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Recent Advances in Surface-Energy-Regulated Marine Antifouling Coatings for Concrete: Focusing on Superhydrophobic Surfaces

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ABSTRACT

Concrete structures exposed to marine, hydraulic, and urban environments are susceptible to multiple fouling processes, including sediment deposition, salt crystallization, organic contamination, and biological attachment, which accelerate surface degradation and reduce durability. Surface coatings are widely applied for concrete protection due to their practical applicability. Conventional barrier-type coatings protect concrete by blocking water and aggressive ion penetration, but their long-term performance is often limited by aging, interfacial degradation, and mechanical damage. Anti-organic-fouling coatings reduce oil and organic adhesion and show effectiveness in specific scenarios, although durability and environmental adaptability remain challenging. In recent years, surface-energy-engineered superhydrophobic coatings have attracted increasing attention. By combining micro-/nanostructured surfaces with low-surface-energy materials, these coatings impart high contact angles and low adhesion, effectively suppressing liquid wetting, particulate accumulation, and early-stage biofouling. This review systematically summarizes fouling mechanisms on concrete surfaces, compares different anti-fouling coating strategies, and discusses current challenges and future directions toward durable and practical concrete protection.

INTRODUCTION

Concrete is one of the most widely used structural materials in marine engineering, hydraulic infrastructure, and coastal constructions. During long-term service in harsh environments characterized by high humidity, high salinity, strong corrosion, and intense biological activity, concrete surfaces are highly susceptible to multi-source contamination and degradation. In marine environments, the coupled effects of chloride ingress, sediment deposition, organic pollutant adsorption, and biofouling by microorganisms and macro-organisms significantly accelerate surface deterioration, resulting in reduced service life, increased maintenance costs, and potential safety risks. Therefore, the development of efficient, durable, and environmentally friendly antifouling technologies for concrete surfaces has become a critical scientific and engineering challenge in marine engineering[1-3].

Conventional antifouling strategies for concrete mainly rely on biocidal coatings or dense barrier coatings, which retard deterioration by releasing active agents or blocking the penetration of aggressive species. However, these approaches often suffer from environmental concerns, limited service life, and poor adaptability to concrete substrates, making them insufficient for long-term applications in marine environments[4]. In recent years, inspired by advances in biomimetic interface science and wetting theory, surface-energy-regulated antifouling strategies have attracted increasing attention. By reducing surface free energy and constructing micro/nanostructures,

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the interfacial interactions between contaminants and substrates can be significantly weakened, thereby suppressing fouling at the source[5].

In this context, superhydrophobic coatings, characterized by high water contact angles, low sliding angles, and excellent liquid repellency and self-cleaning properties, have been regarded as promising candidates for non-adhesive antifouling protection of concrete surfaces. Numerous studies have demonstrated that superhydrophobic surfaces can effectively reduce the adhesion of sediments, organic pollutants, and early-stage biofilms, while simultaneously retarding chloride penetration and reducing water absorption thus offering synergistic improvements in antifouling performance and durability. Nevertheless, their practical application is still hindered by challenges such as insufficient mechanical robustness, limited long-term durability, and difficulties in large-scale fabrication on rough concrete substrates[6-7].

Against this background, this review systematically summarizes recent advances in antifouling coatings for concrete in marine environments, with a particular focus on surface-energy-regulated and superhydrophobic coatings. Their working mechanisms, advantages, limitations, and future research directions are discussed to provide guidance for the development of durable antifouling strategies for concrete structures.

1.Types and Formation Mechanisms of Surface Fouling on Concrete

Concrete surfaces are highly susceptible to multiple pollutants during service, and different fouling types often act synergistically to accelerate deterioration. Based on contaminant characteristics and mechanisms, surface fouling can be classified into four categories: inorganic salt fouling, organic fouling, sediment and particulate pollution, and biological fouling.

1.1.Inorganic Salt Fouling

Inorganic salt fouling arises from the migration, crystallization, and deposition of soluble salts (e.g., Cl^-, SO_4^{2-}) on concrete surfaces [8]. In humid or saline conditions, salts accumulate via capillary transport and precipitate during wet-dry cycles or evaporation [9], as shown in Table1. Although its effect on structural capacity is limited, salt crystallization markedly reduces durability. It can increase surface roughness by about 60%, while crystal growth and pore blockage diminish freeze-thaw resistance, abrasion resistance, and resistance to moisture and ion transport [10]. Liang et al. [11] further reported that banded deposits formed under flowing water reduce surface compactness and enhance adhesion, promoting particulate accumulation, deeper carbonation, microcrack propagation, and up to a 40% drop in impermeability.

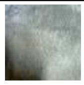
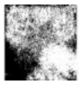
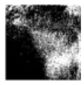
Specimen	MK-0	MK-5	MK-10	MK-15	MK-20
Efflorescence image					
Efflorescence area image					
Area(%)	60.16	50.91	42.24	34.12	30.27

Table.1. Relative efflorescence area of concrete with different mix proportions

* Source: Study on the efflorescence behavior of concrete by adding metakaolin [10]

1.2.Organic Fouling

Organic fouling occurs because the porous concrete matrix readily adsorbs and retains oils and hydrocarbons, forming sticky contamination layers [12]. Their oxidation products and associated microbes reduce alkalinity and induce chalking, as shown in Fig1. Prolonged grease exposure may cause tackiness, discoloration, mold, and compressive strength losses exceeding 60% [13]. Low-viscosity fuels such as gasoline and diesel, though weakly corrosive, can dissolve loose surface phases and weaken steel-concrete bonding, causing an 18-22% strength reduction after 150 days [14]. In heavily oil-contaminated industrial environments, oxidized mineral oils combine with dust to form sludge, producing dark staining and reducing the elastic modulus (~18%) and friction coefficient (~37%) [15].

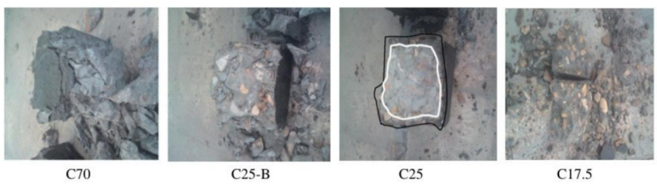


Fig.1. Penetration of petroleum through different types of concrete

* Source: Compressive strength performance of low-and high-strength concrete soaked in mineral oil [15]

1.3.Sediment and Particulate Fouling

Sediment and particulate fouling commonly occurs in environments with flowing water or airborne dust. Fine particles increase surface roughness, promoting the retention of dust, organics, and microbes and raising the risk of secondary contamination [16]. Particle impact under water or wind erosion further induces abrasion and microcrack propagation, reducing compactness as well as impermeability and abrasion resistance [17]. Fernandez [18] reported that airborne particulates not only alter surface appearance but also adsorb moisture and acidic species, accelerating weathering and alkalinity loss. Notably, the increasing proportion of carbonaceous and nitrogenous particles enhances SO_2 oxidation and gypsum formation, triggering “black crust” development and advancing calcite sulfate conversion, thereby compromising surface integrity [19].

1.4.Biological Fouling

Biological fouling is a major deterioration process in moist, nutrient-rich, and mild-temperature environments[21], as shown in Fig2. It is driven by the adhesion, growth, and metabolism of bacteria, fungi, algae, and macrofoulers, typically progressing through initial attachment, biofilm formation, metabolite accumulation, and microbial corrosion.

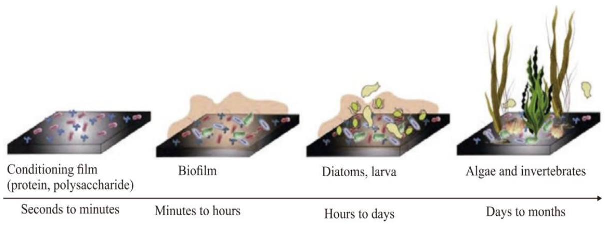


Fig.2. Typical growth processes of algal organisms
* Source: Latest Research Progress of Marine Microbiological Corrosion and Bio-fouling, and New Approaches of Marine Anti-corrosion and Anti-fouling [20]

It is characterized by concealed onset, cumulative effects, and complex mechanisms. Existing studies generally categorize it into three types[22]:

(1) Non-structural fouling

Caused by the deposition of microbial pigments (e.g., melanin, carotenoids, phycobilins), producing black, yellow, or green staining. Although it does not directly damage the material, it degrades appearance and alters optical and moisture-related surface properties, facilitating further microbial colonization [23].

(2) Functional fouling

Originates from biofilm formed by extracellular polymeric substances (EPS). Biofilms increase roughness and enhance adhesion of dust, particulates, and organics, and may clog capillary pores, impeding moisture and gas transport. This leads to scaling, chalking, and surface softening, reducing impermeability and self-cleaning ability and fostering composite fouling layers [24].

(3) Structural fouling

Driven by corrosive microbial metabolites such as organic acids, sulfides, and ammonia, causing dissolution, alkalinity loss, pore structure alteration, and elevated moisture content, as shown in Fig3. These changes accelerate carbonation, decalcification, and sulfate reactions [23]. In marine settings, microbial-induced corrosion (MIC), combined with the localized stress from barnacles and mussels, disrupts surface uniformity and promotes microcrack initiation, significantly reducing durability [25-26].

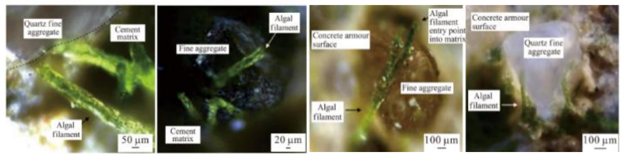


Fig.3. Algae filaments grow inside the concrete
* Source: Microscopic Study into Biodeterioration of Marine Concrete [26]

2.Progress in Anti-Fouling Coatings for Concrete

2.1.Barrier-Type Coatings

Barrier-type coatings form dense, continuous layers on concrete surfaces to block moisture, Cl^-, SO_4^{2-}, and acidic media, delaying degradation and enhancing durability. Common materials include epoxy, polyurethane, acrylic, and inorganic silicate coatings.

Epoxy coatings feature high crosslink density and low porosity; for instance, kaolin/epoxy composites still exhibit ~80% lower Rp than uncoated samples after three wet-dry cycles [27], as shown in Fig4. Polyurethane coatings, valued for flexibility, suit microcracked or impact-prone concrete; asphalt-polyurethane (As/PU) composites maintain ~0.9× compressive strength after 28-day immersion in 3% H_2SO_4 [28]. Bio-based polyurethanes show improved dynamic performance, with bending strain rate rising from 0.00033 to

0.067 s^{-1} and impact strain energy density increasing ~11.3× under dynamic loading [29], as shown in Fig5(a). Acrylic coatings can penetrate 20-30 mm into concrete to fill microcracks; after fluorosilane modification, contact angle increased from 82.0° to 93.7°, and surface energy decreased from 33.8 to 24.0 mJ/m^2 [30], as shown in Fig5(b).

However, long-term weathering and environmental stability remain concerns. Epoxy loses interfacial adhesion under heat, moisture, and UV [31]; TDI monomer release during polyurethane curing may reach 0.3 mg/m^3, accelerating aging at crack tips [32]; acrylics often retain residual monomer, a potential carcinogen, though modification can reduce it below 0.05%. Moreover, acrylics have poor water compatibility and relatively lower hardness and abrasion resistance.

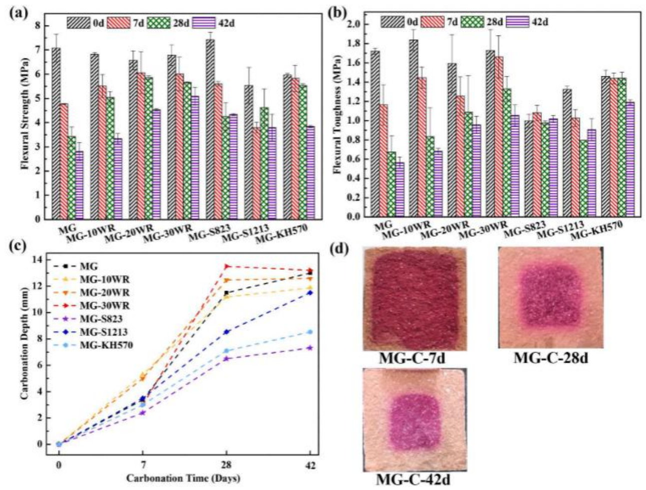


Fig.4. Increase of Rp of the cylinders coated with MG,MG-WR and MG-SCA compared to uncoated samples cured for different ages and conditioned for (a)0,(b)2 and (c)3 cycles of seawater wet-dry conditioning, and(d)the decrease of Rp after 2 and 3 wet-dry conditioning cycles

* Source: Coating performance, durability and anti-corrosion mechanism of organic modified geopolymer composite for marine concrete protection [27]

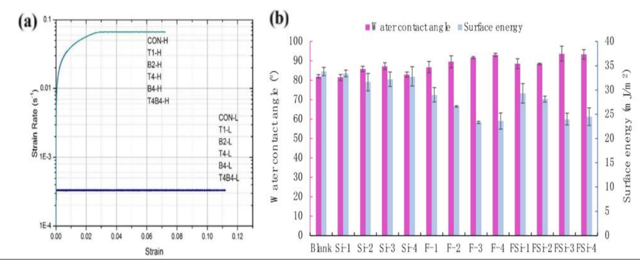


Fig.5.(a) The actual strain rate-strain curves of test specimens at varying strain rates,(b) Contact angle and surface energy of the hardened modified resins

* Source: Behaviour of concrete specimens retrofitted with bio-based polyurethane coatings under dynamic loads [29] Multiscale modification on acrylic resin coating for concrete with silicon/fluorine and graphene oxide (GO) nanosheets [30]

2.2.Anti-Organic-Fouling Coatings

Concrete in traffic, food-processing, and marine environments is prone to oil and organic contamination, which affects appearance and surface performance. Superhydrophilic hydration layer coatings have recently attracted attention [33]. Their mechanism involves introducing hydrophilic polymer chains on the surface, which rapidly absorb water to form a stable hydration layer.

This layer exhibits low oil adhesion and excellent self-cleaning. PSBMA significantly enhances surface hydrophilicity and reduces protein adsorption; Cu-modified PDA-based coatings show >90% antibacterial efficiency and 85% reduction in protein adsorption. PEG coatings rely on ether-water hydrogen bonding to resist adsorption of diverse organics; TEOS-modified PEG emulsions reduce capillary water absorption by ~84.1% (C40) and 83.1% (C50) [34], as shown in Fig6. Superhydrophilic coatings from TiO_2 nanoparticles and siloxane oligomers reduce water uptake by >85%, display a 152° contact angle with chloroform, and allow easy removal of oil and dust without detergents [35].

Compared with traditional barrier coatings, hydration-layer coatings offer environmental friendliness and high biocompatibility, showing potential for marine oil spill protection and nearshore anti-fouling applications [36]. However, chemical, mechanical, and long-term stability remain limited; in 3.5 wt.% NaCl, pH 5, and pH 9 solutions, performance declines. Molecular design, interfacial engineering, and fabrication optimization are required to achieve durable, high-efficiency anti-fouling [37].

