistically described using stata16.0 software. The descriptive statistics of related variables are shown in Table 1.

Table 1. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
ROA	902	0.00923	0.0216	-0.551	0.117
DAR	902	0.491	0.132	0.0148	0.993
SIZE	902	9.732	0.598	8.609	11.85
DSO	902	0.231	0.296	0.000	9.521
DPO	902	0.277	0.251	0.000	1.824
OCR	902	0.793	0.0891	0.295	1.061
ITR	902	3.293	3.083	0.159	26.59
PPEI	902	9754	5893	-45139	85314

From the descriptive statistical results in Table 1, it can be seen that the maximum return on assets is 0.117, the minimum is -0.551, and the standard deviation is 0.0216, indicating that there are large differences in the profitability of the sample companies. The average debt asset ratio is 0.491, and the optimal ratio should be between 0.4 and 0.6, in this interval, it means that the capital of the enterprise is operating normally, and the enterprise can have sufficient funds to carry out business activities. The higher the asset-liability ratio, the more debt the enterprise has, the less tax it may pay, and the lower tax burden, but if it is too high, it will make it difficult for the enterprise to raise funds and operate. Therefore, the automotive manufacturing industry generally has a good solvency. The maximum value of the enterprise size is 11.85, and the minimum value is 8.609, so it can be shown that there is no big difference in the scale of the automobile manufacturing industry. The maximum values of days sales outstanding and days payable outstanding are 9.521 and 1.824, indicating that auto companies are more dependent on dealers and are in a weak position in price negotiations with dealers. There is a big gap between the maximum and minimum values of PPE investment and

inventory turnover rate, which shows that the management methods of inventory and PPE of automobile enterprises are very different.

Hausman test was performed before regression analysis. According to the test results, the P value of the Hausman test is 0.0000<0.05, indicating that the null hypothesis is rejected. Therefore, it is more appropriate to choose a fixed effect regression model.

Taking return on assets (ROA) as the explained variable, comparing the impact of twice VAT tax rate adjustment on the performance of automobile manufacturers, the regression results are shown in Table 2.

Table 2. Regression results of VAT tax rate adjustment on corporate performance

VARIABLES	ROA
RAT1	-0.004592
	(-2.533)
RAT2	-0.002472***
	(-0.145)
DAR	-0.112597***
	(-5.638)
SIZE	0.068581***
	(4.984)
DSO	-0.031419***
	(-5.573)
DPO	0.001659
	(0.577)
OCR	-0.123926***
	(-6.784)
ITR	6.01E-05
	(0.173)
PPEI	9.81E-13
	(0.665)
Prob>F	0.000
R-squared	0.258369

Notes: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

According to the results in Table 2, R2 is 0.258369. Observing the F test and P value, it can be seen that P is 0.0000, which is obviously less than 0.01, indicating that there is a clear correlation between the independent variable and the dependent variable, and the regression model is overall significant. The correlation coefficient of the explanatory variable Rate1 is -0.004592, the correlation coefficient of Rate2 is -0.002472, in 2018, the significance test was not passed. In 2019, the VAT tax rate was negatively correlated with corporate performance, and the assumption was not verified. This happens for the following reasons:

The tax rate fell by 1% in 2018 and 3% in 2019, which shows that the greater the tax rate reduction, the greater the impact on corporate performance. The insignificant 2018 may be because the tax rate reduction is too small, and there are many factors that affect corporate performance. Enterprise performance is more related to the enterprise's own asset structure and financial status.

The ratio of cost to income can reflect the company's ability to control costs. The higher the ratio, the lower the company's operating profit. Operating cost ratio and debt asset ratio are significantly negatively correlated with corporate performance at the 1% level, indicating that the more operating costs and corporate debt, the lower corporate performance.

The correlation coefficient of enterprise scale is 0.068581, indicating that enterprise scale and performance are significantly positively correlated, the larger the enterprise scale, the more obvious the performance improvement.

There is a negative relationship between days sales outstanding and firm performance at a significance level of 1%. Therefore, the higher the bargaining power of dealers, it will weaken the bargaining power of auto companies themselves, resulting in relatively weak bargaining power of the companies themselves, and the period of accounts receivable is too long. Automobile manufacturers are in a weak position in price negotiations, and dealers will force them to make price concessions, which will lead to a decline in the profit margin and performance of the automobile manufacturing industry.

For the problem that the days payable outstanding of the enterprise did not pass the significance test, by looking at the financial reports of automobile manufacturers, it is found that the "sales ratio of the top five customers" of automobile companies is much higher than the "proportion of purchases from the top five suppliers". This shows that for automobile manufacturers, the concentration of dealers is very high, and the strong bargaining power of dealers will put the company in a weak position in price negotiations with dealers, and its performance will be easily affected, while the suppliers are very scattered, which has little impact on the performance of automobile manufacturers.

The robustness test replaces ROA in the original model with return on equity (ROE). The results show that the overall model is significant, Rate1 fails the significance test, and the correlation coefficient of Rate2 is -0.003694. There is a negative relationship between days sales outstanding and corporate performance at a significance level of 1%, which is similar to the above empirical results. In summary, it shows that the above empirical research is robust.

In Hangzhou, China, we can clearly see the chain effect of the VAT rate cut and supporting policies on the automotive industry chain. In April 2019, the manufacturing tax rate was reduced from 16% to 13%. Hangzhou Geely Automobile Co., Ltd. estimated that it could pay 75 million yuan less in VAT that year. Combined with a one-time deduction of 23 million yuan for real estate and a 20-million-yuan tax refund at the end of the period, it released more than 110 million yuan in funds throughout the year. The company then used all this "tax reduction benefit" for equipment renewal and technology upgrades, and lowered the prices of some models to pass the policy dividends directly to consumers. In the upstream of Geely's supply chain, Zhejiang Jingang Automobile Co., Ltd. added 4.46 million yuan in deductions in 2016 because the input tax on factory construction was deductible. In 2017, it continued to deduct 2.97 million yuan. After the company's cash flow improved, it quickly expanded its fixed asset investment. What is more noteworthy is that the "bank-tax interaction" mechanism between Geely and Jingang has played an amplifying effect: relying on its A-level tax credit for three consecutive years, Jingang Automobile obtained a low-interest loan of 50 million yuan from Hangzhou Bank, with the interest rate 15% lower than the benchmark, further strengthening the virtuous cycle of tax reduction-capacity expansion-reinvestment.

5. Conclusion

This paper uses the data of 82 Shanghai and Shenzhen A-share vehicle companies from 2017Q3 to 2020Q1 as samples to empirically test the impact of the two VAT cuts on corporate performance. The results show that the coefficient of -0.0046 in 2018 (a decrease of 1%) is not significant, and the coefficient of -0.0025 in 2019 (a decrease of 3%) is significantly negative. The greater the reduction, the more obvious the negative impact, indicating that the tax reduction is insufficient or the company's weak ability to pass on has led to the failure to realize dividends. The operating cost rate and debt-to-asset ratio

have a significant negative impact on performance. Companies need to strictly control expenses and optimize capital structure; scale expansion has a positive but marginal diminishing effect on performance, and should avoid blind expansion. The turnover days of accounts receivable and accounts payable reflect the bargaining power of upstream and downstream: when customers or suppliers are strong, the tax burden is difficult to pass on, and the benefits of tax reduction are eroded.

Value-added tax runs through the entire process of procurement, production, and sales. Enterprises must strengthen tax planning and financial management: regularly clean up inventory and reduce backlogs; adjust the pace of procurement according to the tax rate nodes to increase input tax deductions; negotiate price cuts with upstream and downstream companies to share dividends; the financial department should follow the policy and legally strive for preferential treatment.

At the government level, the three tax rate simplifications from 2017 to 2019 were aimed at stimulating domestic demand and improving distribution, but the annual adjustment rhythm has raised the adaptation costs of enterprises and tax authorities. In the future, we should fully evaluate industry differences, set a reasonable transition period, reduce policy friction, and continuously optimize the tax rate structure to balance fiscal sustainability and corporate burden reduction.

This paper takes the automobile manufacturing industry as the research object, establishes a fixed effect model to measure the impact of the VAT rate reduction on the performance of the automobile manufacturing industry, and analyzes the data disclosed by its listed companies with quantitative and qualitative research methods.

Discuss from the micro perspective of the enterprise, through the establishment of a model, measure the impact of VAT tax rate reduction on the performance of the automobile manufacturing industry. It also analyzes the differences in the impact of twice tax rate adjustments, providing direct evidence for the impact of tax rate reductions on automobile manufacturers. Based on this, it puts forward targeted suggestions from the perspectives of both enterprises and the government. The VAT rate adjustment has not been implemented for a long time, and the research on the impact on the automobile manufacturing industry can be further improved and supplemented. Therefore, its long-term effects and related effects with other industries can be analyzed in depth in future research.

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Opportunities and Challenges in the Development of Autonomous Driving in China and the United States

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Abstract. This article conducts a systematic analysis of the opportunities and challenges in autonomous driving technology development across China and the United States. It evaluates comparative advantages in both nations through the lenses of market scale, policy frameworks, and technological innovation, while critically examining industry-wide barriers, including safety challenges, raw material supply risks, environmental impacts and unresolved liability frameworks. The study further presents market penetration forecasts and actionable policy recommendations to guide future progress. Practically, these insights inform stakeholders' strategic prioritization of safety-driven innovation and cross-sector collaboration, underscoring the imperative to address technical and regulatory gaps for sustainable global adoption.

Keywords. Autonomous driving, Artificial intelligence, Safety, Liability division, Market penetration rate

1. Introduction

Autonomous driving technology, as a typical representative of the integration of artificial intelligence and the automotive industry, has become a strategic highland in global technological competition. China and the United States, leveraging their respective advantages in market size, technological innovation, and policy support, have become the leaders in global autonomous driving development. According to McKinsey's prediction, by 2030, the global market size of autonomous vehicles will reach $400 billion, with the Chinese and American markets accounting for more than 75% of the share. However, the rapid development of technology is accompanied by many challenges. To contextualize these issues, it is essential to understand the SAE International's six-tiered classification system (L0-L5), which defines automation levels based on human-machine roles: Level 2 (Partial Automation): Systems simultaneously manage steering and acceleration/braking, but drivers must maintain constant supervision and readiness to intervene. Level 3 (Conditional Automation): Vehicles handle all driving tasks within specific operational domains (e.g., highway driving at set speeds), though human intervention remains legally required when systems issue takeover requests. Level 4 (High Automation): Fully autonomous operation without

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human intervention is possible in predefined geofenced areas. Level 5 (Full Automation): The pinnacle of automation, where vehicles perform all driving functions under all conditions—urban, rural, extreme weather, etc.—without geographic or environmental limitations. No steering wheel or pedals are required, as human intervention becomes technically obsolete. This hierarchical framework directly impacts safety and responsibility allocation, but raw material challenge and environmental impact further complicate commercialization. For instance, geopolitical fragmentation disrupts raw material supply chains—China controls 95% of global gallium production critical for lidar sensors, while U.S. export restrictions on NVIDIA A100 GPUs hinder Chinese development of deep learning algorithms. Concurrently, environmental sustainability remains uncertain. Although optimized route planning could reduce energy consumption, the carbon footprint of high-performance computing systems and battery recycling challenges for electric fleets may offset anticipated ecological benefits.

2. Opportunities for the Development of Autonomous Driving in China and the United States

2.1. Extensive market size

Both China and the United States have the world's largest automotive consumer markets, providing ample application scenarios for autonomous driving technology. According to data from the China Association of Automobile Manufacturers, in 2022, China's sales of new energy vehicles reached 6.887 million units, increasing by 93.4% year-on-year. Among them, vehicles with L2-level autonomous driving functions accounted for over 40%. The US market also shows a rapid growth trend. According to Statista data, in 2022, the market size of autonomous driving technology in the US reached $4.86 billion, and it is expected to increase to $8.23 billion by 2025 [1]. As the world's largest automobile consumer markets, China and the United States provide unique conditions for the development of autonomous driving technology, and their huge market size lays a solid foundation for the wide application of autonomous driving technology.

Table 1. Forecast of Market Penetration Rate of Autonomous Driving in China and the United States (2023-2030)

Year	L3+ penetration rate in China (%)	L3+ penetration rate in United States (%)	The scale of the Chinese market ($B)	The scale of the United States market ($B)
2023	2.5	3.8	58	52
2025	8.2	10.6	185	168
2028	22.7	25.4	520	480
2030	35.2	38.9	890	820

Data source: IHS Markit Autonomous Driving Market Forecast Report (2023).

2.2. Complementary technology routes

Chinese enterprises focus on the vehicle-to-everything (V2X) technology route and make up for the deficiency of single-vehicle intelligence through the construction of infrastructure such as 5G and edge computing. Taking Beijing Yizhuang Economic Development Zone as an example, more than 300 intelligent intersections have been

deployed within 600 square kilometers, and each intersection is standard equipped with Multi-access Edge Computing (MEC) and C-V2X communication modules to form a holistic traffic perception network. This roadside intelligent facility can process multi-modal data from lidar, cameras and weather monitoring equipment in real time, and accurately push the traffic situation within 200 meters ahead to the vehicle through the 5G network. American enterprises are more focused on single-vehicle intelligence. Companies like Waymo and Cruise maintain a leading position in L4-level autonomous driving algorithms. The lidar point cloud density carried by Waymo's sixth generation autonomous driving system reaches 1.2 million points per second, and with the vision large model of Transformer architecture, the behavior prediction of 32 types of traffic participants within 300 meters can be completed in 0.1 seconds. The MotionLM model improves the interaction success rate of vehicles to 92% in complex road conditions in San Francisco by deconstructing traffic scenes into ‘multi-agent conversations’ Cruise's original ‘Virtual Blind Spot Compensation’ technology, which uses generative AI to simulate the potential risks of occluded areas, reduced the response time of collision warning at a San Francisco T-junction to 0.3 seconds, better than the average reaction time of human drivers of 0.8 seconds.