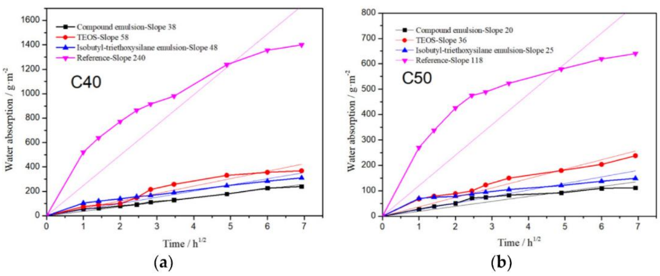


Fig.6. Effects of capillary water absorption of concrete for different coating: (a) C40; (b) C50

* Source: Preparation of Modified Silane Composite Emulsion and Its Effect on Surface Properties of

Cement-Based Materials [34]

2.3.Antimicrobial / Anti-Biofouling Coatings

Concrete structures in marine, hydraulic, and high-humidity environments are prone to biofouling by bacteria, fungi, algae, and larger organisms, which increase surface roughness and promote biofilm formation, accelerating microbiologically influenced corrosion (MIC) and compromising durability [38-39]. Antimicrobial/anti-biofouling coatings inhibit microbial attachment and growth via chemical, photocatalytic, or contact-killing mechanisms [40].

Chemical killing relies on active metal ions (e.g., Ag^+, Cu_2O, ZnO) to disrupt microbial metabolism. ZnO-NPs combinations can suppress biofilm formation by 65–85% [41], while Ag-NPs reduce E. coli by ~5.8 log CFU/cm² and S. aureus by ~4.11 log CFU/cm^2 [42]. However, these coatings mainly act in early fouling stages, and sustained ion release poses environmental risks; for example, organotin compounds (TBT) persist in marine environments, bioaccumulate, and disrupt endocrine systems [43]. In addition, metal ion agents may be incompatible with coating matrices, e.g., Cu_2O in epoxy or fluorocarbon systems can weaken crosslinking, reducing adhesion and tensile strength [44].

Photocatalytic killing, exemplified by TiO_2, generates OH^- and O_2^- under UV or visible light, oxidizing microbial membranes and DNA, as shown in Table2. Fe-doped TiO_2 (1 g/L) achieved 3.57 ± 0.21 log (E. coli) and 3.49 ± 0.42 log (S. aureus) reduction under 240 min visible light, reaching 99.97% killing efficiency [45]. Effectiveness declines under low light or underwater conditions [46]; element doping, graphene composites, or noble metal modifications expand light response but increase cost and environmental concerns [47].

Contact-killing coatings introduce cationic groups (e.g., quaternary ammonium salts, guanidine polymers) that disrupt microbial membranes electrostatically. QAC-functionalized coatings reduce E. coli, drug-resistant A. baumannii, and Listeria monocytogenes by >5.0 log CFU/cm^2 (~99.999%) within seconds [48]. However, covalently grafted functional polymers lose activity if the coating suffers mechanical damage, chemical cleaning, or aging, limiting long-term efficacy [49].

Overall, antimicrobial/anti-biofouling coatings effectively suppress microbial adhesion and biofilm formation, offering a key strategy against concrete bio-corrosion. Yet, chemical toxicity, photocatalytic light dependence, and contact-killing durability remain challenges, necessitating further optimization in material design, interface engineering, and ecological safety.

Table.2. Photocatalytic efficiency of cementitious materials with titanium dioxide incorporation

Material	Application Process	Quantity	Efficiency	Environmental Conditions	Observations
Anatase I	Mixing technique	10% by weight	44.1 mg $\times h^{-1} \times m^{-2}$	Flow rate 1.0 L $\times min^{-1}$; UV-A radiation 10 ± 2 W $\times m^{-2}$, relative atmospheric humidity 50 ± 5% and pollutant concentration (NO_x) 20 ppmv.	The efficiency is in terms of removal of NO_x.
Anatase II			11.71 mg $\times h^{-1} \times m^{-2}$		
Rutile			37.24 mg $\times h^{-1} \times m^{-2}$		
Nano-TiO_2-SiO_2	Dip coating	-	87% of MG, 80% MB and 65% MO	UV irradiation, room temperature.	The photocatalytic material was added to WPC blocks. The efficiency is in terms of percent of decomposit

					ion of dyes.
P25 (75 % anatase and 25% rutile)	Mixing technique	2% by weight of binders	NOx removal rate: 28 µmol $m^{-2}\times h^{-1}$. NO_x removal ratio: 5.8%	24 h UV-A irradiation.	The TiO_2 was incorporated in self-compacting glass mortar (SCGM). WPC and metakaolin were used as cementitious materials.
Nano-TiO_2	Dip coating and vacuum saturation	TiO_2 ethanol suspension of 0.05 g $\times$ mL^{-1}	Toluene removal efficiency: 95 % elimination rate: 60–70 mg $\times$ $m^{-2}\times h^{-1}$	24 °C, 52% relative humidity.	Initial toluene concentration: 15 ppmv gas residence time: 3 min.

* Source: Challenges and Opportunities of Using Titanium Dioxide Photocatalysis on Cement-Based Materials [46]

3.Surface-Energy-Controlled Coatings

Surface-energy-controlled coatings reduce the free energy of concrete surfaces, hindering wetting or adhesion of dust, sediments, oils, and biofouling proteins, thereby achieving anti-fouling and self-cleaning. Inspired by the lotus effect (static water contact angle >150°, roll angle ~2°) [50-51], as shown in Fig7.superhydrophobic coatings are created by combining micro/nano surface structures with low-surface-energy materials, forming a solid-gas-liquid interface. Droplets rest on trapped air within the microstructures (Cassie state) [52].

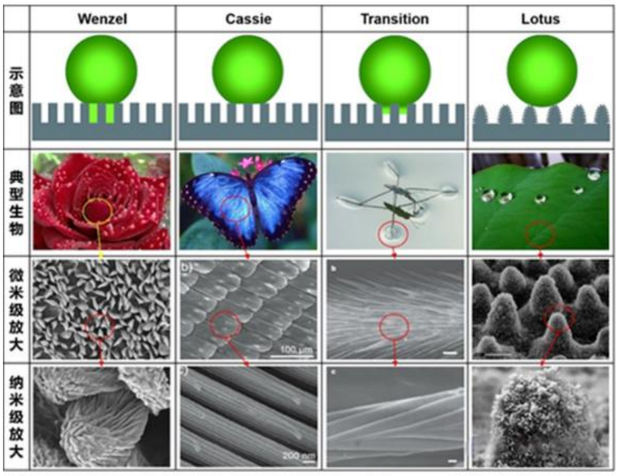
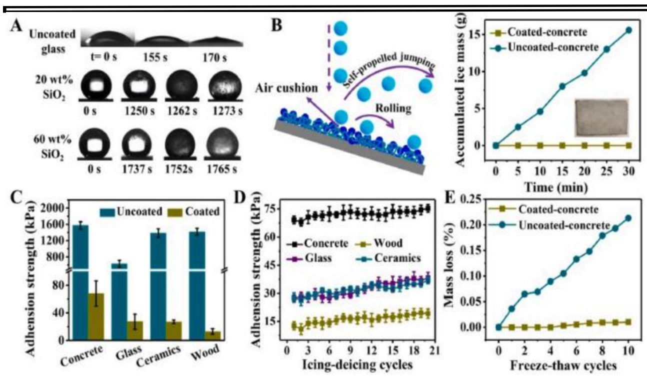


Fig.7. Superhydrophobic Phenomenon in Nature

Yang et al. [53] developed a sprayable superhydrophobic antibacterial coating exploiting concrete hydrophilicity and capillarity, reaching 162.4° contact angle, 5° roll angle, >70% water repellency improvement, and 84.6% (E. coli) / 90.4% (S. epidermidis) antibacterial rates. Song et al. [54] produced low-cost, fluorine-free, mechanically robust coatings (160 ± 1° contact, 6.5 ± 0.5° roll) maintaining superhydrophobicity after blade scratches and sandpaper abrasion, with excellent anti-icing, corrosion resistance, and low ice adhesion. Gu et al. [55] reported multi-layer surfaces retaining 154.4° contact and 4.3° roll after 115 days outdoor exposure. Wu et al. [56] used perfluorinated copolymers with SiO_2 nanoparticles to delay ice formation 1765 s at -20 °C and reduce ice adhesion 22-fold, as shown in Fig8. Kong et al. [57] fabricated hierarchical DE/Al_2O_3@STA-geopolymer surfaces, achieving 159.1 contact angle and 4.5° roll angle, with excellent water repellency, self-cleaning, and resistance to Cl^- corrosion and mechanical abrasion.

However, the Cassie state is thermodynamically metastable and vulnerable: static pressure or impacts exceeding the Laplace limit, prolonged immersion, or droplet evaporation can collapse the air layer; mechanical wear or oil contamination damages microstructures; its energy barrier is lower than the Wenzel state, allowing irreversible transition to full wetting [58-60]. These intrinsic limitations critically restrict long-term stability and anti-fouling performance of superhydrophobic coatings in real-world applications.



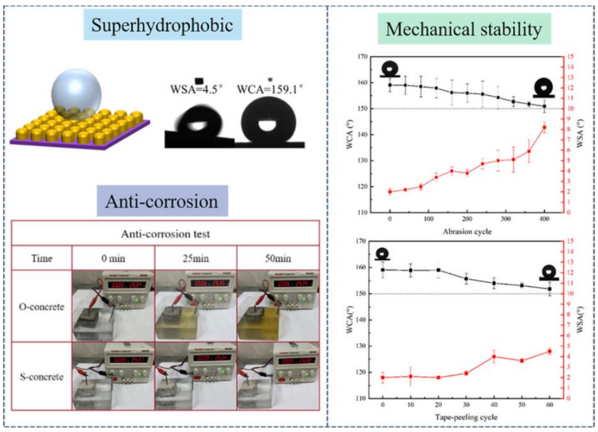


Fig.8. Anti-icing performance of the FSC4/SiO2F composite coating.(A)Photographs showed dynamic icing process of 2 uL water droplets on the untreated and FSC/SiO2-F coated surface at -20 "C.(B)Schematic illustration of the cold-rain simulated experiments, and the accumulated ice mass as a function of the treating time.(C)Ice adhesion strength of various FSC4/SiO2-F coated substrates.(D)Ice adhesion strength as a function of icing-deicing cycles.(E)Mass loss of coated and uncoated concrete as a function of freeze-thaw cycles. (F) The surface contact angle and rolling angle of superhydrophobic concrete

* Source: An extremely chemical and mechanically durable siloxane bearing copolymer coating with self-crosslinkable and anti-icing properties.[56] Superhydrophobic concrete coating with excellent mechanical robustness and anti-corrosion performances.[57]

Conclusion

Surface fouling and bioadhesion are critical factors that limit the long-term durability of concrete structures in marine environments. Compared with conventional antifouling strategies based on the release of active agents, surface-energy-regulated coatings can fundamentally reduce fouling by weakening the interfacial interactions between contaminants and substrates, offering clear advantages in terms of environmental friendliness and long-term stability. Among them, superhydrophobic coatings, featuring low surface energy, micro/nanostructured roughness, and excellent self-cleaning behavior, have demonstrated considerable potential in suppressing sediment deposition, organic contamination, and early-stage biofouling.

Nevertheless, the engineering application of superhydrophobic coatings on concrete still faces several challenges, including insufficient mechanical robustness of micro/nanostructures under abrasion and erosion, limited adhesion to concrete substrates, and difficulties in large-area and complex-surface fabrication. In addition, issues related to material cost, process complexity, and long-term performance degradation require further investigation.

Future efforts should focus on enhancing mechanical durability and interfacial bonding, developing multifunctional protective systems, and promoting scalable fabrication techniques suitable for practical engineering applications. With continuous advances in surface engineering, materials science, and construction technologies, surface-energy-regulated superhydrophobic coatings are expected to play an increasingly important role in antifouling protection and durability enhancement of marine concrete structures.

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Research on Intelligent Education Management under Intelligent Education System

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KEYWORDS

Intelligent education system;

Intelligent education management;

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ABSTRACT

With the rapid advancement of intelligent technologies, the intelligent era has fully arrived, presenting unprecedented opportunities and challenges for intelligent education management within the intelligent education system. By closely integrating intelligent systems with intelligent education management, we can better meet diverse educational needs, enhance teaching quality, and promote the development of intelligent education under the intelligent education framework. However, amidst the wave of the intelligent era, intelligent education management faces numerous challenges and opportunities. This paper actively explores research on intelligent education management within the intelligent education system, analyzes the value of intelligent transformation in education management, and proposes strategies to reconstruct innovative pathways for intelligent education management driven by the intelligent education system.

INTRODUCTION

In the new era of rapid scientific and technological development, the influence of intelligent education systems in the field of education is also increasing, becoming an important technical means to drive innovation in intelligent education management. The market size and growth rate of China's intelligent education industry from 2019 to 2024 can directly reflect the growing attention that intelligent education management is receiving from more people. (As shown in Figure 1) This indirectly reflects that the quality of education is directly related to the quality of talent cultivation, which not only affects individual career prospects but also impacts the development of future society. However, under the wave of development in the information age, the challenges and opportunities faced by research in intelligent education management are increasing, making it even more difficult to meet the developmental demands of the intelligent education system. The widespread application of intelligent technology in education makes the intelligentization of education management more urgent. This transformation is not only reflected in the improvement of education management efficiency and precision, the promotion of personalized education and student development, but also in the advancement of modernization and innovation in education governance. Building an intelligent management platform, promoting the precise allocation of curriculum resources, improving policy and legal support, strengthening information security construction, establishing a comprehensive protection system, accelerating the integration and innovation of information technology, enhancing application efficiency, and strengthening the training of education management personnel further drive the reconstruction of innovative pathways in intelligent education management under the intelligent education system. This is not only a promotion of progress in intelligent education management but also an important guarantee for the long-term development of the intelligent education system.

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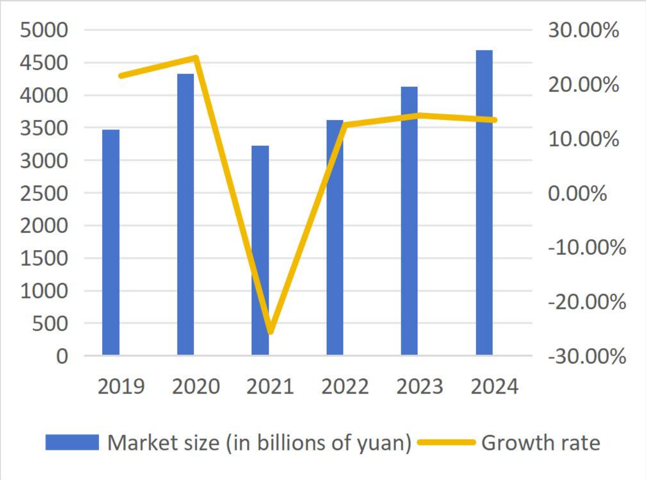

Fig.1. China's smart education industry market size and growth rate from 2019 to 2024

1.Problems and Opportunities of Intelligent Education Management under Intelligent Education System

1.1.Problems of Intelligent Education Management under Intelligent Education System

The fragmentation of information systems and poor data sharing have become critical challenges in smart education management. During implementation, the most prominent issue stems from disjointed systems developed by separate departments, creating severe data silos. The lack of effective inter-system connectivity and collaboration directly undermines information sharing efficiency. With no unified management or integration of data, information flows become inefficient, hindering the development of comprehensive and timely decision-making support. Furthermore, these fragmented systems increase operational costs and maintenance complexity, severely limiting the digital transformation and overall effectiveness of smart education management.

The data security framework remains inadequate, exposing high risks in digital transformation. In the development of smart education management systems, data security issues have become increasingly prominent. Many existing security mechanisms lack robust safeguards, creating significant risks. Frequent incidents such as cyberattacks, data breaches, and hacker intrusions threaten the security of critical data and information systems in smart education management. Furthermore, users' weak security awareness exacerbates these risks, disrupting system operations and posing potential threats to smart education management.

The pace of technological advancement in information systems remains sluggish, with application capabilities requiring enhancement. Despite the rapid evolution of digital technologies, the implementation of smart education management systems still lags behind, as many hardware devices and software systems have remained outdated for years, failing to meet the demands of modern digitalization. This not only hinders the adoption of new technologies but also compromises the efficiency and performance of management systems. The low proficiency in applying information technologies, coupled with insufficient technical expertise and operational skills among administrators, ultimately prevents information systems from reaching their full potential.