2.3. Differentiated policy support

China has adopted the policy path of ‘top-level design + pilot demonstration’. Since 2020, it has issued policy documents such as ‘Strategy for Innovative Development of Intelligent Vehicles’ and ‘Development Plan for New Energy Vehicle Industry (2021-2035)’, and set up intelligent connected vehicle demonstration zones in Beijing, Shanghai and other places [2]. The United States pays more attention to legislative safeguards and technical standards, with the ‘AV START Act’ passed at the federal level and differentiated regulations introduced by states.

3. Challenges in the Development of autonomous driving

3.1. Security challenges

Autonomous driving in China and the US faces many challenges in terms of safety.

3.1.1. Perception System Risks

In terms of perception system, it is necessary to deal with the recognition problem in complex environment. MIT research shows that in rain and snow weather conditions, the ranging error of lidar may increase by 15%-20%, and the target recognition accuracy of camera in low light environment decreases by more than 30% [3]. Corner cases are particularly difficult to deal with. NHTSA statistics show that about 23% of autonomous vehicle accidents involve misjudgments about rare traffic scenarios.

3.1.2. Algorithmic Transparency

At the decision algorithm level, the "black box" characteristic of deep learning algorithms makes the decision process difficult to explain. According to a study

published in IEEE Transactions on Intelligent Transportation Systems, adversarial example attacks can make autonomous driving systems make wrong decisions in 98% of test cases. The decision optimization in multi-agent game scenarios is still a technical difficulty [4], especially in complex scenarios such as unprotected left turn and confluence area. In addition, network information security risks are increasingly prominent with the popularization of Internet of vehicles technology.

3.1.3. Software security

Software security has emerged as a silent threat to AD systems. In 2023, Tesla's Full Self-Driving (FSD) system was hacked via a CAN bus injection attack, exposing vulnerabilities in its over-the-air (OTA) update protocol. Similarly, China's Baidu Apollo platform suffered localization errors in Guangzhou due to GPS spoofing, highlighting risks in infrastructure-dependent systems.

3.2. The problem of raw material support

Geopolitical fragmentation exacerbates raw material issues issues. China controls 95% of global gallium production, critical for lidar and advanced radar chips, while U.S. export controls on NVIDIA A100 GPUs disrupt Chinese training pipelines for deep learning models. Data localization policies further complicate cross-border collaboration, with China's Data Security Law mandating domestic storage of AD-related data and the U.S. lacking federal data standards, leading to fragmentation across 38 state-level regulatory regimes. Standard-setting wars, such as China's push for C-V2X versus the U.S.'s DSRC protocol, create compatibility risks for automakers.

3.3. Environmental impact

In addition to safety and liability concerns, the environmental impact of autonomous driving introduces another layer of complexity. While optimized route planning and shared mobility models could theoretically reduce energy consumption and emissions, the technology's real-world ecological footprint remains ambiguous. The energy demands of high-performance computing systems, battery recycling challenges for electric fleets, and potential rebound effects from increased vehicle utilization may offset anticipated sustainability gains.

3.4. The problem of responsibility division

In the commercialization process of autonomous driving technology, the division of responsibility has become a common problem faced by China and the United States. The United States adopts the legislative model of separation of powers between federal and state governments. The federal government formulates the macro regulatory framework through the Autonomous Driving Act, but the specific responsibility determination rules are legislated by each state on its own, resulting in significant regional differences in judicial practice and inconsistent standards. For example, California requires mandatory disclosure of accident data, while Arizona focuses more on post-hoc accountability, making compliance more difficult for companies operating across state lines. China has established a unified liability determination system

through documents such 'Road Test Management Specification for Intelligent Connected Vehicles'. However, in the L3 level and above autonomous driving scenarios, the liability boundary between human drivers and intelligent systems is still not clear enough [5]. When artificial intelligence decision-making conflicts with traditional traffic laws and regulations, the current tort liability law is difficult to directly adapt to the technical characteristics, and the technical "black box" characteristics create challenges in determining the cause of the accident and collecting evidence. A deeper challenge is that when the system faces ethical dilemmas such as trolley problem, the law how to balance principle of technology neutrality and human values. This philosophical dispute is remaking the legal basis of liability division, requiring legislators to break through the traditional fault liability framework and construct a multi-dimensional liability system including technical safety benchmarks, ethical guidelines and insurance relief.

4. Recommendations

4.1. Strengthen the research and development of security technologies

Firstly, a national autonomous driving safety test platform should be established, and a test scenario library covering more than 90% corner cases is constructed. The platform should integrate virtual simulation and real vehicle testing capabilities, and form a test system of 'combination of virtual and real, collaboration of software and hardware'. The scenario library construction should adopt the 'data-driven + expert knowledge' dual-track method, systematically collect road traffic accident data, combine expert experience to construct high-risk scenarios, and generate diversified test conditions through parametric mutation. In particular, higher density test coverage should be designed for high-risk scenarios such as extreme weather and complex road conditions. Refer to the UL 4600 standard to establish the whole life cycle safety assessment system. The UL 4600 standard focuses on the safety demonstration of unmanned driving systems, covering the full life cycle from design and testing to operation and retirement. It is suggested to build a closed-loop security management mechanism of 'design-verify-monitoring-upgrade', introduce formal verification and fault injection test methods, and establish an OTA upgrade security evaluation process to ensure that no new risks are introduced into software iteration.

4.2. Supply diversification and tech innovation

The geopolitical fragmentation of critical mineral supplies necessitates a multifaceted strategic approach. First, enterprises must diversify procurement channels for strategic materials such as gallium, establishing partnerships with multiple global suppliers to reduce dependency on single-source nations. Simultaneously, accelerated research and development efforts should focus on identifying alternative materials and technological solutions−for instance, developing radar systems that eliminate reliance on gallium-based components. Furthermore, fostering international collaboration to establish universally adopted technical standards for autonomous vehicles (AVs) can mitigate compatibility risks arising from divergent regulatory frameworks, such as the ongoing C-V2X versus DSRC protocol competition.

4.3. Enhance Tech and Policy for Environment

To address the environmental challenges posed by autonomous driving, a dual focus on technological optimization and regulatory frameworks is essential. Technologically, advancements in energy-efficient algorithms and powertrain systems are critical. This includes refining route planning algorithms to minimize energy consumption and developing lightweight materials to reduce vehicle weight. Policymakers must enact stringent environmental regulations, such as mandating the use of clean energy sources for autonomous vehicle fleets and establishing comprehensive battery recycling programs to manage end-of-life electric vehicle batteries.

4.4. Improve the regulatory and standard system

To solve the problem of responsibility division for autonomous driving, China and the United States should explore a multi-dimensional collaborative governance path. At the legislative level, it is suggested to build a three-level coordination mechanism of 'federal to state to industry', in which the federal will unify the framework of technical safety standards and ethical guidelines, give the states moderate discretion in the responsibility determination procedure, and promote industry organizations to formulate dynamically updated technical standards and data sharing agreements to alleviate the pressure of cross-regional operation compliance. China can further refine the fault determination rules of autonomous driving scenarios in the Road Traffic Safety Law, establish a hierarchical responsibility system of 'human supervisors, system designers and operating subjects', clarify the mandatory installation of Event Data Recorder (EDR) and Data Storage System for Automated Driving (DSSAD) in vehicles above L3 level, and break the dilemma of technical black-box forensics.

5. Conclusion

The development of autonomous driving technology in China and the United States presents significant opportunities and challenges. Both countries boast vast automotive markets, driving innovation through complementary technological approaches−China emphasizes vehicle-to-everything (V2X) infrastructure, while the United States leads in single-vehicle intelligence. Policy frameworks differ, with China adopting top-down design and pilot programs, and the U.S. relying on federal legislation and state-level regulations. Key challenges include safety risks from perception limitations and algorithm opacity, geopolitical supply chain fragmentation, environmental impacts of high-energy computing, and unresolved liability frameworks. Addressing these issues requires enhanced safety research, diversified resource strategies, eco-friendly technological advancements, and collaborative regulatory reforms to ensure sustainable progress.

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CTA Image Segmentation of Pulmonary Embolism Based on RAUNet

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Abstract. Pulmonary Embolism (PE) is an acute circulatory system disease caused by emboli (such as thrombi, fat, air or tumor cells, etc.) from the systemic circulation blocking the pulmonary artery or its branches. Its severity is second only to myocardial infarction and sudden death, highlighting the need for efficient diagnostic methods. UNet is a classic image segmentation model that has shown great potential in medical image segmentation. However, its limitations in segmenting small targets result in the blurring or omission of small thrombi or micro-foci in PE, making it difficult to accurately distinguish low-contrast or highly inter-class difference lesions. To address this issue, this study proposes a RAUNet model based on a residual attention perception mechanism. The model builds upon the classic UNet architecture by introducing residual learning modules and attention mechanisms. The stacking of residual blocks effectively alleviates the vanishing gradient problem in deep network training, while the attention module adaptively weights the feature maps to enhance the feature expression ability of key parts. Experimental results show that the model achieves a Dice coefficient of 79.1% on the FUMPE dataset, demonstrating its great potential in the segmentation of PE images.

Keywords. PE, Image segmentation, RAUNet, Residual Attention Mechanism, Dice Coefficient

1. Introduction

Pulmonary embolism is a fatal disease caused by the detachment of intravascular emboli and the obstruction of the pulmonary artery or its branches. According to the location of the embolus obstruction, it can be classified into central type, lobar type, segmental type and subsegmental type. Large emboli can lead to acute right heart failure and even sudden death. The mortality rate without treatment is as high as 30%, while it can be reduced to 2% - 11% with timely intervention. Epidemiological data show that the annual incidence rate of pulmonary embolism among hospitalized patients in China is 14.19 per 100,000, and it increases significantly with age, with over 75% of patients being over 60 years old [1]. Computed tomography pulmonary

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angiography (CTPA) is the "gold standard" for diagnosing PE. Through contrast enhancement, it can clearly show the filling defect in the pulmonary artery. However, the diagnosis of PE faces multiple challenges: radiologists often need to analyze many CT slices, which is time-consuming and prone to fatigue and misdiagnosis; and the precise interpretation of imaging features is highly dependent on the experience of radiologists. To improve the efficiency of pulmonary embolism diagnosis, extract lesions in a timely manner, and reduce the workload of doctors, computer-aided detection (CAD) technology is usually adopted in clinical practice.

In recent years, UNet has gradually become a classic model in the field of medical image segmentation due to its symmetrical encoder-decoder structure and skip connection design. Its core lies in fusing features of different resolutions through skip connections, preserving low-level detail information and enhancing the reconstruction ability of high-level semantic features, significantly improving the segmentation accuracy in various complex medical tasks [2]-[4]. However, the traditional UNet network still has problems such as insufficient multi-scale feature fusion, leading to loss of detail information and large segmentation errors in boundary blur areas; it is difficult to adaptively adjust the focus area for complex lesion regions and is easily disturbed by noise [5]. To address these issues, researchers have proposed various improvement schemes. For example, UNet++ redesigns the network structure through dense skip connections to enhance the aggregation ability of multi-scale features [6],[7]. ResUNet alleviates the vanishing gradient problem in deep networks through residual connections [8]-[10]. Attention UNet introduces an attention mechanism to dynamically weight the features of key regions and reduce the interference of irrelevant background [11]-[13]. Based on the above research, this paper uses RAUNet (Residual Attention U-Net) to segment pulmonary embolism images. This model adopts ResidualBlock in the encoder to preserve shallow details through skip connections, alleviate the vanishing gradient problem, and improve the training stability of deep networks. In the decoding stage, the AttentionGate module is introduced to dynamically fuse the features of the encoder and decoder through a gating mechanism, enhance the boundary response of lesion regions, and suppress background interference. By integrating residual learning and attention mechanisms, it significantly improves the segmentation accuracy of pulmonary embolism while retaining the advantages of UNet, providing more reliable support for clinical diagnosis.

2. Methods

2.1. Data sources

This study employs the publicly available FUMPE (Ferdowsi University of Mashhad's PE dataset) as the research dataset. It contains a total of 8,792 slices of CTA images from 35 subjects, with 3,438 PE regions labeled in binary form, far exceeding similar datasets. The original images are in DICOM format, and the Mask files are in MAT format [14]. The large data scale and diverse embolism morphologies of this dataset can provide massive and precise data support for model training and evaluation. The dataset can be freely downloaded from figshare (https://figshare.com/collections/FUMPE/4107803).

2.2. RAUnet model

Like many medical imaging tasks, pulmonary embolism segmentation faces the challenge of scarce annotation data. Recent research [15] shows that the learning algorithm optimized for small data can effectively alleviate this problem, which prompted us to introduce the residual and attention mechanism into RAUNet to improve the performance of the model. The RAUNet model is an improved medical image segmentation model based on the classic UNet architecture [2]. Its core innovation lies in the introduction of residual learning mechanisms and dynamic attention feature calibration strategies. The model consists of multi-level residual encoding modules, multi-scale attention gating modules, and feature refinement modules. The overall structure of the model adopts a symmetrical encoder-decoder architecture.

For the encoding part, we introduce a residual feature extraction module, which uses a double convolutional layer structure and establishes cross-layer shortcut connections through identity mapping [16]. This residual module is composed of two 3×3 convolutional layers, each followed by batch normalization (BatchNorm). Then, we use the parametric rectified linear unit (PReLU) [17] as the activation function for this part. At the same time, we set padding=1 to keep the size of the feature map unchanged and disable the bias, transferring the bias function to the batch normalization layer (BatchNorm).

In the decoding stage, this model achieves adaptive fusion of features from the encoder and decoder by introducing an attention mechanism [18] to enhance the semantic expression of key regions. This module consists of three parts: channel compression, feature fusion, and attention weight generation. First, 1×1 convolutions are used to compress the channel dimensions of the gating signals from the decoder and the skip connection features from the encoder, projecting them into a shared intermediate channel space to effectively reduce computational complexity. Then, the skip features are upsampled to the spatial resolution of the gating signals through bilinear interpolation [19] and elementwise added to the gating features. After activation by the parametric rectified linear unit (PReLU), the combined feature response is generated. Next, a 1×1 convolution is used to compress the combined features into a single-channel spatial attention map, which is normalized to a probability distribution through the Sigmoid function. Finally, this weight is used to spatially modulate the original gating signal to achieve feature selection. The overall model structure is shown in Fig 1.

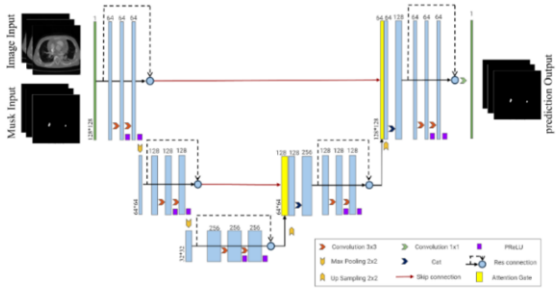


Figure 1. The model structure of our RAUNet

3. Results

In the task of data splitting, this study employed the hold-out validation method for dataset partitioning. Specifically, the original dataset was divided into a training set and a validation set in an 8:2 ratio through stratified random sampling, with 20% randomly selected as the hold-out validation. Subsequently, the performance of the RAUNet model was evaluated using metrics such as the Dice coefficient, F1 score, accuracy, sensitivity, and precision. The visualization of its performance over 100 epochs is shown in Fig 2.

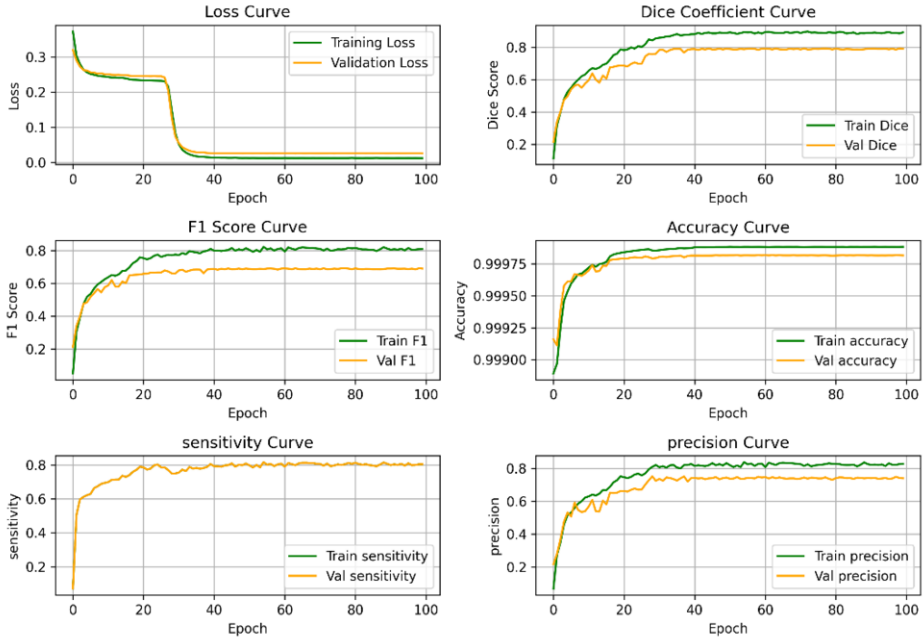


Figure 2. Graphs of the evaluation metrics

We compared the predicted images with the original images and the gold standard images annotated by doctors and overlaid the predicted masks on the original images for comparative analysis, as shown in Fig 3. The leftmost image is the original CTA image of pulmonary embolism in the FUMPE dataset, followed by the gold standard image, the segmentation result predicted by the model, and the rightmost image shows the original image overlaid on the lesion area.

Finally, to verify the model's performance, we conducted a comparative experiment between RAUNet and the classic UNet and ResUNet under the same experimental conditions and preprocessing methods. The results showed that the Dice coefficient of the RAUNet model in the pulmonary embolism task was superior to the latter two. The average Dice coefficient of RAUNet after stabilization reached 79.1%. The comparison chart is shown in Fig 4.

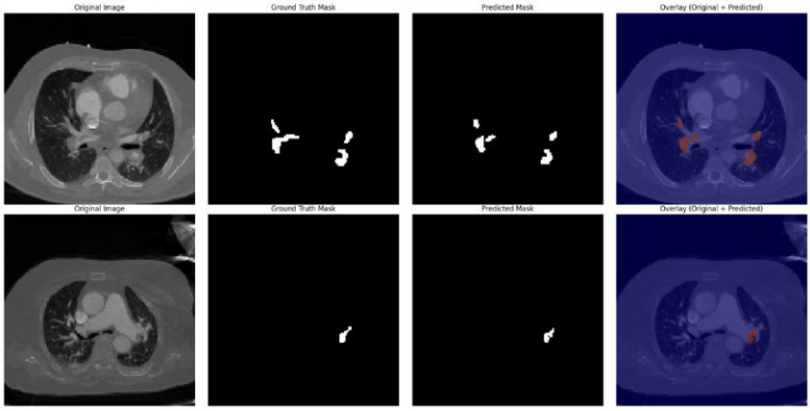


Figure 3. Comparison of binary masks with predictions

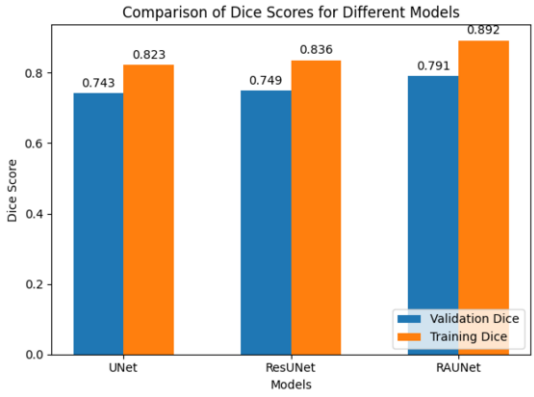


Figure 4. Dice coefficient comparison

4. Discussion

Firstly, we downloaded the CTA images of pulmonary embolism and the corresponding binary masks from the open-source website and stored them in a one-to-one correspondence. Meanwhile, to ensure the efficient completion of the segmentation task and reduce problems such as excessive training time and gradient explosion caused by too many parameters during model training, as well as to alleviate the difficulty of the model in extracting image features, we uniformly scaled the original CTA images of size 512*512 and their binary masks in the dataset to 128*128. Since the mask itself is binary, to ensure the integrity of the discrete labels, we used the nearest neighbor interpolation for image scaling [20]. Then, the preprocessed images were input into RAUNet for training, with a training period of 100 epochs and a batch size of 8.

At the training level, this model adopts a hybrid loss function combining BCEWithLogitsLoss and Dice Loss [21] for parameter tuning, which effectively complements the architectural innovation of the model. From the results, the RAUNet

model proposed in this study shows significant advantages in the segmentation task of pulmonary embolism CTA images, with a Dice coefficient of 79.1%, outperforming the classic UNet and ResUNet models. This result validates the effectiveness of the residual connection and attention mechanism in the model design.

Compared with the traditional UNet architecture, this model adds residual modules in the encoding stage, enhancing feature reuse through residual connections. The model retains shallow feature information such as texture details in the deep network, alleviating the problem of gradient vanishing. Compared with the ordinary convolutional blocks in the traditional UNet, the residual structure enables the network to learn complex features more efficiently, making the model's segmentation of small embolism lesions more complete. For the decoding stage, we added an attention gate to optimize feature fusion. Through dynamic weight allocation, it suppresses the interference of background regions such as vessel walls in the skip connections, while enhancing the feature response in the lesion regions. The comparison between RAUNet and ResUNet in Figure 4 shows that the attention mechanism significantly improves the accuracy of small target segmentation, verifying the adaptability of the attention gate in complex anatomical structures. At the same time, to adapt and reduce the demand for computing power [22],[23], in the AttentionGate module, we introduced an inter_channels to compress the input feature channels, significantly reducing the number of model parameters, thereby meeting the training requirements under low computing power.

The high-precision segmentation of RAUNet can provide reliable support for the computer-aided diagnosis (CAD) system of pulmonary embolism. However, this study still has the following limitations:

(1) Insufficient data diversity: The training data is only from a single center (FUMPE dataset);

(2) Single pathological type: The current model is only trained for pulmonary embolism.

For the first issue, in the future, we will incorporate multi-center and multi-device data for training to verify generalization; for the second issue, in the future, the method of transfer learning can be used for reference [24] and extended to other segmentation tasks such as aneurysm and vascular stenosis to carry out transfer learning of similar tasks.

During the training, we used NVIDIA GeForce GTX 1660 Ti as the training equipment. The model trained 100epoch in total, and the training time was 4 hours and 9 minutes. At the same time, input a single 512*512 CTA image into the trained model, and the segmentation results can be output within 2 seconds. In the future, we will use more GPUs to verify the lightness of our model.

5. Conclusions

This study proposes the RAUNet model that integrates residual learning and attention mechanism, achieving a Dice coefficient of 79.1% on the FUMPE dataset, providing an efficient solution for intelligent diagnosis of pulmonary embolism. In the future, computational efficiency will be optimized and multi-center validation will be expanded to promote the practical application of clinical auxiliary systems.

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Numerical Simulation Verification of Unsteady Aerodynamic Model with Forced/Free Vibration of Airframe/Propulsion Integrated Aircraft Based on Parametric Dynamic Derivative

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Abstract. In the field of aerodynamics, the mathematical model of unsteady aerodynamic forces is typically employed to identify the motion state variables that aerodynamic forces depend on and to establish the mathematical relationships among these variables. In this paper, the unsteady aerodynamic parameter model is established based on the improved Etkin model by using the concept of parameterized dynamic derivative, which can better describe the nonlinear characteristics of dynamic characteristics in large amplitude of vibration. In the hypersonic condition, the airframe/propulsive integrated aircraft is used to calculate different dynamic parameters of unsteady aerodynamic model. The simulation of the air-breathing hypersonic vehicle shows that the unsteady aerodynamic model based on the parameterized dynamic derivative concept can accurately predict the aerodynamic data and flow field parameters under nonlinear conditions. Large angle of attack and complex shape of unsteady flow field have strong hysteresis effect, and the influence of time-history effect on unsteady aerodynamic forces cannot be ignored. Therefore, the simulation accuracy of aerodynamic model for large angle of attack vibration is reduced, but it can still reflect the variation trend of dynamic aerodynamic forces.

Keywords. Pneumatic model, unsteady, hypersonic, forced vibration, free vibration

1. Introduction

In the process of aircraft design and development, acquiring the dynamic handling stability characteristics within the flight envelope is both challenging and resource-intensive. Phenomena such as shock wave-induced separation, vortex motion and breakdown, along with their interactions, cause fluid motion to exhibit pronounced unsteady and nonlinear behaviors, often imparting unforeseen aerodynamic effects on aircraft and potentially leading to disruptive outcomes [1]. To enhance the prediction of unsteady aerodynamic characteristics, aerodynamic modeling techniques have been extensively employed in aircraft design processes [2]. The methodology for modeling

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unsteady aerodynamics has consistently been a critical research focus in aerodynamics [3]. A mathematical model of unsteady aerodynamic forces is utilized to identify the state variables that aerodynamic forces depend on and establish the mathematical relationships among them.

Although the computational fluid dynamics (CFD) method is capable of capturing detailed flow field information, offering a high degree of freedom (typically exceeding 10^4), and enabling dynamic simulation of unsteady complex flow fields, the computational cost associated with directly applying the CFD method to complex flow fields remains prohibitively high. This limitation restricts its application in multidisciplinary optimization, aeroelasticity, and flight dynamics research [4-5]. To address this challenge, the rapidly advancing reduced-order modeling techniques developed in recent years can either fully or partially substitute for the fundamental dynamic characteristics of the original complex systems [6]. Through mathematical simplification, the computational cost (including computer memory, computing time, and design cycle) of reduced-order models is reduced by several orders of magnitude compared to the original complex system. For CFD, the adoption of aerodynamic reduced-order models can significantly decrease system computation time while expanding their scope and depth of application. Currently, widely used aerodynamic reduced-order models in flight dynamics research primarily include the Volterra series model, the proper orthogonal decomposition model, the regression model, the radial basis function interpolation model, and the surrogate model [7-9]. These models improve computational efficiency by 1-2 orders of magnitude while reflecting the nature of statically dominated nonlinear flows [6]. However, when dealing with nonlinear dynamic problems such as aerodynamic bifurcation phenomena and flow field hysteresis, the simulation accuracy of these models tends to decline. Moreover, the current application scope of reduced-order models is predominantly limited to subsonic and transonic simulations of simple geometries like wings, with further development required for the simulation of complex supersonic shapes.