Outdated management models and a lack of comprehensive planning in digital infrastructure development pose critical challenges in smart education management systems. Many universities lack systematic top-level design and long-term planning during digital transformation, resulting in fragmented initiatives without unified objectives. For instance, when advancing smart education systems, departments often independently initiate projects without coordinated resource integration, leading to redundant infrastructure and resource waste. Furthermore, the management framework for digital infrastructure suffers from significant deficiencies. Information management departments struggle to meet rapidly evolving digital demands in terms of functional positioning, resource allocation, and performance evaluation.

1.2.Opportunities for Intelligent Education Management under Intelligent Education System

Intelligent education management can be supported by robust data. In the era of artificial intelligence and big data analytics, traditional research methods like field surveys and online questionnaires are no longer sufficient to track the evolving trends in intelligent education management. By leveraging big data analytics to collect relevant information, we can more accurately reflect current characteristics of intelligent education management and enhance its role in education. Big data technology effectively collects, integrates, and analyzes developmental data, providing managers with objective, detailed, and actionable insights to formulate effective educational policies and implementation plans. Artificial intelligence, combined with computational technologies, computer vision, and machine learning, enables precise and scientific analysis and prediction. Through systematic research and in-depth investigations using intelligent technology systems, we can identify future trends, provide effective guidance for intelligent education management, and better understand and control the development progress of intelligent education management within the intelligent education framework.

Intelligent education management can achieve greater transparency and personalization. In today's digital and information-driven era, it faces dual opportunities: transparency and personalization. Transparency requires maintaining open, fair, and impartial information flow throughout decision-making, resource allocation, and teaching evaluation processes, ensuring administrators fully understand educational management procedures and outcomes. Personalization represents another crucial direction for intelligent education management. Each student is unique with distinct thinking patterns, preferences, and behavioral habits. Therefore, intelligent education management must address individual differences by providing personalized educational services. In curriculum design, teaching methods, and student assessment, it should fully respect students' individual characteristics, innovate educational models, and meet diverse learning needs.

The effectiveness of intelligent education management can be monitored and evaluated. With continuous technological advancements, artificial intelligence has become a crucial tool for assessing the quality of smart education. Its capabilities include precise data analysis, rapid response mechanisms, and regular report generation, enabling us to gain a comprehensive understanding of learner groups and develop more targeted educational strategies to enhance teaching quality. If the monitoring system detects anomalies in the actual educational environment, it will immediately activate the early warning mechanism, allowing teaching administrators to promptly identify potential risks and take preventive measures.

2.The Value of Intelligent Transformation of Educational Management

2.1.Improving the efficiency and precision of education management

In previous educational management practices, human bias was difficult to avoid, and the emergence of intelligent educational management has brought a turning point for resolving this dilemma. Intelligent education management is capable of deep mining and analysis of student data, including academic performance, attendance records, and consumption behavior, which can provide more refined data support for education management and decision-making. For example, when formulating enrollment plans, artificial intelligence accurately predicts the number of applicants and the appropriate enrollment scale for each major by analyzing historical enrollment data, major application trends, job market demand, and other big data. This avoids the problem of unreasonable enrollment plans caused by human judgment errors, making the enrollment work more scientific and efficient. Universities can use artificial intelligence technology to build real-time monitoring and warning mechanisms, quickly grasp the usage of various resources, such as classroom usage, frequency of experimental instrument operation, etc., and optimize resource allocation. When there are problems with resource utilization, managers can respond quickly, such as taking timely measures to adjust classrooms or supplement teaching staff when the number of course selections suddenly increases, to ensure the safe progress of teaching activities. Teacher allocation also benefits from artificial intelligence. By integrating multi-dimensional data such as teacher evaluation, course requirements, and professional expertise, better scheduling plans can be generated, and teacher efficiency can be improved. Ultimately, precise allocation of educational resources can be achieved, and educational management efficiency can be comprehensively improved.

2.2.Promoting Personalized Education and Student Development

The intelligent mentor system is increasingly vital in supporting students 'academic and psychological development, as traditional education models often fail to address individualized needs. Powered by AI-driven analytics, this system comprehensively evaluates learning progress, assignment quality, and assessment fluctuations to create personalized development plans. When detecting learning challenges in specific subjects, it instantly delivers targeted study materials and instructional videos to help students overcome obstacles. In psychological support, the system identifies potential issues by analyzing students' social media activity patterns, club participation, and online interactions, providing early intervention suggestions. The differentiated teaching management framework addresses diverse student needs through stratified categorization, tailoring instructional content and methods to each group. For high-achieving students with academic interests, the system recommends advanced courses and research projects; for those lacking practical skills, it offers corporate collaboration internships and hands-on training. Moving beyond standardized testing, the system employs multi-dimensional evaluation methods based on personalized learning trajectories, ensuring comprehensive assessment of academic achievements. This truly implements differentiated instruction that fosters holistic development for every student.

2.3.Promoting the Modernization and Innovation of Educational Governance

The emergence of intelligent education management provides an opportunity to break existing constraints, with its focus on building an integrated intelligent education management information platform to achieve instant information sharing and rapid circulation. Taking student affairs management as an example, processes such as leave requests and excellence evaluations can be efficiently handled online through intelligent systems, enabling relevant departments and personnel to obtain information promptly and take swift action, thereby significantly shortening the processing cycle. Departmental collaboration can also be deepened through a unified data platform, allowing departments such as academic affairs, student affairs, and finance to share student data via artificial intelligence systems, achieving more efficient coordination in policy formulation and implementation, thereby optimizing management efficiency, shaping a flat and collaborative governance structure, streamlining intermediate steps, and enhancing the scientific nature of decision-making and the effectiveness of execution. The application of intelligent education management has brought profound changes to education management. The digital transformation of intelligent education has become a wave of the times, with intelligent technologies emerging as the core engine for innovation in the intelligent education system. The pioneering application of artificial intelligence in the field of intelligent education management has established a replicable transformation paradigm. Numerous aspects of academic affairs management, administrative services, and even teaching and learning have taken on a new digital appearance due to the intervention of intelligent means, giving rise to intelligent online teaching platforms and increasingly mature smart library management systems. Such innovative practices are too numerous to list. As shown in the distribution of China's intelligent education application scenarios, the demonstrative effects of intelligent education management under the intelligent education system will continue to be unleashed, strongly driving the overall evolution of higher education toward deeper intelligence and digitization. (As shown in Figure 2)

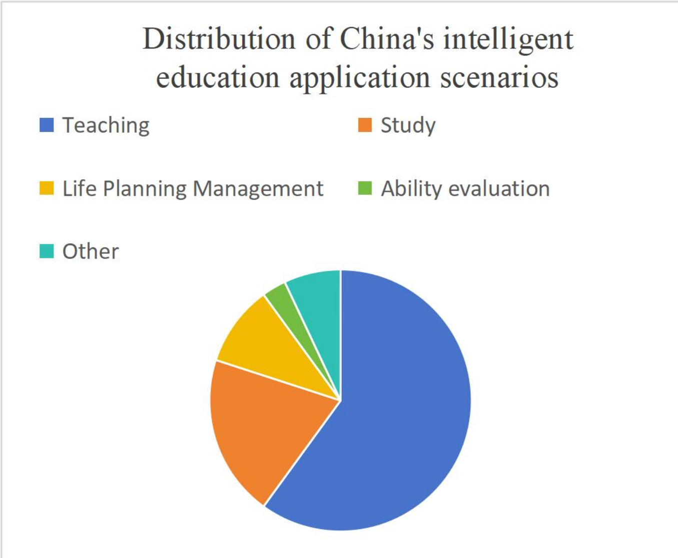

Fig.2. Distribution of China's intelligent education application scenarios

3.Reconstruction Strategy of Intelligent Education Management Innovation Path Driven by Intelligent Education System

3.1.Exploring the Innovative Integration of Technology and Education

xTo address the challenges posed by intelligent technologies in educational management, education authorities should spearhead the integration of research data and technical insights from smart education systems. This involves establishing an open data-sharing network to advance intelligent education management and strengthen foundational theoretical research. Educators should be encouraged to conduct applied research based on frontline teaching and research needs, allowing practical applications to inform theoretical development and drive continuous innovation in "AI + Education". Building on this foundation, interdisciplinary exchange platforms should be developed to foster intellectual exchanges among educators from diverse fields, sparking innovative synergies. Through case studies and workshops, teachers should be motivated to explore how intelligent education management can enhance curriculum design and teaching strategies, thereby continuously improving educational quality. Concurrently, a robust evaluation system must be established to dynamically monitor the effectiveness of educational reforms and ensure the implementation of all measures.

3.2.Improving policy and regulatory support

The integration of artificial intelligence with higher education management requires policy and regulatory support to ensure standardized application and healthy development of the technology. The Chinese government has initiated a series of measures to promote innovation and application of AI in education. These policies and action plans reflect the nation's emphasis on educational modernization and its strategic layout to drive AI integration through policy guidance. With continuous technological advancements and improved policies, this integration will become more profound and extensive, necessitating further refinement of policies and regulations to promote the transformation of higher education management through legal and standardized approaches. First, it is essential to establish technical application standards for educational data, data usage principles, and data sharing scopes, define standardized procedures for open technology applications, and improve regulations for AI in education to ensure data security and digital copyright protection. Second, potential biases and discriminatory practices should be assessed, and effective systems should be established to identify, mitigate, and resolve potential harm.

3.3.Strengthen information security construction and build a comprehensive protection system

In the intelligent era, information security has become paramount in the digital transformation of smart education management. As technological advancement accelerates, data and information systems in this field face growing threats including data breaches, cyberattacks, and system failures. To ensure information confidentiality, integrity, and availability, it is essential to strengthen cybersecurity infrastructure through comprehensive protection frameworks. This requires implementing multi-layered safeguards such as firewalls, intrusion detection systems, data encryption technologies, along with robust security protocols and emergency response mechanisms. During the digital transformation of smart education management, adopting advanced cybersecurity technologies and establishing multi-tiered defense systems is crucial. Deploying efficient firewalls and intrusion detection systems enables real-time monitoring of network traffic, identifying and blocking potential threats. This approach effectively prevents hacker intrusions and malicious attacks, safeguarding critical school data and systems.

3.4.Strengthening professional training for teachers and administrators

The adoption of artificial intelligence in smart education management has charted a new course for teachers 'professional growth, equipped them with innovative tools, and set new benchmarks for educators. To implement smart education management, it is imperative to enhance training for both teachers and administrators, boosting educators' AI application skills to meet the demands of intelligent education systems. Concurrently, standardized protocols for AI usage must be established: in teaching, implementing scientific restrictions on student data access; in research, requiring authors to rigorously label AI-generated content and take responsibility for its accuracy; in administration, preventing data security breaches or biased conclusions caused by human errors.

Conclusion

This study conducts a comprehensive analysis of intelligent education management within the smart education framework, examining both challenges and opportunities in this context. The research further highlights the value of intelligent transformation in educational administration, focusing on three key dimensions: enhancing management efficiency and precision, advancing personalized education for student development, and promoting modernization and innovation in educational governance. By identifying existing issues and opportunities in intelligent education management, the paper proposes strategies to reconstruct innovative pathways under the smart education system. These include exploring innovative integration of technology and education, improving policy and regulatory support, strengthening information security infrastructure, establishing comprehensive protection systems, and enhancing professional training for educators and administrators. These measures aim to ensure intelligent education management fulfills its essential role in promoting educational equity and improving educational quality.

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Risk Assessment and Response Strategies for Corporate Human Resource Integration in the Context of Mergers and Acquisitions

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KEYWORDS

Mergers and acquisitions;

Human resource Integration;

Business economy

ABSTRACT

Against the backdrop of intensified market competition, mergers and acquisitions (M&A) and restructuring have become an important path for enterprises to optimize resource allocation, yet improper human resource integration is a major cause of M&A failures. This paper, supported by Hofstede's Cultural Dimensions Theory, Human Capital Theory, and other relevant theories, focuses on two core risks: cultural conflicts and staff placement. It combines multiple types of cases, such as cross-border M&A and mixed-ownership reforms of state-owned enterprises, and applies scientific assessment methods including core talent inventory and cultural compatibility evaluation.Through the in-depth integration of theory and practice, the paper draws logical countermeasures from successful cases, including respecting cultural differences, locking in core talents, implementing incremental integration, and enabling mutual empowerment. It aims to achieve prevention before M&A, implementation during M&A, and optimization after M&A, providing a reference with both theoretical depth and practical value for human resource integration in enterprise M&A and restructuring, and helping to realize the M&A value of "1+1>2".

INTRODUCTION

Against the backdrop of economic globalization and intensifying market competition, mergers and acquisitions (M&A) and restructurings have become an important path for enterprises to expand their scale and optimize resource allocation.M&A can not only fail to enhance the market value of the acquirer, but also exert negative impacts. Even if an enterprise achieves positive short-term announcement returns after an M&A, such gains are difficult to sustain in the long run.[1,2]

M&A and restructurings are divided into three types: horizontal M&A, vertical M&A, and conglomerate M&A. They are not a simple addition of assets. Instead, they help enterprises enhance their core competitiveness by rapidly expanding scale and acquiring technologies and resources.

Among the many links of M&A and restructurings, human resource integration cannot be ignored, as it directly affects whether the M&A value can be realized.Traditional human resource integration has excessively focused on the isolated optimization of functional modules such as recruitment, training, and compensation, while neglecting the realization of overall strategic synergy effects.[3,4]Statistics show that more than 60% of M&A failures stem from improper human resource integration, with risks such as cultural conflicts and staff placement being particularly prominent.

1.Types of Mergers, Acquisitions and Restructurings and Core Risks in Human Resource Integration

1.1.Inter-organizational cultural conflict

Cultural conflict is the most prevalent core risk in various types of mergers and acquisitions. Currently, scholars hold different attitudes regarding the impact of cultural conflict on corporate M&A and restructurings. Some scholars argue that it exerts a negative influence on the development of enterprises, while others contend that it can facilitate enterprises in absorbing more advanced management

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experience, thereby playing a positive role in promoting corporate development.[5] This paper maintains that cultural conflict has both negative impacts and positive driving effects on the two enterprises involved, and their relationship should be viewed dialectically. From the perspective of human resource integration, this paper examines the impact of cultural conflict on enterprises and analyzes the issue from a new angle.

In horizontal M&A, two enterprises operating in the same industry may develop distinctly different corporate cultures due to variations in their development histories and management models. For instance, if one enterprise emphasizes innovation and flexibility while the other focuses on standardized processes, employees from the two sides tend to have conflicts in terms of work methods and value perceptions.

Vertical M&A involve upstream and downstream enterprises. Owing to differences in industry attributes, the rigorous culture of upstream manufacturing enterprises is prone to colliding with the efficient culture of downstream service-oriented enterprises.

From the perspective of conglomerate M&A (mixed M&A), cross-industry cultural barriers are more prominent. Cognitive biases in fields such as technology, management, and operations may trigger resistance among all employees.

1.2.Staff Placement Risks

Staff placement risks are directly related to the adjustment of organizational structure after M&A. In horizontal M&A, the overlap of departments between the two companies leads to redundant positions, making it impossible to accurately identify core talents and resulting in chaotic talent resources. How to optimize staffing allocation and avoid the loss of core talents has become a key issue. Vertical M&A requires integrating the human resources of upstream and downstream enterprises, posing challenges to position adaptability and cross-departmental collaboration capabilities. The work content of upstream and downstream enterprises differs significantly: upstream enterprises are mostly technology-oriented, while downstream ones are mainly sales-focused. This means that employees of the merged company will face a new environment. Technical talents may encounter difficulties in career development, and sales talents may choose to resign due to factors such as corporate regulations and company location. The lack of technical talents can cause supply chain problems, while the loss of sales talents may lead to overproduction and market chaos. In conglomerate M&A, due to the significant differences in business areas, the difficulty of staff reassignment and retraining is higher, and the corresponding cost of human resource integration is also greater. In addition, differences in salary and welfare systems, changes in promotion paths, and other factors after M&A may also arouse employee dissatisfaction and exacerbate the risk of talent loss.

2.Case Analysis of Mergers, Acquisitions and Restructuring Enterprises

2.1.The Merger and Reorganization of Suzhou Taijinuo New Material Technology Co., Ltd. by Yantai Debang Technology Co., Ltd.

The core value of Taijinuo lies in technologies such as liquid metal thermal interface materials and the corresponding patent reserves, and these core resources are highly dependent on its R&D and technical team. Debang Technology did not adopt a radical personnel replacement strategy; instead, it retained key personnel by stabilizing the organizational structure after the equity transfer. After the completion of industrial and commercial registration changes, Taijinuo still operates as an independently held subsidiary. This model can reduce the impact of management level changes on the core team and prevent the loss of technical talents due to organizational turbulence.

For technical personnel in core business lines such as supplying NVIDIA, the continuity of their positions and responsibilities is maintained to ensure the inheritance of core technologies and the stability of production and delivery. This acquisition has set up targeted performance commitments and compensation mechanisms, deeply binding the interests of Taijinuo's core personnel with the operating results after the merger and acquisition.

Companies whose stock options have been exercised are more likely to include performance commitment clauses in M&A transactions, and are less likely to engage in opportunistic "precise target achievement" during the performance commitment fulfillment phase.[6]In the transaction, the relevant parties are clearly identified as compensation obligors, who commit to achieving a cumulative net profit of no less than 42.33 million yuan from 2024 to 2026. If the target is not met or specific performance conditions are not satisfied, compensation shall be paid to Debang Technology. Such arrangements essentially strongly link the income of the core team with Taijinuo's performance. It not only urges core personnel to fully engage in business operations after the merger and acquisition to ensure the efficiency of key links such as R&D, production, and customer maintenance, but also reduces the risk of core personnel resignation through interest binding, prompting them to actively promote the enterprise to achieve performance goals.

At the same time, the transaction consideration is paid in phases, and the remaining funds are paid only after the performance commitment period expires and there is no compensation obligation, which further strengthens the restraint and incentive for core personnel.

Considering the differences in management methods and corporate culture between the two parties, Debang Technology did not rush to promote large - scale personnel restructuring, but avoided the practice of blindly merging departments and cutting personnel. Debang Technology itself is advancing the development goals of "groupization, digitalization, scale, and globalization" and has a standardized management system. For example, it has established professional committees such as the Remuneration and Assessment Committee to improve governance efficiency. During the integration process, Taijinuo's human resource management will most likely be gradually integrated into Debang Technology's standardized system.

As a holding subsidiary, Taijinuo maintains a relatively independent organizational structure, which can reduce personnel conflicts caused by overlapping positions. For back - office positions such as administration and finance, efficient collaboration may be achieved by sharing the group resources of Debang Technology instead of duplicating positions. This not only reduces operating costs but also avoids internal friction caused by the integration of back - office personnel, allowing core human resources to focus on R&D and front - line business.

2.2.The Issues Arising in Human Resource Integration during the Merger, Acquisition and Restructuring between Aokang International and Lianhe Storage

The two companies operate in completely separate industries, and their teams differ significantly in professional competence, work modes, and corporate culture—posing major obstacles to human resource integration.

The team of Aokang International primarily focuses on the design, production, offline channel development, and terminal sales of footwear products. Its work rhythm and core assessment criteria revolve around supply chain management and store performance. In contrast, the team of Lianhe Storage concentrates on chip R&D, technological iteration, and high-end customer engagement. Its work relies more on long-term R&D investment, with core assessments centered on technological breakthroughs and patent outputs. As a result, the two teams struggle to quickly adapt to each other's work logic.

Their corporate cultures also show distinct differences. Companies in the traditional footwear and apparel industry prioritize terminal sales and cost control, while semiconductor companies emphasize product innovation and R&D. This cultural conflict is directly reflected in daily work collaboration. Rushing into human resource integration would lead to issues such as inefficient communication and hindered collaboration, and Aokang International lacks corresponding training programs for cultural integration and personnel adaptation.

Building a human resource structure and enabling departmental collaboration after mergers and acquisitions is crucial to ensuring the target company's integration into the group. However, Aokang International has not developed any feasible plans for this.

Aokang's back-office departments (e.g., administration and finance) are familiar with the accounting standards and management processes of traditional manufacturing. They cannot meet the professional needs of Lianhe Storage, such as semiconductor industry-specific R&D expense accounting and technical asset valuation. A simple merger of back-office departments would cause work chaos; retaining independent back offices, on the other hand, would increase operating costs—leaving Aokang in a dilemma.

From the perspective of business collaboration: Aokang's sales team cannot help Lianhe Storage expand new customers for its chip products, and Lianhe Storage's technical team cannot provide technical support for Aokang's footwear business. The two teams fail to complement each other; instead, they may conflict over internal resource allocation within the group.

Additionally, Aokang itself has suffered consecutive losses and lacks strong financial strength. It cannot support the labor costs required for the parallel operation of the two teams, which deprives the integration of the human resource structure of basic financial security.

3.Research on Countermeasures of Human Resource Integration under the Background of M&A and Restructuring

The completion of an M&A transaction is merely the starting point; what truly creates value is the integration process after the transaction closes. Among all integration aspects, human resource integration emerges as the most complex and critical link, as it involves human emotions, cultures and interests. Based on the case analyses presented earlier, this paper proposes the following systematic integration countermeasures.

3.1.Clarify the Integration Model and Core Preservation Objects

The formulation of integration strategies must be premised on strategic assessment to avoid arbitrary integration. The acquirer must address a core question during the due diligence phase: Where does the core value of this M&A lie? If the core value hinges on specific technical teams, R&D capabilities, or customer relationships, the focus of human resource integration must be on protection and motivation. If the M&A is merely aimed at acquiring fixed assets, market share, or simply pursuing economies of scale, a deeper level of assimilation and restructuring may be considered.

For target enterprises highly dependent on human capital and organizational knowledge, retention-oriented integration is the optimal choice. The acquired enterprise should be allowed to maintain its independence in operations, culture, and branding for a certain period. A case in point is Debang Technology's operation of Teginor as an independent controlled subsidiary. This approach minimized the impact of organizational restructuring on the core R&D team and avoided the "acclimatization" and brain drain caused by abrupt changes in management models. Conversely, forced integration between two completely disconnected industries, as exemplified by Aokang and Lianhe Storage without any isolation or buffering measures, is bound to trigger severe cultural conflicts and talent attrition.

3.2.Establish a Talent Retention Mechanism That Balances Incentives and Restraints

Ensure the Continuity of Organizations and Responsibilities. In the initial stage of M&A and restructuring, priority should be given to maintaining the unchanged organizational structure, reporting lines, and job responsibilities of core business and technical teams. Debang Technology adopted the practice of "keeping the job positions and responsibilities of technical personnel in core business lines such as NVIDIA supply unchanged"—this measure ensured the uninterrupted operation of core technologies and the stability of key customers, laying a solid foundation for the smooth operation after the M&A.

Establish a Long-term Incentive and Restraint Mechanism. This serves as a key tool for retaining core talents. The vital interests of management and core personnel should be strongly linked to the company's long-term operational performance. This effectively drives the core team to sustain their commitment after the M&A and significantly reduces the risk of their short-term turnover. Delaying the payment of a portion of the transaction consideration until the expiration of the performance commitment period further enhances the binding force of the aforementioned mechanism. It ensures that core obligors must accompany the enterprise through the most critical integration period before receiving full remuneration, thereby achieving deferred incentives and risk-sharing.

3.3.Promote the gradual and orderly integration of corporate culture and back-office functions

Cultural integration is a subtle and gradual process, whereas back-office integration should follow the principle of efficiency—neither should be rushed. A progressive integration strategy should be adopted. Both parties involved in M&A and restructuring must acknowledge and respect existing cultural differences. They should build communication bridges and gradually cultivate a shared cultural system by establishing joint project teams, organizing cultural exchange activities, and conducting cross-cultural training programs. Debang Technology did not rush into large-scale personnel restructuring, which created a valuable time window for progressive integration. In contrast, Aokang made no effort to address the enormous cultural gap between the merged entities, laying significant hidden risks for future collaboration.

Implement the collaborative model of "independent front office, shared back office". For mid-and back-office departments that do not directly create value but are indispensable, reference can be made to Debang Technology's approach: achieve efficient collaboration by sharing the parent company's resources instead of duplicating positions. This method enables the parent company to leverage its economies of scale and reduce overall operational costs. It also avoids power struggles and personnel attrition caused by the forced merger of similar positions, thereby allowing high-quality human resources to focus more on value-creating frontline work such as R&D and marketing.

Conclusion

Human resource integration in mergers, acquisitions, and restructuring is never a simple process of personnel superposition or organizational restructuring. Instead, it is a systematic project that bears on the inheritance of core values, the efficiency of organizational synergy, and cultural symbiosis.

The success of Debang Technology lies in its adherence to the principle of "stability as the foundation, interests as the bond, and synergy as the guideline", which enables it to accurately grasp the key points of retaining core personnel and adapting to organizational needs. In contrast, the predicament of Aokang International serves as a warning that integration efforts ignoring cultural differences, lacking planning and financial support are destined to be fraught with difficulties.

In the final analysis, the core of human resource integration is "people-oriented". It requires not only designing scientific mechanisms to retain key talents and bind core interests, but also adopting an inclusive attitude to resolve cultural conflicts and build bridges for synergy, and further formulating long-term plans to consolidate the foundation of integration. Only in this way can the merged and restructured organization get rid of internal friction, pool synergistic forces, truly unleash the M&A value of "1+1>2", and inject sustained impetus into the long-term development of the enterprise.

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Research on the Threshold Effect of Digital Transformation on Corporate Performance in Manufacturing Enterprises

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KEYWORDS

Digital Transformation; Corporate Performance; Manufacturing Enterprises; Threshold Effect

ABSTRACT

In the digital economy era, as a pillar of China's economy, the manufacturing sector must pursue digital transformation, which is crucial to high-quality development and modernization goals. Using Shanghai and Shenzhen A-share manufacturing enterprises from 2015 to 2023 as samples, this paper explores the threshold effect of digital transformation on corporate performance, analyzes heterogeneity, relevant moderating and mediating roles, and provides suggestions for enterprises' transformation.

INTRODUCTION

Guided by national policies, China's digital economy has leapfrogged as a key economic engine. Corporate performance is critical to overall economic progress. With advancing digitalization, academic research on their link has deepened yet divided: some scholars argue for a linear positive correlation—e.g., Chen Xu, Jiang Yao, et al. hold it boosts performance via cost optimization and efficiency gains [1]; others note transformation cannot be rushed—Fu Ying, Xu Qi, et al. found misalignment with enterprises' resources/capabilities often reduces performance [2]. Current research mostly focuses on linear relationships, with no consensus on nonlinear dynamics or mechanisms. As a national economic pillar, exploring this threshold effect in manufacturing is vital. Drawing on relevant theories, this paper uses a threshold model to verify the "first promoting, then inhibiting" nonlinear relationship, clarifies mechanisms of variables like financing constraints and the threshold value, enriches theories, and provides enterprise transformation guidance to mitigate risks and enhance performance.

1.Theoretical Analysis and Research Hypotheses

1.1.The Threshold Effect of Digital Transformation on Corporate Performance

Digital resources, an emerging production factor, have an inverted U-shaped "first promoting, then inhibiting" impact on corporate performance due to the law of diminishing marginal returns, with a significant threshold effect. This can be analyzed from two core dimensions: technology and organization.

In the early stage, technological empowerment delivers tangible benefits: data infrastructure breaks barriers, cloud computing and big data integrate multi-business data, speed up information flow and cross-departmental sharing, and enhance decision-making efficiency. Meanwhile, digital-tech integration with operations replaces repetitive labor with automation and intelligence, achieving standardized production, economies of scale, and lower unit costs.

In the later stage, the "digital paradox" emerges: incompatible interfaces across systems create data silos, compelling enterprises to invest heavily in custom interfaces. High costs and delays in cross-platform integration seriously hamper supply chain and sales response efficiency. Rapid tech iteration brings dual pressures: system maintenance and

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upgrades consume significant resources, crowding out innovation funding. When iteration pace exceeds enterprises' absorption capacity, they fall into a "obsolete upon introduction" vicious cycle, hindering the conversion of tech input into outputs.

Early on, digitalization spurs organizational change: traditional "pyramid" structures shift to "networked" ones, shortening response cycles and breaking hierarchical barriers. A "data-driven culture" reforms management thinking, shifting decision-making from "experience-driven" to "data-driven." It also helps enterprises deepen customer ties, co-construct a digital supplier ecosystem, and build an integrated supply-production-marketing model.

In the later stage, organizations show a "rejection response" to tech shocks: organizational inertia and path dependence cause delayed structural adjustments, sparking employee resistance and talent drain. Moreover, digital system complexity fosters strict control mechanisms that conflict with digitalization’s need for agility, stifling creativity and flexibility, and undermining the transformative organizational environment—ultimately dragging down performance.

Therefore, this paper proposes Hypothesis H1: Digital transformation of manufacturing enterprises has a threshold effect on corporate performance.

1.2.Moderating Effect of Digital Transformation on Corporate Performance

1.2.1. Moderating Effect of Financing Constraints

Financing constraints moderate the relationship between digital transformation and corporate performance through two aspects, ultimately showing a differentiated effect: "low constraints promote growth, while high constraints inhibit it."

Firstly, they affect input-output capacity. Under low constraints, enterprises have strong capital access, enabling sufficient investment in advanced technologies and equipment for digital transformation without crowding out resources for core links like production and sales. This ensures coordinated progress of transformation and daily operations, maximizing digitalization’s performance-enhancing effect. Conversely, high constraints leave enterprises short of transformation funds; forced advancement causes resource misallocation, leading to capital turnover difficulties, equipment idleness, unsold products, and reduced performance.

Secondly, financing constraints restrict strategic adjustment flexibility. In the digital era with rapid market and technological iteration, enterprises with low constraints can flexibly raise funds to adjust transformation plans, adapt to market changes and organizational needs, and optimize paths to boost performance. However, those with high constraints, limited by capital, struggle to make dynamic adjustments and can only stick to existing plans, making path deviations likely and preventing digital transformation from empowering performance.

Based on this, this paper proposes Hypothesis H2: Financing constraints play a moderating role in the threshold effect of digital transformation on corporate performance in manufacturing enterprises.

1.2.2.Moderating Effect of Agency Costs

Agency costs significantly moderate the relationship between digital transformation and corporate performance: transformation boosts performance under low agency costs but inhibits it under high costs.

Under low agency costs, enterprises feature efficient information communication—digital transformation-related information is transmitted accurately and timely, facilitating progress tracking, problem-solving, and scientific decision-making to enhance transformation success. Sound supervision and goal-aligned incentives align managers’ and shareholders’ interests, enabling resource allocation based on overall corporate goals, avoiding delays/waste, and driving efficient transformation. Additionally, a good governance structure attracts external resources, creating a favorable environment for digitalization and improving performance.

Under high agency costs, poor inter-departmental information flow, coupled with information asymmetry and incomplete contracts, makes it hard for external shareholders to select optimal management or supervise them effectively. This leads to managers seizing control, misallocating resources for personal gain, and wasting resources in transformation. Moreover, if managers’ incentives are decoupled from long-term corporate performance, they may prioritize personal interests over transformation goals, leaving digitalization without proper direction or sufficient support and ultimately hindering performance improvement.