To address the limitations of the order reduction model, the CFD solution method for dynamic derivatives is employed to predict unsteady aerodynamic forces. Bryan and Etkin proposed that dynamic derivatives remain constant over time. However, this assumption has frequently been challenged in the field of unsteady aerodynamics [10-11]. The enhanced Etkin model incorporates time t as a parameter in the reference state, differing from the original model. Calculated or measured dynamic derivatives typically vary with time, aligning with the definition of dynamic stability parameters [12]. When an aircraft operates at small angles of attack, the flow predominantly exhibits adherent characteristics. In such cases, aerodynamic forces often exhibit a linear relationship with motion state parameters. Consequently, dynamic derivatives can be approximated as constants, enabling simplified modeling of unsteady aerodynamic forces. At present, for flight with large angle of attack, there is no proper dynamic model that can fully reflect the characteristics of strong nonlinear dependence of aerodynamic attack angle, time delay effect and cross-coupling of aerodynamic force.

The design of the shape and motion mode of modern aircraft is significantly more intricate compared to that of traditional aircraft. Flight conditions involving high angles of attack and non-zero sideslip angles often lead to highly complex aerodynamic phenomena. Specifically, shock-induced separations, vortex dynamics and breakdowns, as well as their interactions, result in fluid motions exhibiting pronounced unsteady and nonlinear characteristics [13]. The dynamic derivative is no longer a constant, but related to parameters such as angle of attack, angle of sideslip and frequency of reduction, which

has the property of parameterization. Internationally renowned unsteady aerodynamicist Orlik-Rückemann proposed to replace the traditional concept of dynamic derivative with "dynamic stability parameter". In this paper, based on the improved Etkin model, the unsteady aerodynamic parameter model is established by using the concept of parameterized dynamic derivative, which can better describe the nonlinear characteristics of dynamic characteristics in large amplitude of vibration. Under the hypersonic condition, this paper adopts the airframe/propulsion integrated aircraft [14] to carry out the calculation of different dynamic parameters by using the unsteady aerodynamic model, in view of the different forms of forced vibration and free vibration, from the vibration type, the motion parameters, calculation form, comprehensive comparison on accuracy of aerodynamic model based on parameterized dynamic derivative and the aerodynamic force and flow field parameters predicted by CFD method, the accuracy of mathematical models of pneumatic is proved.

2. Computational Fluid Dynamics Formulation

Three-dimensional dimensionless equation Navier-Stokes is used as the governing equation of fluid motion:

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+\frac{\partial G_v}{\partial z} \tag{1}$$

Q is a conserved variable, E, F and G are convective fluxes, E_v, F_v and G_v are viscous fluxes, and the specific form is:

$$Q=(p,pu,pv,pw,pe)^T \tag{2}$$

$$E=\begin{pmatrix} pu \\ pu^2+p \\ puv \\ puw \\ phu \end{pmatrix}, E_v=\frac{1}{Re}\begin{pmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{xz} \\ u\tau_{xx}+v\tau_{xy}+w\tau_{xz}+k'\frac{\partial T}{\partial x} \end{pmatrix} \tag{3}$$

$$F=\begin{pmatrix} pv \\ puv \\ pv^2+p \\ pvw \\ phv \end{pmatrix}, F_v=\frac{1}{Re}\begin{pmatrix} 0 \\ \tau_{yx} \\ \tau_{yy} \\ \tau_{yz} \\ u\tau_{yx}+v\tau_{yy}+w\tau_{yz}+k'\frac{\partial T}{\partial y} \end{pmatrix} \tag{4}$$

$$G=\begin{pmatrix} pw \\ puw \\ pvw \\ pw^2+p \\ phw \end{pmatrix}, G_v=\frac{1}{Re}\begin{pmatrix} 0 \\ \tau_{zx} \\ \tau_{zy} \\ \tau_{zz} \\ u\tau_{zx}+v\tau_{zy}+w\tau_{zz}+k'\frac{\partial T}{\partial z} \end{pmatrix} \tag{5}$$

e is total energy, h is total enthalpy, τ_{ij} is the viscous stress, k' is the heat transfer coefficient. The LU-SGS method only has first-order accuracy, and the numerical simulation of unsteady problems requires the accurate solution of time derivative term [15]. Direct use of the LU-SGS method cannot meet the requirements [16]. Jameson [17] proposed a Dual-timestep method, which can introduce the newton-like virtual time iteration process to the frozen physical time point of ADI or LU type implicit approximate fast algorithm, and improve the lost time precision in the approximate process by sub-iteration [18].

This article uses time derivative of the implicit difference discrete item Eq. (1) of second order $(\theta = 2)$, at the same time introducing virtual items and set as first-order backward difference discrete:

$$J^{-1}\frac{(\theta+1)Q^{p+1}-2\theta Q^{n}+(\theta-1)Q^{n-1}}{2\Delta t}+J^{-1}\frac{Q^{p+1}-Q^{p}}{\Delta\tau}+R(Q^{p+1})=0 \tag{6}$$

It can be combed as:

$$\left(\frac{\theta+1}{2\Delta t/J^{-1}}+\frac{1}{\Delta\tau/J^{-1}}\right)\Delta Q^{p}=-R(Q^{p+1})-\frac{(\theta+1)Q^{p}-2\theta Q^{n}+(\theta-1)Q^{n-1}}{2\Delta t/J^{-1}} \tag{7}$$

The second term in the middle right end of Eq. (7) is the unsteady driving term caused by the duel- time- step method, which is the known term. Linearize Eq. (7), and obtain:

$$\left[\frac{\theta+1}{2\Delta t/J^{-1}}+\frac{1}{\Delta t/J^{-1}}+\left(\delta_{\xi}A+\delta_{\eta}B+\delta_{\zeta}C\right)^{n}\right]\Delta Q^{n}=-R^{*}(Q^{n}) \tag{8}$$

In Eq. (8)

$$R^{*}(Q^{n})=R(Q^{n})-\frac{(\theta+1)Q^{p}-2\theta Q^{n}+(\theta-1)Q^{n-1}}{2\Delta t/J^{-1}} \tag{9}$$

Combed as:

$$(D+L)D^{-1}(D+U)\Delta Q_{i,j,k}^{p}=-R^{*}(Q^{p}) \tag{10}$$

In Eq. (10)

$$D=\left[\frac{\theta+1}{2\Delta t/J^{-1}}+\frac{1}{\Delta t/J^{-1}}+\rho(A)+\rho(B)+\rho(C)\right]I \tag{11}$$

$$L=-A_{i-1,j,k}^{+}-B_{i,j-1,k}^{+}-C_{i,j,k-1}^{+} \tag{12}$$

$$U=+A_{i+1,j,k}^{-}+B_{i,j+1,k}^{-}+C_{i,j,k+1}^{-} \tag{13}$$

The method SGS (Symmetric Gauss-Seidel) is used to solve the problem step by step:

$$\Delta\tilde{Q}_{i,j,k}^{p}=-D^{-1}\left[R(Q^{p})+L\Delta\tilde{Q}_{i,j,k}^{p}\right] \tag{14}$$

$$\Delta\tilde{Q}_{i,j,k}^{p}=-D^{-1}\left[R(Q^{p})+L\Delta\tilde{Q}_{i,j,k}^{p}\right] \tag{15}$$

$$\Delta Q_{i,j,k}^{p}=\Delta\tilde{Q}_{i,j,k}^{p}-D^{-1}U\Delta Q_{i,j,k+1}^{p} \tag{16}$$

Update the flow field of the moment $p+1$ to:

$$Q^{p+1}=Q^{p}+\Delta Q^{p} \tag{17}$$

When the iteration index is $p\to\infty$, virtual time tends to zero, at this time, $Q^{n+1}=Q^{p+1}$, solving the Eq. (1) with time second order accuracy. The dual time step method improves the time accuracy of unsteady flow simulation. The virtual time derivative term adopts the LU-SGS implicit time method, which relaxes the limitation to time step and improves the efficiency of unsteady calculation.

3. Aerodynamic modeling of parameterized dynamic derivative concept

3.1 Mathematical model establishment

The aerodynamic force/moment coefficient C_{λ} is a functional of the Angle of attackα, the siderage Angleβ and its rate of change, as well as the angular velocity components

$p, q, r$of the rolling axis X_b, the pitch axis Y_b, and the yaw axis Z_b. C_λ is related to the entire history of the motion state before the time t under study and can be written in the following form:

$$C_\lambda(t) = C_\lambda\big(\alpha(\xi), \beta(\xi), p(\xi), q(\xi), r(\xi)\big) \qquad -\infty < \xi \le t \tag{18}$$

If only the relationship between the aerodynamic torque coefficient C_m and the Angle of attack $\alpha(\xi)$ is discussed, the Eq. (18) can be simplified as:

$$C_m(t) = C_m\big(\alpha(\xi)\big) \qquad -\infty < \xi \le t \tag{19}$$

Assume the aircraft before $\xi = 0$is steady liner flight, angle of attack isα_0, The following two forms are the motion state:

$$\alpha_1(\xi) = \begin{cases} \alpha(\xi) & 0 \le \xi \le \tau \\ \alpha(\tau) & \xi > \tau \end{cases} \tag{20}$$

$$\alpha_2(\xi) = \begin{cases} \alpha(\xi) & 0 \le \xi \le \tau \\ \alpha(\tau) + \Delta\alpha & \xi > \tau \end{cases} \tag{21}$$

In the Eqs. (20-21), ξ is the time coordinate, τ is a fixed time, when$\xi \le \tau$, $\alpha_1 = \alpha_2$, when $\xi > \tau$, $\alpha_1 - \alpha_2 = \Delta\alpha$. Set t as τ, time axisξ examined at any time corresponding to the state of Eqs. (20-21), its moment coefficients in accordance with Eq. (19) is $C_{m1}(t) = C_m\big(\alpha_1(\xi)\big)$, $C_{m2}(t) = C_m\big(\alpha_2(\xi)\big)$, the $\xi \le t$. When$t > \tau$, $C_{m1}(t) \ne C_{m2}(t)$. If $\Delta C_m(t) = C_{m2}(t) - C_{m1}(t)$, if $\lim\limits_{\substack{\Delta\alpha\to 0 \\ t>\tau}} \frac{\Delta C_m(t)}{\Delta\alpha}$, There is a unique limit, define this limit as an indicator function(indicial response):

$$A = \lim_{\substack{\Delta\alpha\to 0 \\ t>\tau}} \frac{\Delta C_m(t)}{\Delta\alpha} \tag{22}$$

For the Eq. (22), it is not difficult to conclude that aerodynamic moment coefficient difference $\Delta C_m(t)$ under the two kinds of t time is not only related to starting moment$\tau$and observation time t, but also related to the $\Delta\alpha$ and attack angle α before τ:

$$\Delta C_m(t) = \Delta C_m[\alpha(\xi); \Delta\alpha, \tau, t] \qquad -\infty \le \xi \le \tau \tag{23}$$

Based on Eq. (23):

$$A = A[\alpha(\xi); t, \tau] \qquad -\infty \le \xi \le \tau \tag{24}$$

According to the definition of indicating function Eqs. (23-24), when $t>0$, aerodynamic moment coefficient can be written as:

$$C_m(t) = C_m(0) + \int_0^t A[\alpha(\xi); t, \tau]\, \frac{d\alpha}{d\tau} d\tau \qquad (0 \le \xi \le \tau) \tag{25}$$

The above equation is actually using the initial conditions: when $\tau < 0$, $\frac{d\alpha}{d\tau} = 0$. Eq. (25) describes the aircraft's response when starting from the reference flight condition under the condition that $\xi = 0$. It represents either the aircraft's response to initiating a maneuver under the action of control surfaces or the transient process during which the aircraft begins to deviate from the reference flight state under the influence of disturbances.

In order to simplify the operation, we assume that $\alpha(\xi)$could expand as Taylor series for convergence near the$\xi = \tau$, the Eq. (25) can be equivalent to write to:

$$A[\alpha(\xi); t, \tau] = A(t - \tau; \alpha(\tau), \dot{\alpha}(\tau), \ddot{\alpha}(\tau), \cdots) \tag{26}$$

In the Eq. (26), $t-\tau$appears alone by replacing t,τ , its physical meaning righteousness is clear, namely when $\tau,\alpha(\tau),\dot{\alpha}(\tau),\ddot{\alpha}(\tau),\cdots$is given, change history of $\alpha(\xi)$ has been given, the transient response $t-\tau$, rather than related with t,τ respectively. Therefore, Eq. (25) can be written as:

$$C_m(t)=C_m(0)+\int_0^t A(t-\tau;\alpha(\tau),\dot{\alpha}(\tau),\ddot{\alpha}(\tau),\cdots)\,\frac{d\alpha}{d\tau}d\tau \tag{27}$$

According to the definition of the indicated response, when $t-\tau\to\infty$, indicial response $A(t-\tau;\alpha(\tau),\dot{\alpha}(\tau),\ddot{\alpha}(\tau),\cdots)$ tends to rely on the constant of $\alpha(\tau)$, its limit is $A\big(\infty;\alpha(\tau)\big)$. the deficiency function is defined as:

$$F(t-\tau;\alpha(\tau),\dot{\alpha}(\tau),\ddot{\alpha}(\tau),\cdots)=A\big(\infty;\alpha(\tau)\big)-A(t-\tau;\alpha(\tau),\dot{\alpha}(\tau),\ddot{\alpha}(\tau),\cdots) \tag{28}$$

When $t-\tau\to\infty$, $F\to 0$, substitute Eq. (28) into Eq. (27):

$$C_m(t)=C_m\big(\infty;\alpha(t)\big)-\int_0^t F(t-\tau;\alpha(\tau),\dot{\alpha}(\tau),\ddot{\alpha}(\tau),\cdots)\,\frac{d\alpha}{d\tau}d\tau \tag{29}$$