Thus, this paper proposes Hypothesis H3: Agency costs play a moderating role in the threshold effect of digital transformation on corporate performance in manufacturing enterprises.

1.3.Mediating Effect of Digital Transformation on Corporate Performance

1.3.1.Mediating Effect of Organizational Resilience

Organizational resilience is a core organizational capability of enterprises, enabling them to address crises and resist risks in an uncertain environment [3], stabilize operational rhythms, and activate resource advantages. Enterprises with strong resilience have competitive advantages such as rapid environmental responsiveness and flexible structures. Their three dynamic capabilities—perception, integration and coordination, and learning—work synergistically to enhance risk resistance, optimize operational efficiency and decision-making quality, and inject sustained momentum into performance growth.

However, the effective exertion of organizational resilience relies on a mature and stable organizational structure and operational system. The core logic of digital transformation, by contrast, is to break this original stability and drive disruptive changes [4]. Such transformation triggers multiple uncertain shocks; technological dependence during the transformation period is also prone to deriving various risks, generating a "digital disempowerment" effect [5] that weakens organizational resilience's shock resistance. In addition, substantial resource investment in the early stage of digital transformation crowds out the redundant resources required to maintain resilience, restricting its restoration and effectiveness and thereby hindering its positive supporting role in corporate performance.

Therefore, this paper proposes Hypothesis H4: Organizational resilience plays a mediating role in the promoting effect of digital transformation on corporate performance.

1.3.2. Mediating Effect of Technological Innovation Input

Digital transformation is not a linear value-adding process but exhibits a significant threshold effect. Beyond the threshold, "post-threshold redundancy" tends to occur due to inadequate matching of funds, technologies, human resources, and organizational resources, triggering enterprises' "R&D expansion inertia"—stemming from path dependence in resource allocation. Driven by innovation-oriented cognitive inertia and industry competition pressure, management tends to channel redundant resources into R&D, continuously increasing technological innovation input even amid late-stage transformation resource constraints.

The "current cost characteristics" of technological innovation input (long payback period, high risk, and resource intensity) lead it to compete for resources with late-stage digital transformation needs such as system optimization and operation maintenance upgrades. Coupled with the financial pressure from early-stage investment, this forms "dual cost pressure," amplifying the inhibitory effect of transformation on performance. Existing studies support this: Dai Xiaoyong and Cheng Liwei found that excessive R&D input weakens its promotional effect on performance [6]; Han Xianfeng et al. noted that overly high R&D intensity causes resource misallocation and inhibits corporate performance [7].

Therefore, this paper proposes Hypothesis H5: Technological innovation input plays a mediating role in the inhibitory effect of digital transformation on corporate performance.

2.Empirical Design

2.1.Sample Selection and Data Sources

In view of China's official proposal of the concept of digital transformation in 2015, as well as the availability and effectiveness of data, this paper selects data of Shanghai and Shenzhen A-share manufacturing enterprises from 2015 to 2023 to construct a balanced panel data, and studies the threshold effect of digital transformation on corporate performance in manufacturing enterprises. The data are mainly from the CSMAR Database.

2.2.Variable Definition

This paper takes corporate performance (Roa) as the dependent variable; digital transformation (Dt) as the independent variable; financing constraints (ww) and agency costs (Cr) as moderating variables; and organizational resilience (Re) and technological innovation input (Rd) as mediating variables; enterprise age (Age), enterprise growth (Growth), asset-liability ratio (Lev), fixed asset ratio (Far), cash recovery rate of assets (Cash), net asset per share (Navps), and enterprise size (Size) as control variable.

Variable Name	Meaning	Calculation Method
Dt	Digital Transformation	Natural logarithm of digital transformation word frequency
Roa	Return on Assets	Net profit / Total assets
Age	Enterprise Age	Natural logarithm of enterprise age
Growth	Enterprise Growth	Operating income growth / Operating income of the previous year
Lev	Asset-Liability Ratio	Total liabilities / Total assets
Far	Fixed Asset Ratio	Fixed assets / Total assets
Cash	Cash Recovery Rate of Assets	Net cash flow from operating activities / Total assets
Size	Enterprise Size	Natural logarithm of total assets of the enterprise
Navps	Net Asset per Share	Net assets / Number of common shares
ww	Financing Constraints	-WW index
Cr	Agency Costs	Administrative expenses / Operating income
Re	Organizational Resilience	Calculated by entropy weight method
Rd	Technological Innovation Input	0.3791 × R&D investment level + 0.6209 × Proportion of R&D personnel

Table.1. Variable Description

2.3.Model Construction

This paper constructs a single threshold regression model (1) as the basic model.

$$Roa = \beta_0 + \beta_1 Dt \times 1(Dt < r) + \beta_2 Dt \times 1(Dt \geq r) + \sum X + \varepsilon \qquad (1)$$

Where Roa represents the dependent variable corporate performance, Dt represents the independent variable digital transformation, r represents the single threshold value, 1() represents the indicator function, which takes the value of 1 when the condition in the bracket is satisfied and 0 otherwise. ∑X represents control variables such as Age, Growth, Lev, Far, Cash, Size, and Navps, and ε represents the residual term. Dt is the threshold variable.

3. Empirical Test and Result Analysis

3.1.Threshold Effect Test of Digital Transformation on Corporate Performance

3.1.1. Analysis of Test Results

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single Threshold	19.80	0.0033	10.0568	14.2560	17.7751

Table.2. Test Results of Threshold Effect of Digital Transformation on Corporate Performance

Threshold Value	95% Confidence Interval
4.5218	(4.4424, 4.6195)

Table.3. Threshold Estimation Results of Threshold Effect of Digital Transformation on Corporate Performance

From the test results in Table.2. and Table.3. it can be seen that there is a single threshold effect of digital transformation on corporate performance, with a threshold value of 4.5218 and a p-value of 0.0033 < 0.01, which is significant at the 1% significance level.

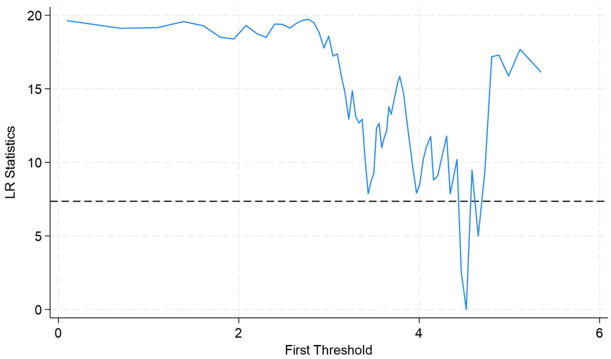

Fig.1. Likelihood Ratio Function Graph of Threshold Effect of Digital Transformation on Corporate Performance

According to Fig1., the lowest point of the LR statistic corresponds to the true threshold value, and the dashed line represents the critical value of 7.3523. Since the critical value of 7.3523 is significantly greater than the single threshold value, and the LR statistic corresponding to this threshold value is 0, it can be considered that the above threshold value is true and effective.

Variable	Regression Coefficient	t-value
Age	-0.00367***	(0.000434)
Lev	-0.227***	(0.0199)
Cash	0.209***	(0.0466)
Size	0.0314***	(0.00564)
Growth	0.0000804***	(0.0000271)
Far	-0.132***	(0.0161)
Navps	0.00133**	(0.000645)
Dt<4.5218	0.000673*	(0.000399)
Dt≥4.5218	-0.00216**	(0.000941)

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

Table.4. Parameter Regression Results of Panel Threshold Model of Digital Transformation on Corporate Performance

According to the parameter regression results, when the value of digital transformation is less than 4.5218, the coefficient of digital transformation on corporate performance is 0.000673, which is significantly positive at the 10% significance level; when the value of digital transformation is greater than 4.5218, the coefficient of digital transformation on corporate performance is -0.00216, which is significantly negative at the 5% significance level. Thus, Hypothesis H1 is verified, that is, the impact of digital transformation on corporate performance presents a threshold effect of first promoting and then inhibiting.

From the influence coefficient of the threshold regression interval results, it can be seen that before reaching the threshold value, digital transformation has a positive impact on corporate performance, but its coefficient is much smaller than the absolute value of the coefficient after the threshold. This may be because digital transformation is a long-term and gradual process, and the investment in digital transformation is difficult to achieve results quickly. When digital transformation reaches the threshold value, the resource misallocation and occupation caused by digital transformation are likely to have a serious impact on the normal operation of the enterprise. Therefore, the inhibition speed of digital transformation on corporate performance is faster than the promotion speed.

3.1.2. Endogeneity Test

Firstly, enterprises with high performance generally have more resources for digital transformation, which may lead to reverse causality; secondly, there may be unobserved factors that affect both digital transformation and corporate performance, and the omission of such variables is also likely to lead to endogeneity problems. Therefore, this paper uses the lagged term of digital transformation as an instrumental variable for endogeneity test, denoted by L.Dt.

The lagged term of digital transformation is highly correlated with the current digital transformation, and past digital transformation decisions have no causal relationship with the current random disturbance term, which meets the selection conditions of instrumental variables. The test results are as follows:

	(1)first stage Dt	(2)second stage Roa
VARIABLES		
L.Dt	0.4192***	
	(14.00)	
Age	-0.0116***	-0.0006***
	(-5.52)	(-5.10)
Growth	0.0274**	0.0008
	(2.12)	(1.59)
Lev	0.1371	-0.1487***
	(1.53)	(-14.91)
Far	-1.4022***	-0.0564***
	(-10.22)	(-7.66)
Navps	-0.0087**	0.0013***
	(-2.48)	(5.38)
Cash	0.0588	0.3534***
	(0.26)	(6.60)

Size	0.1581***	0.0150***
	(8.36)	(11.51)
Dt		-0.0043***
		(-3.88)
Constant	-1.2437***	-0.2306***
	(-3.49)	(-9.38)
Kleibergen-Paap rk LM statistic	309.513***	
Cragg-Donald Wald F statistic	2763.914(Critical value = 16.38)	
Observations	9,480	9,480
R-squared		0.319

Table.5. Endogeneity Test Results

The Kleibergen-Paap rk LM statistic is 309.513 which is significant at the 1% significance level, rejecting the null hypothesis of "underidentification". It indicates that the instrumental variable L.Dt is correlated with the endogenous variable Dt, satisfying the "correlation condition" of instrumental variables, and the identification is effective. The Cragg-Donald Wald F statistic = 2763.914 is much greater than the critical value of 16.38 for 10% bias in the Stock-Yogo weak ID test, indicating that the instrumental variable L.Dt has a strong correlation with the endogenous variable Dt, and there is no "weak instrumental variable" problem, meeting the requirements of a strong instrumental variable.

In the test results of the first-stage regression (1), the coefficient of the instrumental variable L.Dt on the endogenous variable Dt is 0.4192*** (t-value = 14.00), which is significantly positive, further verifying the strong correlation between the instrumental variable and the endogenous variable, and there is no weak instrumental variable problem; in the test results of the second-stage regression (2), the coefficient of the endogenous variable Dt on the dependent variable Roa is -0.0043*** (t-value = -3.88), with a high significance level, indicating that the instrumental variable regression result is stable and effective. Moreover, this endogeneity test is the instrumental variable regression of the overall sample. The significantly negative correlation result in the second stage (2) is consistent with the threshold effect test results of weak positive (coefficient 0.000673, close to 10% significance) and strong negative (coefficient -0.0216, 5% significance). That is, the significance of -0.0043*** is the average result of the "weak positive before the threshold + strong negative after the threshold". Therefore, the regression results can indicate that there is no significant endogeneity problem in this paper.

3.1.3. Robustness Test

The dependent variable corporate performance is replaced by Return on Total Assets (Rota) for measurement (its calculation formula is: (Total profit + Financial expenses) / Average total assets), and the same model (1) is used to test the robustness of the threshold effect of digital transformation on corporate performance.

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single Threshold	16. 58	0.0133	11.4132	13.5187	16.7552

Table.6. Threshold Effect Test Results of Replacing Dependent Variable

Threshold Value	95% Confidence Interval
4.5218	（4.4424,4.6195）

Table.7. Threshold Value Test Results of Replacing Dependent Variable

From the test results shown in Table.6. and Table.7., there is a single threshold value of 4.5218, and the p-value is 0.0133, which is less than 0.05, significant at the 5% significance level.

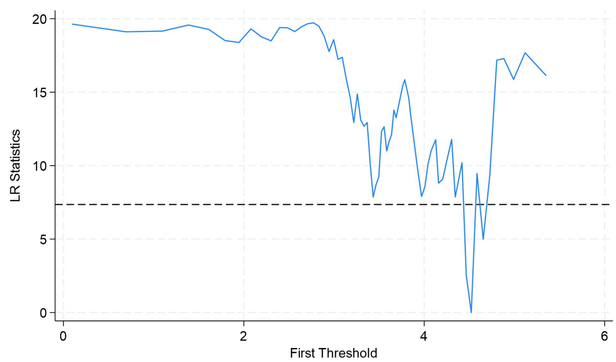

Fig.2. Likelihood Ratio Function Graph of Replacing Dependent Variable

It can also be seen from Fig.2. that the critical value of 7.3523 is significantly greater than the single threshold value, and the LR statistic corresponding to this threshold value is 0, so it can be considered that the above threshold value is true and effective.

Variable	Regression Coefficient	t-value
Age	-0.00473***	(0.000455)

Lev	-0.206***	(0.0208)
Cash	0.237***	(0.0538)
Size	0.0328***	(0.00581)
Growth	0.0000791***	(0.0000268)
Far	-0.131***	(0.0174)
Navps	0.00151**	(0.000683)
Dt<4.5218	0.000810*	(0.000436)
Dt≥4.5218	-0.00198**	(0.001000)

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

Table.8. Parameter Robustness Regression Results of Replacing Dependent Variable

From the regression results in Table.8., it can be seen that when the value of digital transformation is less than 4.5218, the coefficient of digital transformation on corporate performance is 0.000810, that is, for each 1-unit increase in digital transformation, corporate performance increases by 0.000810 units; when the value of digital transformation is greater than 4.5218, the coefficient of digital transformation on corporate performance is -0.00198, that is, for each 1-unit increase in digital transformation, corporate performance decreases by 0.00198 units.

Thus, after replacing the measurement indicator of the dependent variable, the test results are still significant.

3.2. Heterogeneity Analysis

3.2.1. Human Capital Utilization Efficiency

Differences in human capital utilization efficiency are also one of the variables leading to the differentiation of the impact of enterprise digital transformation on corporate performance. The logic of its impact lies in: whether digital transformation can bring corporate performance is not determined by the technology itself, but depends on whether human capital can effectively absorb, adapt to, and control new technologies to maximize the effectiveness of digital technology. When the utilization efficiency of human capital is high, digital input is more likely to be converted into output to improve corporate performance. On the contrary, when the utilization efficiency of human resources is low, it often means that the enterprise's digital technology is difficult to match with human resources, which is likely to cause problems such as internal organizational friction, loss of human resources, and technology idleness, ultimately affecting the improvement of corporate performance.

Therefore, this paper proposes Hypothesis H6: The impact of digital transformation on corporate performance varies with different human capital utilization efficiency.