As conversion$u=t-\tau$, Eq. (29) can be written as:

$$C_m(t)=C_m\big(\infty;\alpha(t)\big)-\int_0^t F(u;\alpha(t-u),\dot{\alpha}(t-u),\ddot{\alpha}(t-u),\cdots)\,\frac{d\alpha(t-u)}{du}du \tag{30}$$

We have assumed that $\alpha(\xi)$could expand as convergent Taylor series. Whileτcould be any point in$[0,t]$, so $\alpha(\xi)$ could expand as convergent Taylor series at any point in$[0,t]$. As $t-u=\tau\in[0,t]$, $\alpha(t-u),\dot{\alpha}(t-u),\ddot{\alpha}(t-u),\cdots$could expand as convergent Taylor series near t:

$$\begin{aligned}\alpha(t-u)&=\alpha(t)-\dot{\alpha}(t)u+\frac{\ddot{\alpha}(t)}{2}u^2-\cdots\\ \dot{\alpha}(t-u)&=\dot{\alpha}(t)-\ddot{\alpha}(t)u+\frac{\dddot{\alpha}(t)}{2}u^2-\cdots\\ \ddot{\alpha}(t-u)&=\ddot{\alpha}(t)-\dddot{\alpha}(t)u+\frac{\ddddot{\alpha}(t)}{2}u^2-\cdots\end{aligned} \tag{31}$$

To substitute Eq. (31) into Eq. (30):

$$C_m(t)=C_m\big(\infty;\alpha(t)\big)+\sum_{i=1}^{\infty}C_i\frac{d^i\alpha(t)}{dt^i} \tag{32}$$

Among which

$$C_i=\frac{(-1)^{i+1}}{(i-1)!}\int_0^t F(u;\alpha(t),\dot{\alpha}(t),\ddot{\alpha}(t),\cdots)\,u^{i-1}du\quad(i=1,2,3,\cdots) \tag{33}$$

Eqs. (32-33) are the function relation between the aerodynamic moment coefficient$C_m(t)$ and the phase space variables when only angle of attack changes. By Eq. (33), it can be seen C_i is explicit function of *t*, namely $C_m(t)$ is not only the function of generalized state variables, but also implict time *t* in the Eq. (34):

$$C_m(t)=C_m(\alpha(t),\dot{\alpha}(t),\ddot{\alpha}(t),\cdots;t) \tag{34}$$

For general movement of all the state variables changes, aerodynamic force/moment coefficient expressions can also be analyzed, then ΔC_λ is related to aircraft motion parameters $\big(\alpha,\dot{\alpha},\beta,\cdots,Ma,h,u,v,\cdots,\delta_e,\dot{\delta}_e\big)$. ΔC_λ is set as function of the state parameter in the Eq. (35):

$$\Delta C_\lambda\big(\alpha,\dot{\alpha},\cdots,\dot{\delta}_e\big)=\frac{\partial C_\lambda}{\partial\alpha}\Delta\alpha+\frac{\partial C_\lambda}{\partial\dot{\alpha}}\Delta\dot{\alpha}+\cdots+\frac{\partial C_\lambda}{\partial\dot{\delta}_e}\Delta\dot{\delta}_e+H.O.T \tag{35}$$

By calculating the time domain data ΔC_λ dynamic derivative$\frac{\partial C_\lambda}{\partial\alpha}$, $\frac{\partial C_\lambda}{\partial\dot{\alpha}}$, $\cdots$ $\frac{\partial C_\lambda}{\partial\dot{\delta}_e}$ is obtained by post processing. The numerical methods include integral method, frequency domain transform method, regression method and phase method.

3.2 Kriging aerodynamic parameter interpolation

Kriging interpolation is an interpolation method based on probability statistics, which is characterized by ensuring the calculated interpolation point physical quantity variance is minimal and can capture the nonlinear behavior of the information.

Suppose the coordinates of the pending interpolation point p are (x_p, y_p, z_p), and the coordinates of n known points are (x_i, y_i, z_i), and the weight is w_i. Kriging interpolation boils down to Eq. (36):

$$Rw = r(x_p) \tag{36}$$

R is the covariance of points and points

$$R = \begin{pmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{n1} & \dots & R_{nn} \end{pmatrix}, w = \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix}, r(x_p) = \begin{pmatrix} R_{1p} \\ \vdots \\ R_{np} \end{pmatrix} \tag{37}$$

Covariance function can be selected:

$$R_{ij}(\theta, d_{ij}) = max(0, 1 - \theta d_{ij}) \tag{38}$$

$$R_{ij}(\theta, d_{ij}) = e^{-\theta d_{ij}} \tag{39}$$

$$R_{ij}(\theta, d_{ij}) = e^{-\theta d_{ij}^2} \tag{40}$$

$$R_{ij}(\theta, d_{ij}) = 1 - 1.5\varepsilon_{ij} + 0.5\varepsilon_{ij}^3, \varepsilon_{ij} = min(1, \theta d_{ij}) \tag{41}$$

$$R_{ij}(\theta, d_{ij}) = 1 - 3\varepsilon_{ij} + 2\varepsilon_{ij}^3, \varepsilon_{ij} = min(1, \theta d_{ij}) \tag{42}$$

$\theta$is control coefficient, general value is around 0.75, d_{ij} is space distance:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \tag{43}$$

In this paper, we choose the Eq. (40), namely the Gaussian covariance function. By solving Eq. (36), the Kriging interpolation weighting coefficient $w_i(i = 1,2, \dots n)$ is obtained. Physical quantities ϕ_p of different point P presented by $\phi_i(i = 1,2, \dots n)$:

$$\phi_p = \sum_{i=1}^{n} w_i \phi_i \tag{44}$$

4. Unsteady aerodynamic model application of forced/free vibration for airframe/propulsion integrated aircraft

In this section, aiming at the airframe/propulsion integrated aircraft WR (Wave Rider), the applicability of the aerodynamic model established based on the concept of parameterized dynamic derivative to the complex shape including internal flow is investigated. The aerodynamic shape of the aspirated hypersonic vehicle WR is modeled on the relatively successful aerodynamic/propulsion integrated design scheme X-51A WR vehicle shown in Fig. 1 designed in the United States. Its ballistic design includes boost stage, climbing stage, cruise stage and subduction stage. This section focuses on the calculation study of two typical ballistic positions of the transition point (booster separation: Ma=4.8, H=18288km) and the design point (cruise state: Ma=6.5, H=24384km).

The total length L of the aircraft design is 4.2672 meters, with a maximum approximate width of 0.5842 meters. The rudder configuration employs a 45-degree "V"-shaped rudder in conjunction with a horizontal rudder, featuring a half-span of 0.7085 meters. Table1 provides a comparison of the external geometric dimensions between WR and X-51A. The wedge-shaped wave-riding configuration of the WR wave-riding vehicle was developed using the inverse design methodology for wave-riding bodies [14]. The external compression section incorporates a multi-channel oblique shock wave compression system combined with isentropic wave compression, while the internal compression section features a mixed-pressure rectangular cross-section intake. The isolation segment is designed with slightly expanded rectangular ducts. The combustion chamber utilizes an open flame-stabilized cavity, measuring 0.1193 meters in length, 0.0178 meters in depth, with a length-to-depth ratio of 6.7 and a trailing edge angle of 30 degrees. The internal flow channel design of WR is illustrated in Fig. 2.



Figure 1. WR-A "Wave Rider"

Table1. Comparison of the geometric dimensions of the wave-multiplying shape

	Total length of the aircraft	maximum width	slenderness ratio	The width of the flow passage inside the engine
X-51A	4.2672m	0.5842m	7.3	0.2286m
WR-A	4.2672m	0.5842m	7.3	0.2286m

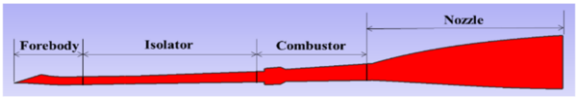


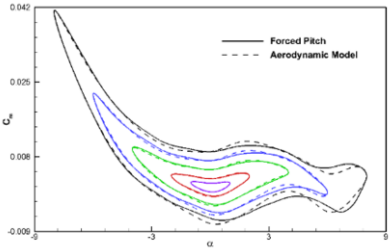
Figure 2. Internal flow channel design of WR

When an aircraft operates in flight regimes with strong nonlinear and unsteady aerodynamic characteristics, the applicability of linearized model equations may become inadequate. In such scenarios, more advanced mathematical models are required to accurately represent nonlinear unsteady aerodynamic behavior. Modern aircraft configurations and motion patterns are significantly more complex than traditional designs, particularly for integrated air-breathing hypersonic vehicles with coupled internal and external flows, where the nonlinearity and unsteadiness of the flowfield can be substantially amplified. Under these conditions, it becomes imperative to evaluate the suitability of dynamic derivative models. Building on a systematic investigation of how varying dynamic parameters influence dynamic derivatives, this study further simulates the high-angle-of-attack motion of an air-breathing integrated vehicle in its nonlinear flight regime. Through comparative validation against predictions from dynamic derivative models, the applicability of these models is rigorously assessed.

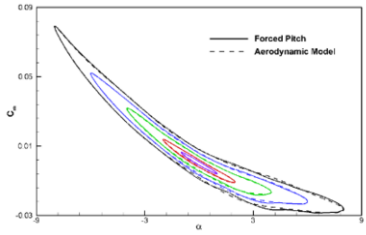
4.1 Dynamic aerodynamic calculation of forced vibration

The initial attack angle of the forced vibration is 0 degrees, the amplitude is 1 to 8 degrees, and the reduction frequency k=0.01. The comparison between the aerodynamic model

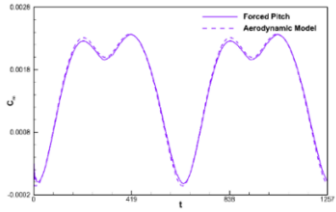
established based on the concept of parameterized dynamic derivative and CFD calculation results is shown in Fig. 3. The aerodynamic characteristics of the turning point of the integrated internal outflow show highly unsteady and non-linear characteristics. When the angle of attack is less than zero, the pitch moment coefficient calculated by the model is consistent with the hysteresis curve calculated by CFD (Fig. 3(a)). When the angle of attack is greater than zero, the curve of pitch moment coefficient begins to show more obvious non-linearity. In Fig. 3, the calculation of the inner model of the hysteresis loop with the amplitude of 4 degrees at the design point is in good agreement with CFD calculation. When the amplitude is 6 and 8 degrees, there are certain differences between the two, but the trend is the same as the hysteresis curve. From the time history curve of the design point, it can be seen that when the motion is in the region with weak nonlinear characteristics, the aerodynamic data predicted by the dynamic derivative model is in good agreement with the unsteady calculation. When the motion is in a region with strong nonlinear characteristics, the calculation of dynamic derivative model is deviated from unsteady calculation, but the general trend is in good agreement. By comparing the calculation results of the transition point and the design point, it can be seen that the time history curve of the transition point is the vibration form of sine function, and the hysteresis loop is also a relatively smooth inclined ellipse. At this point, the aerodynamic model established based on the concept of parametric dynamic derivative is consistent with the CFD unsteady calculation results.



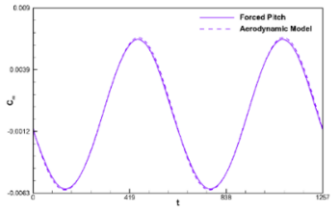
(a)Design point, hysteresis loop



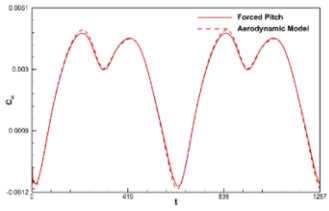
(b)Stage transition point, hysteresis loop



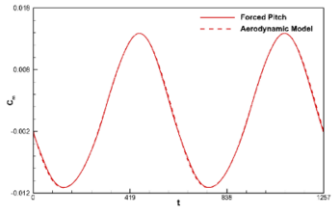
(c)Design point, amplitude 1˚



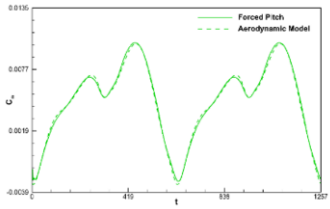
(d)Stage transition point, amplitude 1˚



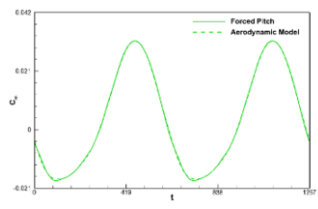
(e)Design point, amplitude 2˚



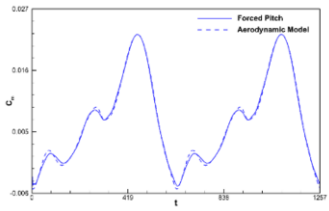
(f)Stage transition point, amplitude 2˚



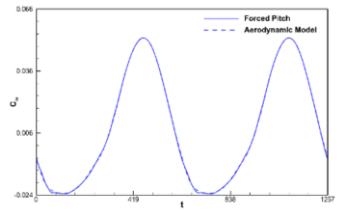
(g)Design point, amplitude 4˚



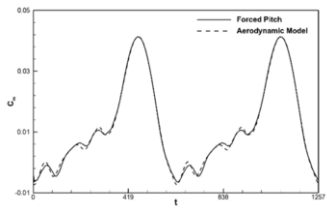
(h)Stage transition point, amplitude 4˚



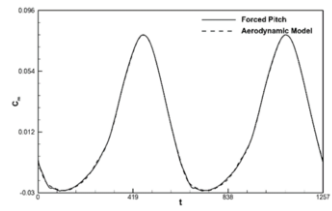
(i)Design point, amplitude 6˚



(j)Stage transition point, amplitude 6˚



(k)Design point, amplitude 8˚

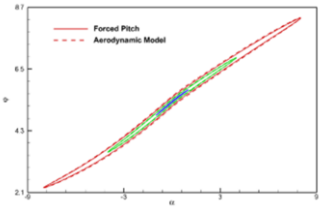


(l)Stage transition point, amplitude 8˚

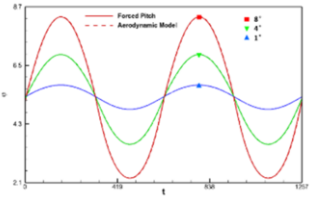
Figure 3. Time course and hysteresis loop of the forced vibration pitch moment coefficient in the integrated internal outflow