Referring to the research of Bai Fuping and Liu Donghui , this paper uses the human capital appreciation coefficient to measure human capital utilization efficiency. The human capital appreciation coefficient is the ratio of the enterprise's human capital to the enterprise's value-added. Among them, human capital is measured by the "cash paid to employees and on behalf of employees" in the cash flow statement of listed companies, and the calculation formula of enterprise value-added is: Enterprise value-added = Total profit + Employee compensation payable + Financial expenses. After dividing the data into two parts according to the level of human capital utilization efficiency, the test results are as follows:

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single Threshold	22.01	0.0067	10.6420	12.3940	17.4374

Table.9. Threshold Effect Test Results of Digital Transformation on Corporate Performance with Low Human Capital Utilization Efficiency

Threshold Value	95% Confidence Interval
4.6634	（4.5109,4.7707）

Table.10. Threshold Value Estimation of Digital Transformation on Corporate Performance with Low Human Capital Utilization Efficiency

From the test results in Table.9. and Table.10., there is a single threshold value of 4.6634, and the P-value is 0.0067, which is less than 0.01, significant at the 1% significance level.

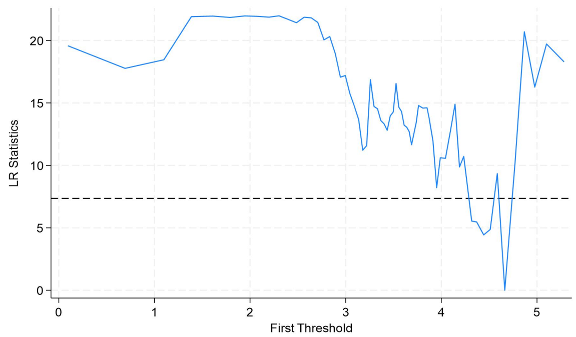

Fig.3. Likelihood Ratio Function Graph with Low Human Capital Utilization Efficiency

It can be seen from Fig.3. that there is a threshold value lower than the critical value of 7.3523, and the LR statistic corresponding to this threshold value is 0, so it can be considered that the above threshold value is true and effective.

Variable	Regression Coefficient	t-value
Age	-0.00391***	(0.000586)
Lev	-0.235***	(0.0261)
Cash	0.242***	(0.0557)
Size	0.0343***	(0.00729)
Growth	0.0000667***	(0.0000160)
Far	-0.121***	(0.0227)
Navps	0.000918	(0.000605)
Dt＜4.6634	0.000230	(0.000585)
Dt≥4.6634	-0.00470***	(0.00164)

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

Table.11. Parameter Regression Results of Panel Threshold Model of Digital Transformation on Corporate Performance with Low Human Capital Utilization Efficiency

The parameter regression results in Table.11.show that when the human capital utilization efficiency is low, digital transformation has a significant threshold effect on corporate performance (threshold value 4.6634): after the transformation crosses this threshold, each 1-unit increase in digital transformation leads to a 0.00470-unit decrease in corporate performance. The core reason is the insufficient adaptation between human capital and digital transformation. On the one hand, the deepening of transformation requires employees to have higher digital skills. If the enterprise neglects skill training and fails to develop employees' innovative capabilities, it will lead to the lag of employees' skills. High-efficiency digital tools cannot be fully utilized, resulting in resource waste; on the other hand, the maintenance and upgrading of digital equipment require matching skill support, while low human capital utilization efficiency makes it difficult to convert digital resources into output. Enterprises are prone to falling into a cycle of "input - ineffectiveness - re-input". Even if training is carried out, the cycle may be too long or the conversion rate may be low due to efficiency issues.

Before reaching the threshold value, the promoting effect of digital transformation on corporate performance is not significant. This is because the fixed costs in the early stage of transformation are high, and the low human capital utilization efficiency makes it difficult for digital resources to exert value through human resources, resulting in low short-term marginal returns; at the same time, low efficiency is often accompanied by path dependence and organizational inertia, and the enterprise's operational processes are rigid, making it difficult to quickly adapt to digital needs for reconstruction and update, thereby leading to difficulty in improving performance.

Similarly, this paper uses the same method to test the threshold effect of data with high human capital utilization efficiency, and the threshold regression results are as follows:

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single Threshold	22.01	0.3333	10.4586	12.0510	15.6248

Table.12. Threshold Effect Test Results of Digital Transformation on Corporate Performance with High Human Capital Utilization Efficiency

The regression results in Table.12. show that P = 0.3333, which fails the significance test. When the human capital utilization efficiency is high, the threshold effect of digital transformation on corporate performance is not significant. At this time, employees can complete tasks efficiently, reduce resource waste, and master digital technologies with low training and learning costs, helping enterprises efficiently promote digital transformation and technology absorption. The two are more likely to present a linear promoting relationship, and the positive interaction will delay the arrival of the threshold value where digital transformation shifts from promoting to inhibiting corporate performance.

Therefore, this paper proposes Hypothesis H7: When human capital is high, digital transformation has a significant promoting effect on corporate performance, and constructs a multiple linear regression model to verify it.

$$Roa_{i,t} = \alpha_0 + \alpha_1 Dt_{i,t} + \sum Controls_{i,t} + Year_t + \mu_{i.t}$$

(2)

Where *Roa* represents the dependent variable corporate performance, α_0 represents the constant term, Dt represents the independent variable digital transformation, ∑Controls represents various control variables, Year represents the year dummy variable, and μ represents the residual term.

VARIABLES	Roa
Dt	0.0037***
	(3.20)
Age	0.0002

	(0.03)
Growth	0.0050***
	(3.01)
Lev	-0.1444***
	(-12.88)
Far	-0.1209***
	(-9.47)
Navps	0.0030***
	(5.09)
Cash	0.1909***
	(12.63)
Size	0.0118***
	(3.27)
Constant	-0.1847*
	(-1.66)
Observations	4,689
R-squared	0.485

Table.13. Multiple Linear Regression Results of Digital Transformation on Corporate Performance with High Human Capital Utilization Efficiency

The test results in Table.13. show that when the human capital utilization efficiency is high, digital transformation has a significant promoting effect on corporate performance (for each 1-unit increase, performance increases by 0.0037 units). It mainly benefits from the technology absorption and innovation capabilities brought by the efficient use of human resources: employees are highly motivated, adapt to high-intensity work, can quickly master digital tools, reduce training costs, and shorten the transformation return cycle; moreover, they have outstanding creativity and technical literacy, can develop digital systems, expand non-preset application scenarios of tools (such as big data empowering business insights and decision-making), and accelerate the conversion of technology into productivity.

Thus, Hypotheses H6 and H7 are verified.

3.2.2. Ownership Concentration

Ownership concentration refers to the distribution of equity among shareholders and the degree of concentration/decentralization of controlling rights. It is a core dimension of corporate governance, directly affecting the enterprise's strategic decision-making, resource allocation, and performance. Under high concentration, major shareholders can supervise management and ensure strategic stability, but are prone to related transactions; under low concentration, decision-making is more diverse, but high agency costs are likely to cause management myopia. Therefore, the impact of digital transformation on corporate performance varies with different ownership concentration. This paper uses the shareholding ratio of the top ten shareholders to measure ownership concentration, and the higher the ratio, the higher the concentration.

Therefore, this paper proposes Hypothesis H8: The threshold effect of digital transformation on corporate performance varies with different ownership concentration.

Firstly, this paper tests the threshold effect when the ownership concentration is low, and the test results are as follows:

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single Threshold	17.82	0.0200	12.0910	14.3362	19.5777

Table.14. Threshold Effect Test Results of Digital Transformation on Corporate Performance with Low Ownership Concentration

Threshold Value	95% Confidence Interval
4.6634	(4.5218, 4.7362)

Table.15. Threshold Value Estimation of Digital Transformation on Corporate Performance with Low Ownership Concentration

According to the test results in Table.14.and Table.15., there is a single threshold value, and the P-value is 0.0200, which is less than 0.05, significant at the 5% significance level.

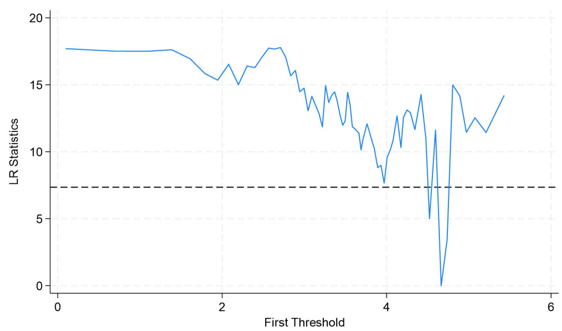

Fig.4. Likelihood Ratio Function Graph with Low Ownership Concentration

By observing Figure 4.4, it can be found that there is a threshold value lower than 7.3523, and the corresponding LR value is exactly 0, proving the existence of this threshold value.

Variable	Regression	t-value

	Coefficient	
Age	-0.00318***	(0.000726)
Lev	-0.245***	(0.0250)
Cash	0.153**	(0.0703)
Size	0.0327**	(0.0134)
Growth	0.0000718***	(0.0000154)
Far	-0.139***	(0.0321)
Navps	0.00284	(0.00178)
Dt<4.6634	0.00103*	(0.000563)
Dt≥4.6634	-0.00380**	(0.00149)

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

Table.16. Parameter Regression Results of Panel Threshold Model of Digital Transformation on Corporate Performance with Low Ownership Concentration

The regression results in Table.16. show that when the ownership concentration is low, digital transformation has a significant threshold effect on corporate performance (threshold value 4.6634): before the threshold, each 1-unit increase in transformation leads to a 0.00103-unit increase in performance; after the threshold, each 1-unit increase leads to a 0.00380-unit decrease in performance.

The early promotion stems from the absence of complex approval from major shareholders. Management can quickly respond to the market and boldly explore high-risk innovative projects, helping performance growth in the early stage of transformation. The later inhibition is due to: difficulty in maintaining long-term investment in core projects. Minority shareholders are unwilling to bear high transformation costs and are prone to free-riding psychology, leading to insufficient resource adaptation; the diverse demands of shareholders make the transformation strategy vague and inconsistent, resulting in the stagnation of projects. Finally, the inhibitory effect is greater than the promoting effect, which is consistent with the previous conclusion that the performance improvement of digital transformation is slow, and the inhibitory effect caused by internal organizational problems after crossing the threshold is more rapid.

Secondly, the test results of the threshold effect when the ownership concentration is high are as follows:

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single	7.94	0.2167	9.9802	12.6155	16.6464
Threshold					

Table.17. Threshold Effect Test Results of Digital Transformation on Corporate Performance with High Ownership Concentration

The test results in Table.17.show (P = 0.2167, failing the significance test). When the ownership concentration is high, the threshold effect of digital transformation on corporate performance is not significant. The core reason is that enterprises with high concentration have high decision-making efficiency and consistent strategies, which can meet the long-term needs of transformation, and major shareholders can concentrate various resources to promote transformation. Therefore, the two are more likely to present a linear promoting relationship.

Thus, this paper proposes Hypothesis H9: When the ownership concentration is high, digital transformation can play a significant promoting role in corporate performance. Since only the specific values change and the variables do not change, this part still uses model (2) to verify the linear relationship between the two.

VARIABLES	Roa
Dt	0.0021**
	(2.15)
Age	0.0055***
	(3.68)
Growth	0.0070***
	(3.55)
Lev	-0.0971***
	(-12.39)
Far	-0.1039***
	(-10.10)
Navps	0.0021***
	(5.57)
Cash	0.2312***
	(19.11)
Size	0.0094***
	(4.31)
Constant	-0.1965***
	(-3.91)
Observations	6,039
R-squared	0.666

Table.18. Multiple Linear Regression Results of Digital Transformation on Corporate Performance with High Ownership Concentration

The multiple linear regression results in Table.18. show that for each 1-unit increase in digital transformation, corporate performance increases by 0.0021. When the ownership concentration is high, enterprises can give full play to the promoting role of digital transformation: first, provide institutional guarantee for strategic formulation. Major shareholders can bear the long return cycle and maintain the consistency of transformation strategies; second, major shareholders dominate resource allocation, which can concentrate various resources to support transformation, improve allocation efficiency, and reduce waste; third, reduce organizational inertia, accelerate the restructuring of structure and talents, and adapt to the needs of digital transformation.

Thus, Hypotheses H8 and H9 are verified.

3.3.Mechanism Analysis

3.3.1.Analysis of the Moderating Effect of Financing Constraints

Since most of the indicators used in this paper are positive, while the measurement indicator of financing constraints, the WW index, is negative, for the smooth conduct of the test, the opposite number of the WW index, ww, is used as the threshold variable for regression to test the moderating role of financing constraints in the threshold effect of digital transformation on corporate performance. Accordingly, this paper constructs a threshold effect model, namely model (3), to test the moderating role of financing constraints.

$$Roa=\beta_0+\beta_1 Dt\times 1(ww<A)+\beta_2 Dt\times 1(ww\geq A)+\sum X+\varepsilon \quad (3)$$

Where Roa represents the dependent variable corporate performance, Dt represents the independent variable digital transformation, A represents the single threshold value, 1() represents the indicator function, which takes the value of 1 when the condition in the bracket is satisfied and 0 otherwise. ∑X represents control variables such as Age, Growth, Lev, Far, Cash, Size, and Navps, and ε represents the residual term. At this time, the threshold variable is the ww value. The test results are as follows:

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single Threshold	85.83	0.0000	11.5268	14.2603	17.6395

Table.19. Test Results of the Moderating Effect of Financing Constraints in the Threshold Effect of Digital Transformation on Corporate Performance

Threshold Value	95% Confidence Interval
0.9921	(0.9893, 0.9941)

Table.20. Threshold Value Estimation of the Moderating Effect of Financing Constraints in the Threshold Effect of Digital Transformation on Corporate Performance

According to the test results in Table.19.and Table.20., there is a single threshold value of 0.9921, and the p-value is 0, which is less than 0.01, significant at the 1% significance level.

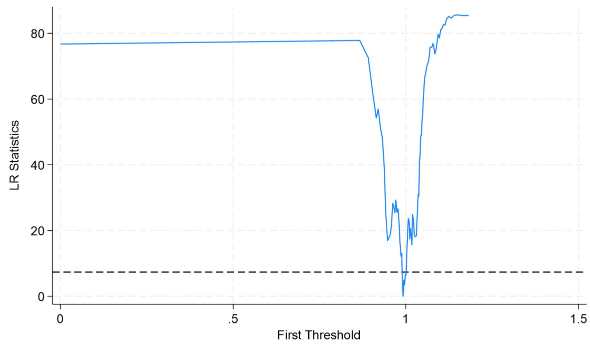

Fig.5. Likelihood Ratio Function Graph of Financing Constraints

It can also be seen from Fig.5.that the critical value of 7.3523 is significantly greater than the single threshold value, and the LR statistic corresponding to this threshold value is 0, so it can be considered that the above threshold value is true and effective.

Variable	Regression Coefficient	t-value
Age	-0.00360***	(0.000441)
Lev	-0.227***	(0.0201)
Cash	0.205***	(0.0465)
Size	0.0274***	(0.00580)
Growth	0.0000707***	(0.0000266)
Far	-0.129***	(0.0162)
Navps	0.00124**	(0.000607)
ww<0.9921	-0.00142***	(0.000510)
ww≥0.9921	0.00255***	(0.000557)

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

Table.21. Parameter Regression Results of Panel Threshold Model of the Moderating Effect of Financing Constraints

According to the regression results in Table.21., when ww <

0.9921, that is, WW > -0.9921, each 1-unit increase in digital transformation leads to a 0.00142-unit decrease in corporate performance, that is, when the financing constraints faced by the enterprise exceed -0.9921, digital transformation has a significant negative impact on corporate performance. Similarly, when the financing constraint is less than -0.9921, digital transformation has a significant positive impact on corporate performance, and each 1-unit increase in digital transformation leads to a 0.00255-unit increase in corporate performance.

Thus, Hypothesis H2 is verified.