4.2 Calculation of dynamic flow field parameters of forced vibration

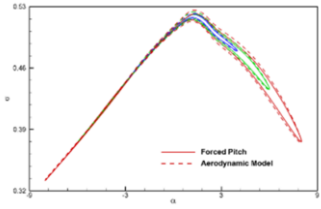
Figs. 4-5 present the characteristic curves of the dynamic derivative model in predicting inlet performance parameters at the design point and transition point, respectively. Unlike the pitch moment coefficient, the dynamic derivative model's predictions for inlet performance parameters (e.g., flow coefficient, pressure rise ratio, and temperature rise ratio) align consistently with unsteady computational results across both positive and negative angle-of-attack ranges. As shown in Figs. 4-5, the flow coefficient, pressure rise ratio, and temperature rise ratio exhibit a linear increasing trend with rising angle of attack, while the average Mach number decreases linearly. In Fig. 4(c), the total pressure recovery coefficient at the design point increases to its peak value at 1.5° angle of attack and then gradually declines. Within the negative angle-of-attack range, the hysteresis characteristics of the total pressure recovery coefficient are minimal, with the upper and lower paths of the hysteresis loop nearly overlapping. However, when the angle of attack exceeds zero, the hysteresis effect becomes pronounced, and the hysteresis loop curve grows "fuller" at larger angles. Fig. 5(c) reveals similar trends for the total pressure recovery coefficient at the transition point, but with distinct hysteresis behavior in the negative angle-of-attack range. Here, the dynamic derivative model's predictions slightly exceed the results from unsteady CFD computations.



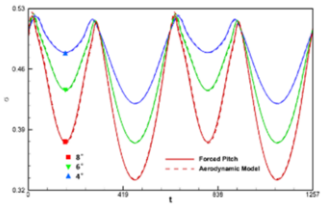
(a)flow coefficient, hysteresis loop



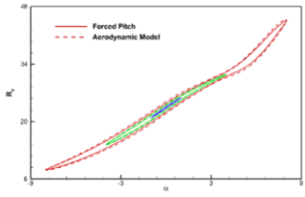
(b)flow coefficient, time history



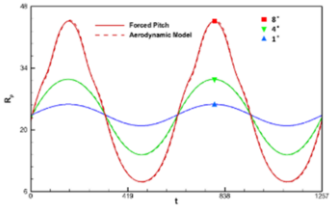
(c)Total pressure recovery coefficient, hysteresis loop



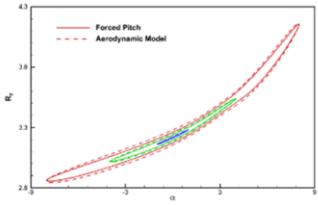
(d)Total pressure recovery coefficient, time history



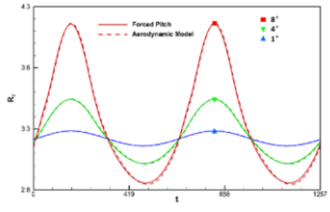
(e)Pressure rise ratio, hysteresis loop



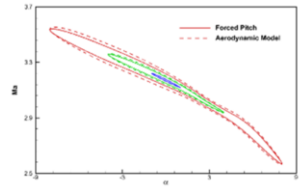
(f)Pressure rise ratio, time history



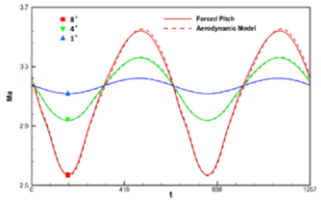
(g)Temperature rise ratio, hysteresis loop



(h)Temperature rise ratio, time history

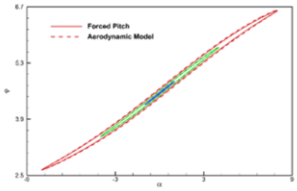


(i)Average Mach number, hysteresis loop

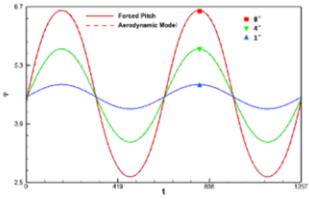


(j)Average Mach number, time history

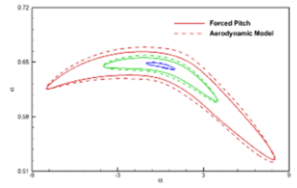
Figure 4. The time history and hysteresis loop of the inlet performance parameters at the design point of integrated internal outflow



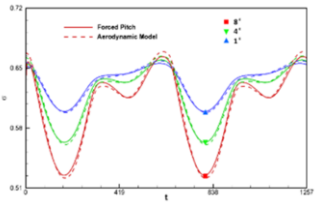
(a)flow coefficient, hysteresis loop



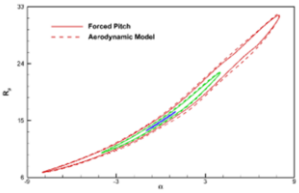
(b)flow coefficient, time history



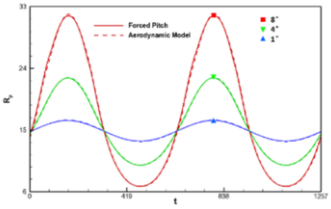
(c)Total pressure recovery coefficient, hysteresis loop



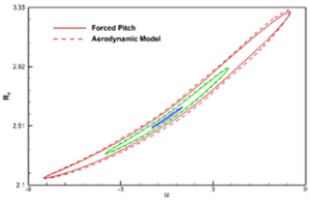
(d)Total pressure recovery coefficient, time history



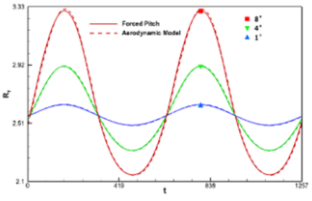
(e)Pressure rise ratio, hysteresis loop



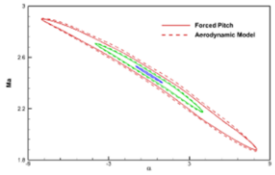
(f)Pressure rise ratio, time history



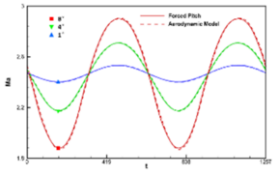
(g)Temperature rise ratio, hysteresis loop



(h)Temperature rise ratio, time history



(i)Average Mach number, hysteresis loop

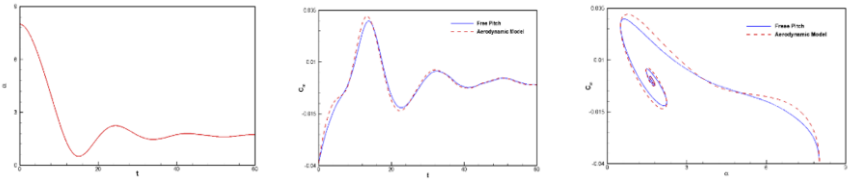


(j)Average Mach number, time history

Figure 5. The time history and hysteresis loop of the inlet performance parameters at the stage transition point of integrated internal outflow

4.3 Analysis of free vibration with small damping

The free vibration morphology of small damping is shown in Fig. 6(a). The comparison between the aerodynamic model established based on the concept of parameterized dynamic derivative and the unsteady aerodynamic force calculated by CFD is shown in Fig. 6(b)(c). The accuracy of the dynamic derivative simulation can significantly affects the accuracy of the aerodynamic model for the complex shape including internal flow. In this paper, the dynamic derivative of the integrated internal outflow is verified by experimental data. The calculation of dynamic derivative is relatively accurate, so the aerodynamic model and CFD calculation trend are in good agreement.



(a) Attack angle, time history (b)Pitch moment coefficient, time history (c) Pitch moment coefficient, hysteresis loop

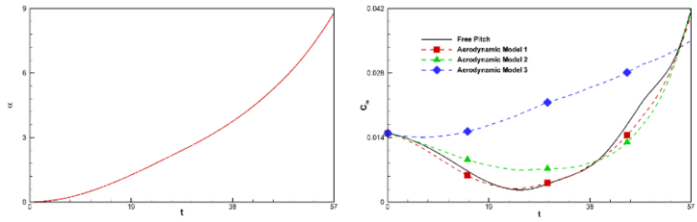
Figure 6. Time history and hysteresis loop of the integrated internal outflow with small damping free vibration

4.4 Analysis of free vibration with large damp

The form of large damp free vibration is shown in Fig.7(a). The comparison between the aerodynamic model established based on the concept of parameterized dynamic derivative and the unsteady aerodynamic force calculated by CFD is shown in Fig.7(b). Aerodynamic model calculation results 1 adopts every 2 ° pneumatic parameter data, results 2 and 3 adopts pneumatic parameter data of every 4 ° and 8 °, as shown in Table 2. From the calculation result of aerodynamic model 1, it can be seen that the simulation accuracy of aerodynamic model decreases slightly for the complex shape including internal flow, but the two are more consistent in the overall trend. The prediction accuracy of the model decreases with the decrease of aerodynamic parameter data. Result 2 is basically consistent with result 1 after dimensionless time t=40, and consistent with unsteady calculation in trend before t=40. Results 3 is far different from unsteady calculation. Therefore, sufficient aerodynamic parameter data is an important guarantee for the prediction accuracy of aerodynamic models. For integrated internal outflow in this section, the aerodynamic parameters in the database, the interval is limited to less than 4 ° in order to satisfy engineering simulation accuracy.

Table 2. Aerodynamic parameters adopted by unsteady aerodynamic models

	0°	2°	4°	6°	8°
Aerodynamic Model 1	✓	✓	✓	✓	✓
Aerodynamic Model 2	✓		✓		✓
Aerodynamic Model 3	✓				✓



(a) Attack angle (b)Pitch moment coefficient

Figure 7. Time history of the large damp free vibration of the integrated internal outflow

5. Conclusion

Based on the improved Etkin model, this paper establishes an unsteady aerodynamic parameter model by using the concept of parametric dynamic derivatives. For the integrated internal and external flow shape, the applicability of the aerodynamic model established based on the concept of parametric dynamic derivatives to the complex shape containing internal flow was investigated. Vibration modes are divided into forced vibration and free vibration. Forced vibration includes two parts of calculation: dynamic aerodynamic force and flow field parameters. For the two different states of small damping and large damping in free vibration, the calculation results of the aerodynamic model and CFD were compared. The calculation of the intra-hysteresis loop model with an amplitude of 4 degrees in the integrated internal and external flow shape design point is in good agreement with the CFD calculation. There is a certain difference between the two when the amplitude is 6 degrees and 8 degrees, but the trend is the same as that of the hysteresis curve. When the motion is in the region with weak nonlinear characteristics, the aerodynamic data predicted by the dynamic derivative model is in good agreement with the unsteady calculation. When the motion is in a region with strong nonlinear characteristics, there is a certain deviation between the calculation of the dynamic derivative model and the unsteady calculation. For complex shapes containing internal flow, the accuracy of dynamic derivative simulation significantly affects the precision of the aerodynamic model. The dynamic derivative of the integrated internal and external flow shape in this paper is verified by experimental data. The calculation of the dynamic derivative is relatively accurate. Therefore, the aerodynamic model and the CFD calculation trend are in good agreement. Furthermore, sufficient aerodynamic parameter data is an important guarantee for the prediction accuracy of aerodynamic models. For the integrated internal and external flow shape simulated, the interval of aerodynamic parameters in the database should preferably not exceed 4° to meet the accuracy requirements of engineering simulation.

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Modeling and Validation of Unsteady Aerodynamic Forces Using Parametric Dynamic Derivatives for HBS Vibration

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Abstract. Based on the dynamic stability parameterization theory, this study improved the traditional Etkin model and constructed a nonlinear aerodynamic prediction model suitable for large-amplitude motions. Through the forced vibration experiments of the hypersonic HBS standard model, the dynamic response differences under harmonic vibration and self-defined vibration were compared and analyzed. The experiments found that under the condition of increasing frequency, the hysteresis loops generated by forced vibration presented a nested distribution feature, and the flow field lag phenomenon was significantly enhanced. As the motion amplitude increased, the nonlinear effect of aerodynamic force caused the hysteresis loop shape to gradually deform from a standard ellipse. At this time, the coupling effect of higher harmonic components and dynamic hysteresis intensified, causing the model prediction accuracy to fluctuate within a controllable range (error amplitude < 8%). This phenomenon revealed the applicability boundary of the existing model under strong nonlinear flow field conditions.

Keywords. Dynamic derivative, unsteady, nonlinear flow, forced vibration

1. Introduction

The field of aircraft design faces technical challenges in predicting dynamic stability characteristics, with the core issue being the complex aerodynamic effects caused by unsteady flow phenomena [1]. Flow field features such as shock boundary layer interaction, vortex evolution and breakdown lead to significant nonlinear characteristics in fluid motion, which often result in aerodynamic responses beyond design expectations and may even cause sudden changes in aircraft dynamics [2]. To address this problem, modern aerodynamic modeling techniques play a crucial supporting role in the aircraft development stage by establishing mathematical mapping relationships between motion state parameters and aerodynamic forces [3].