3.3.2 Analysis of the Moderating Effect of Agency Costs

This paper uses the ratio of administrative expenses to operating income to measure the enterprise's agency costs, that is, agency costs = administrative expenses / operating income, denoted by Cr, and uses it as the threshold variable for regression to verify the moderating role of agency costs in the threshold effect of digital transformation on corporate performance. For this purpose, model (4) is established.

$$Roa = \beta_0 + \beta_1 Dt \times 1(Cr < B_1) + \beta_2 Dt \times 1(B_1 \le Cr < B_2) + \beta_3 Dt \times 1(Cr \ge B_2) + \sum X + \varepsilon \quad (4)$$

Where Roa represents the dependent variable corporate performance, Dt represents the independent variable digital transformation, B1 and B2 represent the two threshold values respectively, 1() represents the indicator function, which takes the value of 1 when the condition in the bracket is satisfied and 0 otherwise. ∑X represents control variables such as Age, Growth, Lev, Far, Cash, Size, and Navps, and ε represents the residual term. At this time, the threshold variable is Cr.

Number of Threshold Values	F-statistic	P-value	10% Critical Value	5% Critical Value	1% Critical Value
Single Threshold	137.20	0.0000	15.2565	17.2573	23.9652
Double Threshold	85.43	0.0000	14.7388	17.9438	23.6759

Table.22. Test Results of the Moderating Effect of Agency Costs

Threshold Value	95% Confidence Interval
0.0548	（0.0521,0.0566）
0.1472	（0.1402,0.1520）

Table.23. Threshold Value Estimation Results of Agency Costs

From the test results in Table.22.and Table.23. there is a single threshold value of 0.0548 and a double threshold value of 0.1472, and the P-values are all less than 0.01, significant at the 1% significance level.

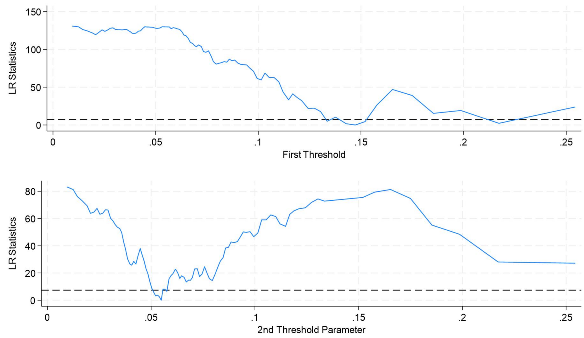

Fig.6. Likelihood Ratio Function Graph of Agency Costs

It can also be clearly seen from Fig.6. that there are threshold values lower than 7.3523, and there are two points where the corresponding LR statistics are exactly 0, thus confirming the existence of double threshold values.

Variable	Regression Coefficient	t-value
Age	-0.00450***	(0.000439)
Lev	-0.225***	(0.0201)
Cash	0.197***	(0.0485)
Size	0.0264***	(0.00550)
Growth	0.0000708***	(0.0000270)
Far	-0.128***	(0.0159)
Navps	0.00140**	(0.000634)
Cr<0.0548	0.00418***	(0.000598)
0.0548≤ Cr<0.1472	-0.0000783	(0.000493)
Cr≥0.1472	-0.00758***	(0.00142)

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

Table.24. Parameter Regression Results of Panel Threshold Model of the Moderating Effect of Agency Costs

According to the test results of different intervals in Table.24., when the agency cost is lower than 0.0548, the impact coefficient of digital transformation on corporate performance is 0.00418, which is significant at the 1% significance level, that is, for each 1-unit increase in digital transformation, corporate performance increases by 0.00418 units. When the agency cost is between 0.0548 and 0.1472, the inhibitory effect of digital transformation on corporate performance is not significant. When the agency cost exceeds 0.1472, each 1-unit increase in digital transformation leads to a 0.00758-unit decrease in corporate

performance, and this negative impact is significant at the 1% significance level. That is, before reaching the first threshold value, agency costs strengthen the promoting effect of digital transformation on corporate performance; after reaching the second threshold value, agency costs enhance the inhibitory effect of digital transformation on corporate performance.
Thus, Hypothesis H3 is verified.

3.3.3. Mediating Effect of Organizational Resilience

To test the mediating effect, this paper constructs the following three models and adopts the three-step method for testing.

$$Roa_{i,t} = \alpha_0 + \alpha_1 Dt_{i,t} + \sum Controls_{i,t} + Year_t + Ind_i + \varepsilon_{i,t} \quad (5)$$

$$X_{i,t} = \beta_0 + \beta_1 Dt_{i,t} + \sum Controls_{i,t} + Year_t + \ln d_i + \varepsilon_{i,t} \quad (6)$$

$$Roa_{i,t} = \gamma_0 + \gamma_1 Dt_{i,t} + \gamma_2 X + \sum Controls_{i,t} + Year_t + Ind_i + \varepsilon_{i,t} \quad (7)$$

Where Roa is the dependent variable, Dt is the independent variable, X is the mediating variable, and Controls are the control variables. Let X = Re to test the mediating effect of organizational resilience, and the test results are as follows:

	(1)	(2)	(3)
VARIABLES	Roa	Re	Roa
Dt	0.0007*	-0.0055***	0.0009**
	(1.81)	(-2.63)	(2.31)
Re			0.0102***
			(3.85)
Age	-0.0037***	-0.0168***	-0.0031***
	(-7.53)	(-17.92)	(-7.89)
Lev	-0.2008***	0.0061	-0.1872***
	(-11.74)	(0.13)	(-12.28)
Cash	0.2185***	-0.2902***	0.2697***
	(4.29)	(-5.28)	(11.54)
size	0.0292***	-0.0153	0.0279***
	(4.63)	(-0.95)	(7.61)
Growth	0.0001***	0.0002***	0.0001***
	(3.71)	(3.13)	(3.38)
Far	-0.1357***	0.0929*	-0.1571***
	(-8.08)	(1.85)	(-9.81)
Navps	0.0013*	0.0082*	0.0011**
	(1.95)	(1.89)	(2.08)
Constant	-0.4732***	1.1541***	-0.4614***
	(-3.62)	(3.56)	(-6.03)
Observations	9,631	9,003	9,003
R-squared	0.202	0.040	0.218
Number of ID	1,151	1,144	1,144

Table.25.Mediating Effect of Organizational Resilience

The result of the first column (1) shows that the regression coefficient of Dt is 0.0007, which is significant at the 10% level, indicating that digital transformation has a significant total effect on corporate performance. The result of the second column (2) shows that the regression coefficient of Dt is -0.0055, which is significant at the 1% level, that is, digital transformation will significantly reduce organizational resilience. After adding both Dt and Re, the regression coefficient of organizational resilience (Re) on corporate performance (Roa) is 0.0102, which is significant at the 1% level, indicating that organizational resilience can positively affect corporate performance; at this time, the regression coefficient of Dt on Roa is 0.0009 (t=2.31), which is still significant at the 5% level, indicating that the direct effect of digital transformation on corporate performance still exists. However, overall analysis shows that the total effect of digital transformation on corporate performance (0.0007) is smaller than the direct effect (0.0009), indicating that the mediating effect of organizational resilience at this time is a suppression effect. Digital transformation reduces organizational resilience, thereby reducing its promoting effect on corporate performance.
Thus, Hypothesis H4 is verified.

3.3.4 Mediating Effect of Technological Innovation Input

Based on the above three models (5), (6), and (7), let X = Rd to test the mediating effect of technological innovation input. The test results are as follows:

	(1)	(2)	(3)
VARIABLES	Roa	Rd	Roa
Dt	-0.0228**	0.0210***	-0.0165*
	(-2.38)	(3.51)	(-1.68)
Rd			-0.3006***
			(-3.43)
Age	-0.0028*	0.0033***	-0.0018
	(-1.91)	(3.83)	(-1.15)

Lev	-0.2614***	-0.0203	-0.2675***
	(-5.92)	(-0.86)	(-5.98)
Cash	0.1731***	-0.0699**	0.1521**
	(2.63)	(-2.27)	(2.35)
Size	0.0262**	-0.0068	0.0241**
	(2.20)	(-1.26)	(2.04)
Growth	0.0055***	-0.0003	0.0055***
	(6.33)	(-0.47)	(6.69)
Far	-0.2957***	-0.0404	-0.3078***
	(-3.07)	(-1.08)	(-3.16)
Navps	0.0007	-0.0001	0.0007
	(0.51)	(-0.14)	(0.48)
Constant	-0.2706	0.1988*	-0.2109
	(-1.02)	(1.83)	(-0.80)
Observations	887	887	887
R-squared	0.207	0.120	0.224
Number of ID	211	211	211

Table.26.Mediating Effect of Technological Innovation Input

The results in Column (1) shows the regression coefficient of Digital Transformation (Dt) is -0.0228, significant at the 5% level, indicating Dt exerts a significant negative total effect on corporate performance. Column (2) reveals Dt's coefficient for technological innovation input (Rd) is 0.0210 (1% significance), meaning Dt significantly boosts Rd. With both Dt and Rd included, Column (3) reports Dt's coefficient of -0.0165 (10% significance), confirming its direct effect on corporate performance persists. Overall, the total effect's absolute value surpasses the direct effect's, implying Rd plays a partial mediating role in Dt's inhibitory impact.

Thus, Hypothesis H5 is verified.

4.Research Conclusions and Policy Recommendations

4.1. Research Conclusions

First, the relationship between digital transformation and corporate performance in manufacturing enterprises is not a simple linear one, but exhibits a significant threshold effect of "first promoting and then inhibiting". Before reaching the threshold, the promoting effect of digital transformation on corporate performance is relatively slow; after crossing the threshold, the inhibitory effect becomes more pronounced, reflecting the non-linear adaptation between the depth of transformation and performance.

Second, heterogeneity analysis shows that human capital utilization efficiency and ownership concentration significantly influence this relationship. When human capital utilization efficiency is low, digital transformation exhibits a significant threshold effect (the inhibitory effect after the threshold is prominent, while the promoting effect before the threshold is insignificant); when efficiency is high, the two variables show a linear promoting relationship. When ownership concentration is low, digital transformation has a threshold effect (promoting before the threshold and inhibiting after the threshold); when concentration is high, the two present a linear promoting relationship.

Third, financing constraints and agency costs play moderating roles. When financing constraints are below the threshold, sufficient funds support the adjustment and implementation of transformation strategies, contributing to performance improvement; when exceeding the threshold, capital constraints lead to high trial-and-error costs and delayed transformation adjustments, hindering performance. When agency costs are below the threshold, the interests of management and the enterprise are aligned, resource allocation is efficient, and transformation empowers performance; when exceeding the threshold, interest conflicts cause resource misallocation, exacerbating management problems in the later stage of transformation and inhibiting performance.

Finally, the mediating effect analysis indicates that before the threshold, digital transformation exerts a suppression effect by reducing organizational resilience, weakening its promoting effect on corporate performance; after the threshold, it strengthens the inhibitory effect on performance by increasing technological innovation input, which plays a mediating role.

4.2. Policy Recommendations

(1)Ensure the Supply and Standardized Use of Transformation Funds

First, establish a standardized data system: integrate financial and operational data via ERP/CRM systems, and secure data traceability with blockchain to boost investor trust. Second, expand diversified financing channels: access credit-backed financing through core enterprise supply chain networks, and realize online pledge of receivables and inventory via third-party platforms. Third, cut costs digitally:

adopt cross-border e-commerce export credit insurance and digital currency settlement to mitigate risks. Establish a phased fund supervision mechanism to ensure targeted investment and prevent misappropriation.

(2)Optimize Governance Structure and Stabilize Digital Decision-Making

Optimize the governance environment by: first, setting up a specialized digital transformation decision-making committee (with independent directors and technical directors) and adopting majority voting for major proposals to ensure decision continuity. Second, building a full-process transparent supervision mechanism to track implementation and reduce resource misallocation. Third, developing a risk early-warning system to adjust transformation directions promptly amid market/technological changes.

(3)Strengthen Human Resource Development and Efficient Utilization

First, conduct targeted technical and innovative skill training in the early transformation stage to accelerate digital-to-efficiency conversion. Second, promote cross-departmental collaboration teams to encourage communication and creativity. Third, improve incentive and care mechanisms: align incentives with transformation goals, provide a favorable working environment, and address employee emotional needs to prevent talent loss from rapid organizational changes.

(4)Break Path Dependence on Blind Investment

Review existing innovation paths based on technological trends and market demands, abandoning "experience-based investment" inertia. Rationalize transformation paths, focus on technological innovation input conversion efficiency, and establish a "digital + innovation" collaboration mechanism to break data-R&D barriers. Allocate resources to balance transformation costs and innovation output, leveraging technological innovation to offset short-term transformation pain and release long-term value.

(5)Address the Dilemma of Organizational Resilience

First, build a flexible organizational structure to enhance dynamic resource allocation. Second, establish cross-departmental collaboration platforms to strengthen information sharing and rapid response. Third, cultivate an agile innovation culture: integrate risk response into transformation planning and improve organizational shock resistance through simulation drills, balancing efficiency and flexibility.

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Research Progress on Carbon Emissions

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KEYWORDS

Carbon emissions;
Carbon accounting;
Driving factors;
Mitigation pathways

ABSTRACT

Driven by the “dual-carbon” goals and the intensifying global climate-governance agenda, carbon-emission research has evolved into a core interdisciplinary theme. Using a narrative literature-review approach, we map the intellectual trajectory of this field through three lenses: accounting methods, driving factors and mitigation pathways. Methodologically, a dual accounting system has emerged that separately tracks production-based and consumption-based emissions. Factor studies concentrate on the interplay among economic growth, energy structure, technological progress and policy regulation.Mitigation options span energy substitution, industrial upgrading, carbon capture/utilization/storage (CCUS) and other technologies, as well as policy instruments such as carbon markets and carbon taxes; trans-regional cooperative mitigation is gaining momentum. Key gaps remain: micro-level behavioural drivers are poorly understood, cross-scale accounting interfaces are weak, and the quantitative coupling effects of technology-policy packages lag behind. Future work should integrate multiple methods, foster cross-disciplinary collaboration and enhance dynamic simulation to deliver precise mitigation insights.

INTRODUCTION

Global climate change has become a critical worldwide threat to human survival and development. The escalating frequency of extreme climate events, which has triggered ecological degradation, food security crises and other related issues, has led countries to reach a consensus on the regulation of greenhouse gas emissions. [1]. The 2015 Paris Agreement locked in the hard target of “holding warming to 1.5°C”[2]; China unveiled its “dual-carbon” strategy in 2020; and the 2021 Glasgow Climate Pact intensified globally coordinated mitigation. As these international accords and national strategies move from pledge to implementation, carbon emissions have shifted from an environmental-science topic to a cross-cutting determinant of economic and social development, emerging as a central interdisciplinary research theme. Systematically charting the evolution and frontiers of carbon-emission studies under this backdrop is therefore of paramount theoretical and practical value for designing precise mitigation policies and refining carbon-governance systems.The evolution of carbon emission research is deeply intertwined with the process of global climate governance, undergoing a logical progression from "emission quantification" to "mechanism analysis" and further to "emission reduction optimization." Early work concentrated on constructing accounting methods — life-cycle assessment [3], emission-factor approaches [4] and other techniques—to deliver accurate measurements at regional, sectoral and corporate scales, thereby furnishing the baseline data needed for target setting. As the core tool for quantifying greenhouse-gas releases, carbon accounting underpins carbon management, emissions trading and policy design; its scientific rigor directly determines the precision of mitigation pathways [5]. Meanwhile, international rules such as the EU’s Carbon Border Adjustment Mechanism (CBAM) are forcing accounting standards to converge with global norms, and digital transformation is opening new avenues for methodological innovation.