Although Computational Fluid Dynamics (CFD) can accurately capture the characteristics of complex flow fields, its high computational cost limits its application in multi-disciplinary coupling analysis. Model reduction techniques (ROM) can improve computational efficiency by one to two orders of magnitude by retaining the core dynamic characteristics of the system. Various methods have been developed, including

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Volterra series, Proper Orthogonal Decomposition (POD), and surrogate models [4-5]. However, existing reduced-order models suffer from accuracy degradation when capturing strong nonlinear features such as flow hysteresis and bifurcation phenomena, and their application is mostly limited to subsonic and simple configurations, making it difficult to meet the requirements of supersonic complex shapes [6].

In response to the limitations of the traditional dynamic derivative model, the improved parametric dynamic derivative concept has emerged [7-9]. The classic Etkin model assumes that dynamic derivatives are time-independent constants, which reveals obvious deficiencies when dealing with the dynamic characteristics at large angles of attack [10-11]. Modern research indicates that dynamic derivatives are essentially functions of parameters such as angle of attack and reduced frequency, and their parametric characteristics are more pronounced especially in complex conditions involving flow separation and shock wave oscillation. The dynamic stability parameter system developed based on this can effectively characterize the time-delay effect and cross-coupling characteristics of aerodynamic forces [12].

To verify the applicability of the new pneumatic model, the study selected typical hypersonic benchmark models (HBS) as object [13]. By comparing key indicators such as aerodynamic force time history and flow field characteristic parameters under forced/free vibration, the prediction accuracy of the parametric dynamic derivative model and the traditional CFD method was systematically evaluated [14]. The experimental results show that the improved model retains the computational efficiency advantage (two orders of magnitude higher than CFD) while keeping the dynamic aerodynamic force prediction error within the engineering allowable range, verifying the engineering applicability of this modeling method.

2. Computational Fluid Dynamics Formulation

Three-dimensional dimensionless equation Navier-Stokes is used as the governing equation of fluid motion:

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+\frac{\partial G_v}{\partial z} \tag{1}$$

Q is a conserved variable, E, F and G are convective fluxes, E_v, F_v and G_v are viscous fluxes, and the specific form is:

$$Q=(p,pu,pv,pw,pe)^T \tag{2}$$

$$E=\begin{pmatrix} pu \\ pu^2+p \\ puv \\ puw \\ phu \end{pmatrix}, E_v=\frac{1}{Re}\begin{pmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{xz} \\ u\tau_{xx}+v\tau_{xy}+w\tau_{xz}+k'\dfrac{\partial T}{\partial x} \end{pmatrix} \tag{3}$$

$$F=\begin{pmatrix} pv \\ puv \\ pv^2+p \\ pvw \\ phv \end{pmatrix}, F_v=\frac{1}{Re}\begin{pmatrix} 0 \\ \tau_{yx} \\ \tau_{yy} \\ \tau_{yz} \\ u\tau_{yx}+v\tau_{yy}+w\tau_{yz}+k'\dfrac{\partial T}{\partial y} \end{pmatrix} \tag{4}$$

$$G = \begin{pmatrix} pw \\ puw \\ pvw \\ pw^2 + p \\ phw \end{pmatrix}, G_v = \frac{1}{Re}\begin{pmatrix} 0 \\ \tau_{zx} \\ \tau_{zy} \\ \tau_{zz} \\ u\tau_{zx} + v\tau_{zy} + w\tau_{zz} + k' \dfrac{\partial T}{\partial z} \end{pmatrix} \tag{5}$$

e is total energy, h is total enthalpy, τ_{ij} is the viscous stress, k' is the heat transfer coefficient. The LU-SGS method only has first-order accuracy, and the numerical simulation of unsteady problems requires the accurate solution of time derivative term [15]. Direct use of the LU-SGS method cannot meet the requirements [16]. Jameson [17] proposed a Dual-timestep method, which can introduce the newton-like virtual time iteration process to the frozen physical time point of ADI or LU type implicit approximate fast algorithm, and improve the lost time precision in the approximate process by sub-iteration.

This article uses time derivative of the implicit difference discrete item Eq. (1) of second order $(\theta = 2)$, at the same time introducing virtual items and set as first-order backward difference discrete:

$$J^{-1}\frac{(\theta+1)Q^{p+1} - 2\theta Q^n + (\theta-1)Q^{n-1}}{2\Delta t} + J^{-1}\frac{Q^{p+1} - Q^p}{\Delta\tau} + R(Q^{p+1}) = 0 \tag{6}$$

It can be combed as:

$$\left(\frac{\theta+1}{2\Delta t/J^{-1}} + \frac{1}{\Delta\tau/J^{-1}}\right)\Delta Q^p = -R(Q^{p+1}) - \frac{(\theta+1)Q^p - 2\theta Q^n + (\theta-1)Q^{n-1}}{2\Delta t/J^{-1}} \tag{7}$$

The second term in the middle right end of Eq. (7) is the unsteady driving term caused by the duel- time- step method, which is the known term. Linearize Eq. (7), and obtain:

$$\left[\frac{\theta+1}{2\Delta t/J^{-1}} + \frac{1}{\Delta t/J^{-1}} + \left(\delta_\xi A + \delta_\eta B + \delta_\zeta C\right)^n\right]\Delta Q^n = -R^*(Q^n) \tag{8}$$

In Eq. (8)

$$R^*(Q^n) = R(Q^n) - \frac{(\theta+1)Q^p - 2\theta Q^n + (\theta-1)Q^{n-1}}{2\Delta t/J^{-1}} \tag{9}$$

Combed as:

$$(D + L)D^{-1}(D + U)\Delta Q^p_{i,j,k} = -R^*(Q^p) \tag{10}$$

In Eq. (10)

$$D = \left[\frac{\theta+1}{2\Delta t/J^{-1}} + \frac{1}{\Delta t/J^{-1}} + \rho(A) + \rho(B) + \rho(C)\right]I \tag{11}$$

$$L = -A^+_{i-1,j,k} - B^+_{i,j-1,k} - C^+_{i,j,k-1} \tag{12}$$

$$U = +A^-_{i+1,j,k} + B^-_{i,j+1,k} + C^-_{i,j,k+1} \tag{13}$$

The method SGS (Symmetric Gauss-Seidel) is used to solve the problem step by step:

$$\Delta\tilde{Q}^p_{i,j,k} = -D^{-1}\left[R(Q^p) + L\Delta\tilde{Q}^p_{i,j,k}\right] \tag{14}$$

$$\Delta\tilde{Q}^p_{i,j,k} = -D^{-1}\left[R(Q^p) + L\Delta\tilde{Q}^p_{i,j,k}\right] \tag{15}$$

$$\Delta Q^p_{i,j,k} = \Delta\tilde{Q}^p_{i,j,k} - D^{-1}U\Delta Q^p_{i,j,k+1} \tag{16}$$

Update the flow field of the moment $p + 1$ to:

$$Q^{p+1} = Q^p + \Delta Q^p \tag{17}$$

When the iteration index is $p \to \infty$, virtual time tends to zero, at this time, $Q^{n+1} = Q^{p+1}$, solving the Eq. (1) with time second order accuracy. The dual time step method improves the time accuracy of unsteady flow simulation. The virtual time derivative term

adopts the LU-SGS implicit time method, which relaxes the limitation to time step and improves the efficiency of unsteady calculation.

3. Application of Unsteady Aerodynamic Model with Forced Vibration of HBS Standard Model

In this section, for the HBS (Hyper Ballistic Shape) standard model of the hypersonic missile, an aerodynamic model based on the concept of parameterized dynamic derivative is adopted to calculate the unsteady aerodynamic force of the forced vibration and is compared with the CFD numerical simulation method. The dynamic characteristics of HBS include the detailed wind tunnel experiment results conducted by the University of Southampton.

HBS shape parameters are shown in Fig. 1, including: $r = 12.5mm, \theta_1 = 5^{\circ}, \theta_2 = 15^{\circ}$. An axisymmetric grid is generated by means of symmetry surface rotation. Fig. 2 shows the HBS model object surface and the symmetrical surface grid, with the number of grids: 131*73*51 (flow direction x circumference x radial direction). Calculation condition is from the wind tunnel experimental conditions: $Ma_{\infty} = 6.85$, head diameter is the reference length of $Re_d = 0.72 \times 10^6$, centroid position of $X_{cg}/L = 0.72$.

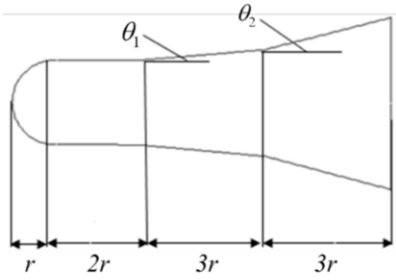


Figure 1. HBS contour parameters

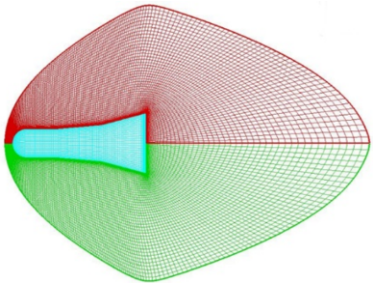


Figure 2. HBS model object surface and symmetrical surface grid

In this paper, the steady calculation under different angles of attack of HBS is firstly carried out, and the obtained flow field data is taken as the initial field of unsteady calculation,it is used to accelerate the convergence rate of unsteady flow field. Then, the dynamic derivative data $C_{m\dot{\alpha}} + C_{mq}$ is obtained through unsteady calculation, as shown in Table 1.

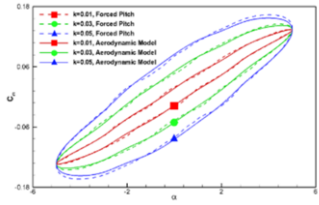
Table 1. Steady aerodynamic and dynamic derivative data of HBS model

Angle(°)	C_m	$C_{m\dot{\alpha}} + C_{mq}$
0	0.000	-20.53
3	0.090	-17.42
5	0.133	-17.02
8	0.165	-17.49
10	0.137	-16.03
13	0.035	-20.01
15	-0.085	-27.04
18	-0.138	-54.99
20	-0.013	-61.25
23	0.239	-54.40
25	0.407	-56.02
27	0.581	-58.52

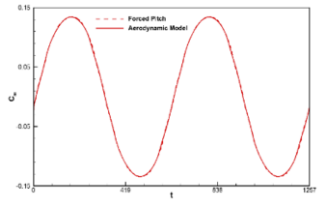
Based on the calculation of different frequencies and amplitudes, the effect of hysteresis of vibration on the simulation accuracy of unsteady aerodynamic model is analyzed, and the applicability of unsteady aerodynamic model to nonlinear state is investigated. In order to verify the universality of unsteady aerodynamic model to different vibration modes, this paper also carried out comparative analysis on four different customized forced vibration modes.

3.1 Hysteresis effect analysis of forced harmonic frequency

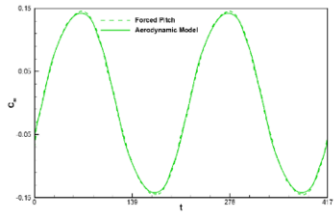
Forced longitudinal vibration mode $\alpha(t) = \theta = \alpha_0 + \alpha_m sinkt$,calculate the initial attack angle $\alpha_0 = 0$, take 5 ° and 10 ° respectively, and the amplitude frequency reduction k are 0.01, 0.03, 0.05. The incoming flow Mach number $Ma_\infty = 6.85$, the Reynolds number $Re_d = 0.72 \times 10^6$. Figs. 3-4 show the hysteresis loop and time history of different frequency of HBS.



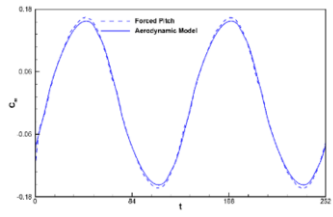
(a) hysteresis loop



(b) k=0.01, time history



(c) k=0.03, time history

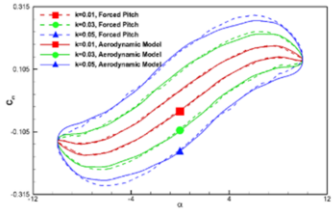


(d) k=0.05, time history

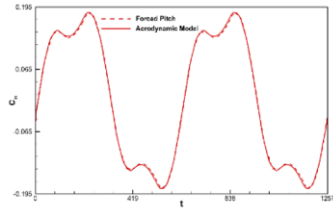
Figure 3. Hysteresis loop and the time course of different frequencies at HBS amplitude of 5 °

As shown in Fig. 3(b), when $k = 0.01$ amplitude of 5 °, CFD numerical simulation is coincide with the model coincides with the CFD results calculation. As the frequency increases, the hysteresis loop is progressively nested outward, and the more obvious the hysteresis effect is, the "fuller" the hysteretic loop curve is (Fig. 3(a)). At this point, there is a slight difference between CFD numerical simulation and unsteady aerodynamic model calculation (Fig. 3(c-d)).

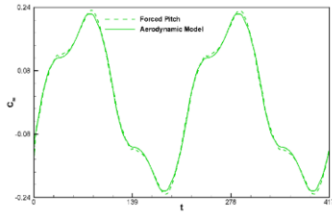
When the amplitude increased to 10 °, contrast Figs. 3-4 show there is an obvious nonlinear aerodynamic force, hysteresis loop curve starting from the smooth oval becomes bent. As shown in Fig. 4(a), although the flow is in a non-linear state, the model coincides with the CFD results equation is instantaneous, and the dynamic derivative is expressed as a function of the vehicle's moving state parameters, which can better predict the nonlinear effect of the aerodynamic coefficient. When the frequency increases, as shown in Fig. 4 (c-d), the unsteady aerodynamic forces not only present non-linear characteristics, but also, the influence of high harmonics and hysteresis effects presented, and the prediction accuracy of unsteady aerodynamic models decreases.



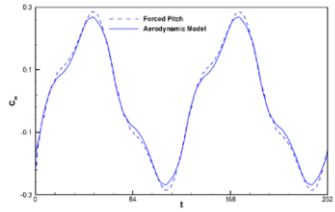
(a) hysteresis loop



(b) k=0.01, time history



(c) k=0.03, time history



(d) k=0.05, time history

Figure 4. Hysteresis loop and the time course of different frequencies at HBS amplitude 10 °

3.2 Influence of amplitude of nonlinear state of forced harmonic oscillations

Forced pitching vibration mode $\alpha(t) = \theta = \alpha_0 + \alpha_m sinkt$, calculate the initial attack angle$\alpha_0 = 0$, reduced frequency is $k = 0.01$, amplitudes are 5 °, 10 °, 18 °, 25 °. The incoming flow Mach number $Ma_\infty = 6.85$, the Reynolds number $Re_d = 0.72 \times 10^6$.

The hysteresis loops and time history curves of different amplitudes are given respectively in Figs. 5-6. With the increase of amplitude, the nonlinear characteristics of aerodynamic coefficients become more and more obvious. When amplitude is less than 18 °, CFD numerical simulation is coincide with the model coincides with the CFD results calculation, as shown in Fig. 5 (a-c). When the amplitude is 25 ° (Fig. 5(d)), aerodynamic force data of the model coincides with the CFD results at the peak is smaller compared with CFD numerical simulation. But the overall trend is consistent. On the whole, the model coincides with the CFD results based on the parameterized dynamic derivative concept can predict the aerodynamic data under nonlinear conditions accurately.

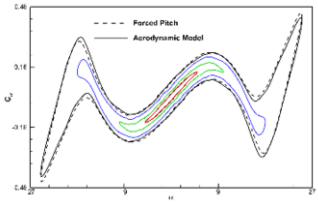
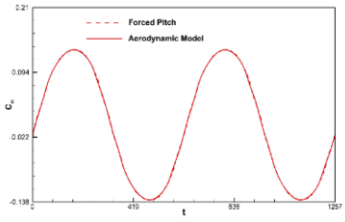
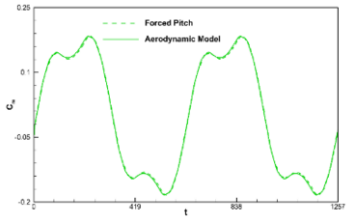


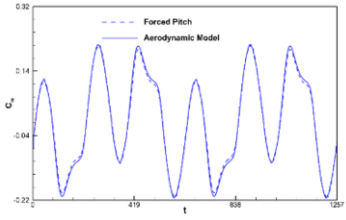
Figure 5. Hysteresis loop of different amplitude of HBS



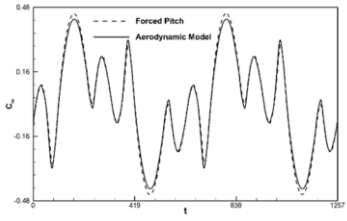
(a)5°amplitude



(b)10°amplitude



(c)18°amplitude



(d)25°amplitude

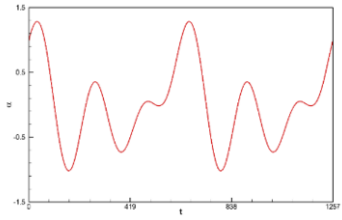
Figure 6. Time history of different amplitude of HBS

3.3 Application of unsteady aerodynamic model in customized forced vibration

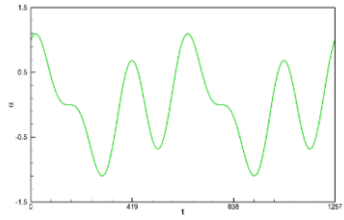
This section carries out comparative analysis of unsteady aerodynamic model and CFD calculation for four different customized forced vibration forms. The customized vibration forms 1-4 are:

$$\begin{cases} \alpha(t) = \alpha_0 + \alpha_m(coskt + cos2kt + sin3kt) \\ \alpha(t) = \alpha_0 + \alpha_m(coskt + sin2kt + cos3kt) \\ \alpha(t) = \alpha_0 + \alpha_m(sinkt + cos2kt + sin3kt) \\ \alpha(t) = \alpha_0 + \alpha_m(sinkt + sin2kt + cos3kt) \end{cases} \tag{18}$$

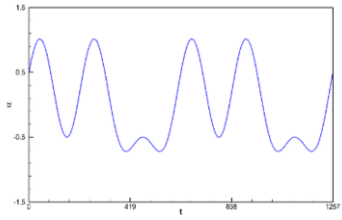
Fig. 7 shows function graphics of a customized vibration mode, values of the parameters in Eq. (18) are $\alpha_0 = 0, \alpha_m = 0.5, k = 0.01$. The vibration within each period in the graph of function is not regular and has strong non-linear characteristics. The universality of unsteady aerodynamic models to different vibration modes is further investigated.



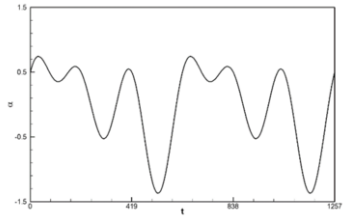
(a)vibration form 1



(b)vibration form 2



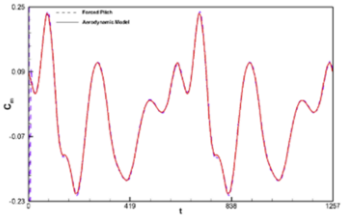
(c)vibration form 3



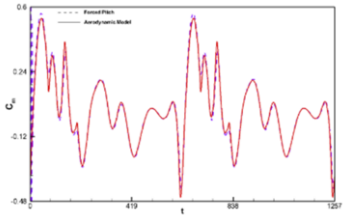
(d)vibration form 4

Figure 7. Different forced vibration forms of HBS

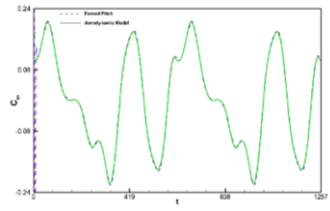
Calculate the initial attack angle $\alpha_0 = 0$, reduced frequency $k = 0.01$, amplitude α_m is 10 ° and 20 °respectively. The incoming flow Mach number $Ma_\infty = 6.85$, Reynolds number $Re_d = 0.72 \times 10^6$. Figs. 8-9 show the time history and hysteresis loop of HBS customized forced vibration.



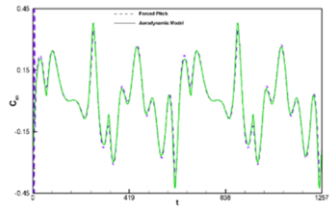
(a)vibration form 1, 10°amplitude



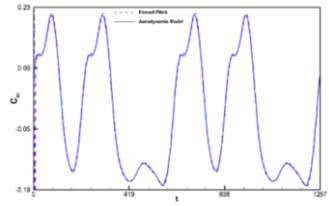
(b)vibration form 1, 20°amplitude



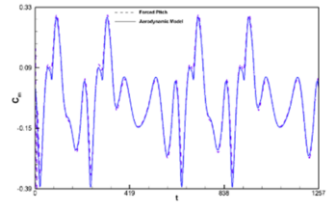
(c)vibration form 1, 10°amplitude



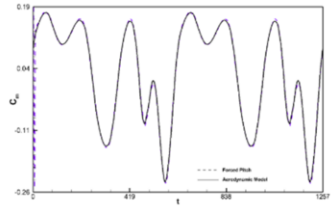
(d)vibration form 1, 20°amplitude



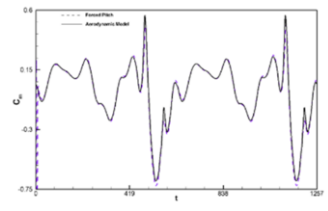
(e)vibration form 2, 10°amplitude



(f)vibration form 2, 20°amplitude

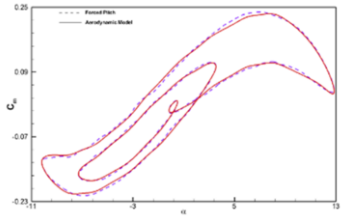


(g)vibration form 2, 10°amplitude

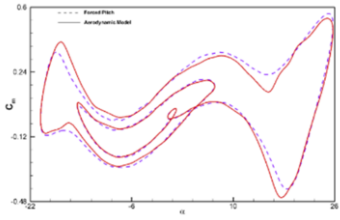


(h)vibration form 2, 20°amplitude

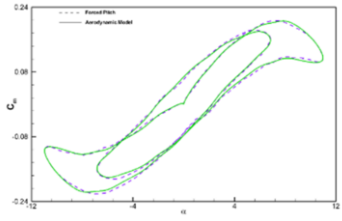
Figure 8. Time history of HBS customized forced vibration



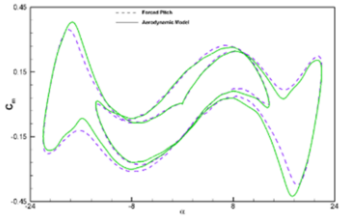
(a)vibration form 1, 10°amplitude



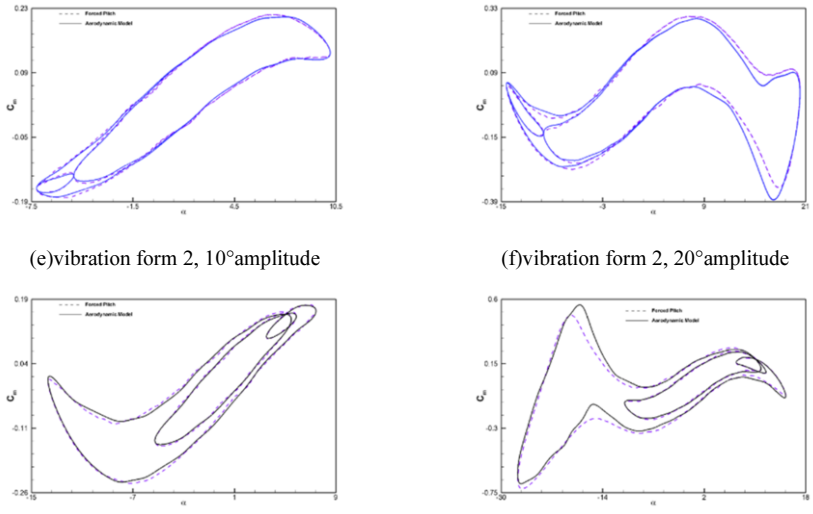
(b)vibration form 1, 20°amplitude



(c)vibration form 1, 10°amplitude



(d)vibration form 1, 20°amplitude



(e)vibration form 2, 10°amplitude (f)vibration form 2, 20°amplitude

(g)vibration form 2, 10°amplitude (h)vibration form 2, 20°amplitude

Figure 9. Hysteresis loop of HBS customized forced vibration

Contrast the time course of 10 ° and 20 °amplitude in the figure, the increase of amplitude makes teh change of aerodynamic coefficient in a cycle more complex, nonlinear characteristics is increasingly obvious. The rotation direction of hysteresis ring represents the direction of aerodynamic work. Hysteresis rings in different vibration forms are nested, but all rotate counterclockwise. It means that HBS does work on the environment, consumes its HBS energy, and it is in a dynamic and stable state. The hysteresis ring area represents the amount of work done by the environment during the HBS vibration.

As shown in Fig. 9, the precision of simulation of the model coincides with the CFD results of 10 ° amplitude of hysteresis loop is better than 20 ° amplitude. As the aerodynamic model expression based on dynamic derivative is non-linear in form as well as a function of instantaneous value of state parameters, so it is more accurate to fit the non-linearity of different vibrations in the figure. When the amplitude increases, the time-history effect has a significant impact on the aerodynamic force. Under these circumstances, the simulation accuracy of the aerodynamic model decreases, but the trend is consistent with CFD calculation.

4. Conclusions

Based on the improved Etkin model, the unsteady aerodynamic parameter model is established by using the concept of parameterized dynamic derivative. As for the HBS shape, the unsteady aerodynamic force of forced vibration is calculated by using the aerodynamic model based on the concept of parametric dynamic derivative, and the results are compared with the CFD unsteady calculation. The results of the study on the influence of frequency show that the CFD numerical simulation and unsteady aerodynamic model calculation are basically coincident. Along with the increase of frequency, nested hysteresis loop formed from within, the hysteresis effect of flow field

is more obvious, hysteresis curve is "fuller" , when there is an obvious nonlinear occurs to aerodynamic, hysteresis loop the curve deforms from a smooth ellipse to a distorted shape, the influence of high harmonics and hysteresis effect began to emerge, the model coincides with the CFD results prediction accuracy reduces. The study result of influence of the amplitude, when the amplitude is less than 18 °, CFD numerical simulation and the model coincides with the CFD results calculation is basically same. When the amplitude is 25 °, the data of unsteady aerodynamic model in aerodynamic force peak is smaller compared with CFD numerical simulation. But the overall trend is consistent. To sum up, the model coincides with the CFD results established by the parameterized dynamic derivative concept can accurately predict the aerodynamic data and flow field parameters under nonlinear conditions. Large angle of attack and complex shape of unsteady flow field have strong hysteresis effect, and the influence of time-history effect on unsteady aerodynamic forces cannot be ignored. Therefore, the simulation accuracy of aerodynamic model for large angle of attack vibration is reduced, but it can still reflect the variation trend of dynamic aerodynamic forces.

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