As research matured, scholars shifted attention to the driving forces of carbon emissions, deploying STIRPAT [6], LMDI [7] and allied models to estimate the mitigation elasticity of population growth, economic development, technological

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progress and other factors, thereby identifying critical leverage points for emission cuts.At present,Carbon emission research exhibits a characteristic of multi-dimensional expansion: in terms of research scale, it has formed full-scale coverage spanning "global—national — regional — urban — enterprise"; in terms of research content, it integrates theories from multiple fields such as energy economics, industrial transformation, and technological innovation to explore the synergistic pathways between emission reduction and development; In terms of research methodology, big data and machine learning technologies are employed to enhance the accuracy of emission forecasting and policy simulation.Yet outstanding problems However, existing studies still face challenges such as inadequate regional adaptability of accounting systems, unclear cross-scale emission transmission mechanisms, and quantification biases in technological emission reduction potential. Against this backdrop, we systematically review advances in carbon accounting, driving mechanisms and mitigation pathways, dissect existing limitations and chart future research directions, offering a theoretical compass for global climate governance and the attainment of the "dual-carbon" target.

1.Carbon-emission accounting

Accurate accounting is the prerequisite for any in-depth analysis of carbon emissions. Viewed through the lens of responsibility, two complementary approaches exist: production-based accounting and consumption-based accounting [8].

1.1.Production-based accounting

Grounded in the "polluter-pays" principle, this method attributes all emissions generated within a given territorial boundary to the jurisdiction where the goods or services are produced. It therefore creates a direct incentive for local producers to improve energy efficiency. Three main techniques are used [9]:

(1) Emission-factor method

Introduced by the IPCC in its first Revised Guidelines for National Greenhouse Gas Inventories (1996), this approach equates emissions with the product of activity data and an emission factor for each source category①.

Equation:GHG emissions = Activity data × Emission factor

The method is simple, transparent and scalable, making it the work-horse for national-, provincial- and city-level inventories [10].

(2) Mass-balance method

This technique tracks carbon inflows and outflows for each process or device. By comparing the carbon content of inputs (feedstock, fuels) with that of outputs (products, wastes), it yields the net CO_2 released.

Equation:CO_2 emissions = (Input mass × C content – Product mass × C content – Waste mass × C content) × 44/12

The method is especially useful for benchmarking individual installations or verifying whether new equipment meets emission standards [11].

(3) Direct measurement (stack-testing) method

Here, flue-gas velocity and CO_2 concentration are measured on site and converted to mass emissions.

Equation:CO_2 emissions = Gas velocity × CO_2 concentration × Unit-conversion factor

Although this gives the highest temporal and spatial resolution, it requires costly high-precision analyzers and is limited to point sources. In practice, samples are often collected in the field and analyzed in certified laboratories, so representativeness and instrument accuracy remain critical uncertainties [12].

1.2.Consumption-based accounting

This approach quantifies the emissions embodied in imported and exported goods—commonly termed the "carbon footprint." By tracing greenhouse gases along global value chains, it reveals the climate impacts driven by consumers rather than producers, thereby informing equitable mitigation strategies and honoring the principle of "common but differentiated responsibilities" [13].

Numerous studies have employed input–output (IO) techniques to map consumption-based emissions at global [14-17], national [18-19] and regional [20-23] scales, highlighting how international trade redistributes carbon burdens. Country-level analyses now exist for Australia [24], China [25], Italy [26], the UK [27] and others. Recent work further refines the method: Kander et al. (2015) [29] advocate adjusting IO tables for sectoral technology

①See https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

differences among exporters, yielding footprint estimates that more accurately predict how national policy shifts propagate through global supply chains. Such consumption-side metrics complement conventional production inventories and offer decision-makers an forward-looking gauge of their policies' worldwide emission consequences.

2.Identifying the drivers of carbon emissions

Decomposing the forces behind emissions has long been a core theme in the literature. Two analytical families dominate: Structural Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA). The key difference is that SDA is built on input–output tables, whereas IDA requires only sector-aggregated data. Hoekstra et al. (2003) show that SDA's richer data requirement is offset by its ability to capture both direct and indirect effects—e.g., how a demand shift in one sector propagates through the entire production network—something IDA cannot detect [30].Among IDA variants, the Logarithmic Mean Divisia Index (LMDI) has become the work-horse model thanks to its solid theoretical foundation, adaptability, lack of residual term and transparent results [31-32].

Recent applications illustrate the expanding research frontier:Liu et al. (2024) couple STIRPAT with scenario analysis for 30 Chinese provinces, decomposing eight drivers into "policy-expected" variables (population, per-capita GDP, urbanization) and "policy-controlled" levers (energy mix, efficiency, industrial structure, transport structure, R&D). They find population, affluence, urbanization and innovation to be the dominant positive drivers, whereas industrial upgrading, energy intensity decline, fuel switching and transport optimization yield significant mitigation [33].Xu et al. (2017) show that economic growth governs sectoral CO_2 emissions, with industrialization exerting a stronger effect in central China than in the east or west. Urbanization's impact weakens as human-capital accumulation and private-car ownership diverge across regions, while the energy-structure effect migrates west-to-east, producing region-specific outcomes [34].Motinho (2015) documents a Europe-wide shift toward lower-carbon final energy consumption, but highlights pronounced spatial and temporal heterogeneity [35].

3.Mitigation pathways

Current studies converge on four complementary tracks:

3.1.Policy & regulatory track

Di et al. (2016) deploy the LEAP model to evaluate Argentina's climate-control policies, projecting energy-efficiency gains and CO_2 trajectories for the energy sector through 2050 [36]. Kadian et al. (2007) apply the same platform to Delhi's residential sector, comparing policy packages and technology choices for reducing household energy use and GHG emissions [37].

3.2.Fiscal & financial track

Hu et al. (2019) couple LEAP with cost-optimization for Shenzhen, demonstrating that sustainable-energy planning can meet municipal CO_2 targets at minimum economic cost [38]. Emodi et al. (2017) run scenario simulations for Nigeria, balancing energy-demand, supply, emissions and cost-benefit metrics to identify fiscally viable low-carbon pathways [39].

3.3.Industrial & energy-structure track

Tao et al. (2011) construct baseline, low-carbon and slow low-carbon scenarios for China out to 2050, driven by per-capita GDP, energy use, energy mix and CO_2 emissions. They find that renewable-energy diffusion, industrial restructuring, efficiency gains and clean-energy development are the most effective levers for achieving a low-carbon economy [40].

3.4.Technology & R&D track

Dehdar et al. (2022) analyze 36 OECD countries (1994-2015), showing that while GDP, fossil-fuel use, industrialization and tax-to-GDP ratios exacerbate emissions, urbanization, environmental patents and environmental-tax shares significantly cut CO_2 [41]. Cheng et al. (2024) demonstrate that upgrading the technology-innovation value chain accelerates green transition [42]. You, Khattak & Ahmad (2024) argue that international R&D cooperation on green technologies enables China to co-develop innovations that raise energy efficiency and lower CO_2 simultaneously [43].

Conclusion

Industrial carbon emissions, their influencing factors, and mitigation pathways constitute a core research agenda in global climate change studies, with a comprehensive "accounting-driving-impact-regulation" framework having been established. As one of the primary sources of carbon emissions, the industrial sector's emission fluctuations directly shape the trajectory of global climate change.Scholars worldwide have produced a rich body of work that is both inspiring and instructive. Yet the deepening of international climate governance, accelerating industrial restructuring and imminent technological revolutions expose critical gaps. No consensus exists on a universal accounting standard; driver and pathway studies abound, but province-level evidence is still sparse. The absence of an agreed, scalable accounting method now constrains further advances in quantification, driver analysis and pathway design. Future research must therefore embrace multi-disciplinary integration, target key scientific questions and deliver systemic innovation in perspectives, methods and content.

(1)In Terms of Research Perspective

It is necessary to deepen the shift from "macro total quantity" to "micro precision" and strengthen multi-scale coupling analysis. Existing studies mainly focus on macro scales such as countries and provinces, while lacking precise accounting and analysis of driving mechanisms at micro scales like parks, enterprises, and products, leading to a disconnect between macro policies and micro practices. In the future, a multi-scale linked research system of "macro-medium-micro" should be constructed:

At the macro level, it is essential to refine the regional decomposition mechanism under the nationally determined contributions (NDCs), integrate the connection between the "dual carbon" goals and global climate agreements, and improve the dynamic simulation of carbon emission peaks and carbon neutrality paths.

At the meso level, the focus should be on key units such as industrial clusters and industrial parks to analyze the carbon emission transfer laws in industrial linkages.

At the micro level, relying on enterprise production data and life cycle assessment (LCA) methods, precise traceability of carbon emissions throughout the product life cycle should be realized to provide targeted schemes for enterprise carbon management.

(2)In Terms of Research Methodology

It is imperative to promote the integration of "traditional econometrics" and "digital technologies" to enhance the precision and predictability of research. Existing studies mostly rely on econometric models and statistical data, which struggle to address the complexity and dynamics of carbon emission systems. In the future, full use should be made of digital technologies such as big data, artificial intelligence, and the Internet of Things:

Based on multi-source data from satellite remote sensing and ground monitoring stations, build a real-time monitoring and dynamic accounting platform for carbon emissions to solve the problems of data lag and large errors in traditional accounting.

Use machine learning algorithms to optimize models for identifying carbon emission driving factors, improving the ability to capture implicit driving factors such as technological progress and consumption upgrading.

Combine system dynamics (SD) and Agent-Based models to simulate carbon emission evolution paths under different policy scenarios, enhancing the scientificity and forward-looking nature of policy formulation.

(3)In Terms of Research Content

Focus should be placed on "emerging fields" and "key issues" to strengthen problem-oriented innovative research:

Pay attention to the carbon emission characteristics of emerging industries and new-type urbanization, analyze the dual impacts of new economic forms such as the digital economy and platform economy on carbon emissions, and clarify the core mechanism of green technological innovation in emission reduction.

Deepen the interactive research between carbon emissions and the climate system as well the ecological environment, quantify the impacts of carbon emissions on extreme climate events and biodiversity, and construct a research chain of "carbon emissions-ecological response-risk early warning".

Improve the research on cross-border and regional carbon emission transfer. Combined with international cooperation initiatives such as the "Belt and Road Initiative", analyze the carbon emission transfer laws in the global value chain, providing theoretical support for building a fair and reasonable global climate governance system.

Additional Research Orientations

(3)Furthermore, it is necessary to strengthen the research orientation of "policy implementation" and "interdisciplinary integration". In the future, efforts should be made to:

Enhance research on the evaluation and optimization of carbon emission policies, quantify policy implementation effects using methods such as quasi-natural experiments, and address problems like the "one-size-fits-all" approach and "rebound effect" in policy execution.Furthermore, research priorities should emphasize both policy implementation and interdisciplinary integration. Future studies should intensify evaluations and optimizations of carbon emission policies, utilizing quasi-natural experiments to quantify policy effectiveness while addressing issues like one-size-fits-all approaches and rebound effects. By fostering deep integration among environmental science, economics, management, and computer science, we can overcome the complexity of carbon emission systems and provide more targeted theoretical frameworks and technical solutions for global climate governance and regional carbon peaking and neutrality (dual carbon) initiatives.

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Research on the Process of Medical Digitalization Based on the Perspective of New Institu

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Institutional change;
Digital economy

ABSTRACT

This article systematically explores the theoretical logic and practical approaches to the digitalization of healthcare from the perspective of new institutional economics. By integrating institutional change theory, transaction cost theory, and digital economy theory, we construct an analytical framework for the digitalization of healthcare. This framework reveals the phased characteristics of China's healthcare digitalization development, the driving mechanisms of institutional change, and the breakthrough paths for this process. Furthermore, we propose an optimization approach. Our findings suggest that the digitalization of healthcare requires the dual driving forces of institutional innovation and technological synergy to achieve optimal allocation of medical resources and improve service efficiency.

INTRODUCTION

Against the backdrop of the rapid development of digital technologies, the healthcare industry is undergoing a critical transformation from a traditional model to one that is intelligent and data-driven. However, China's healthcare system faces three core challenges in this digitalization process: first, significant disparities in access to digital services exist between urban and rural areas and across regions; second, the boundaries between medical data privacy protection and commercial development remain to be clarified; and third, a structural contradiction exists between the existing institutional framework and the demand for technological innovation. Focusing on the perspective of new institutional economics, this article aims to answer the following questions: How can institutional change theory explain the driving mechanisms of healthcare digitalization? How can transaction cost theory guide efficiency improvements in healthcare digitalization practices? And what enabling pathways can digital economic theory provide for the optimal allocation of medical resources? Through theoretical analysis and empirical investigation of these issues, this article constructs a three-dimensional analytical framework: "institutions-technology-costs," offering solutions to overcoming the institutional barriers to healthcare digitalization.

1.Theoretical Framework of Medical Digitalization from the Perspective of New Institutional Economics

1.1.The core logic of institutional change theory

Institutional change theory emphasizes that institutions, as endogenous variables, evolve under the joint drive of technological progress, changes in factor prices, and adjustments in the relative interest structure [1]. In the medical field, the penetration of digital technology has broken the spatial and temporal limitations of traditional medical services. This change has altered the production function of medical services. The service model that originally relied on physical space and face-to-face communication has gradually shifted to a fusion of online and offline services. This transformation inevitably requires corresponding institutional adjustments, because traditional

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institutions are built on the old service model and cannot adapt to the new combination of production factors and service processes[2]. When the potential benefits brought by digital technology are large enough, it will prompt stakeholders to promote institutional change to achieve a new balance of interests and resource allocation efficiency.

1.2.Transaction Cost Theory and Medical Digitalization

Transaction cost theory points out that reducing information asymmetry and coordination costs is the core goal of organizational change[3]. Medical digitalization achieves transaction cost optimization through various paths.

The specific data and analysis are as follows: Information transparency: Sharing of electronic medical records and health records reduces the cost of repeated examinations. According to relevant survey data, in areas where electronic medical record sharing has not been achieved, the proportion of patients undergoing repeated examinations due to referrals and other reasons is as high as 35%, while in areas where sharing has been achieved, this proportion has dropped to about 10%. On average, each patient can reduce the cost of repeated examinations by about 800 yuan per year[4].

Process standardization: The digital platform integrates diagnosis and treatment links and shortens patient waiting time. The medical digital platform built by a certain province has reduced the average waiting time for patients to register from 45 minutes to 15 minutes, and the connection time between each link of the treatment has been reduced by 60%[5].

Trust mechanism reconstruction: Blockchain technology ensures the authenticity of medical data and reduces the risk of contract performance. The data tampering rate of medical data managed by blockchain technology is almost 0, while the dispute rate caused by data errors or tampering under the traditional data management model is about 5%[6].

Dimensions	Before digitalization	After digitalization	Data Source
Single reimbursement processing cost	15.4 yuan	6.3 yuan	True Health Cost Control System (2023)
Financial operating costs	-	38% reduction	True Health Cost Control System (2023)
Drug procurement costs	Baseline value	Down 21.75% (2022)	Qingyuan Municipal Medical Insurance Bureau (2023)

Table.1. The impact of medical digitization on transaction costs

1.3.How digital economy theory empowers medical digitalization

Transaction cost theory pointsDigital economy theory emphasizes the value of data as a core factor of production[7]. In the medical field, data-driven empowerment is demonstrated in the following specific ways:

Accurate decision-making: AI-assisted diagnosis systems can quickly identify disease characteristics by learning and analyzing large amounts of historical case data. For example, in lung cancer diagnosis, AI systems can accurately analyze CT images, achieving a diagnostic accuracy rate of over 90%, comparable to that of experienced doctors, and completing a diagnosis in just one-fifth of the time required for manual diagnosis, significantly improving the accuracy and efficiency of diagnosis and treatment.

Resource Matching: The regional medical big data platform monitors bed usage, equipment status, and other information across hospitals in real time. In the event of a public health emergency, the platform can complete resource scheduling within 30 minutes, assigning patients to the most appropriate medical institution and increasing medical resource utilization by over 20%[8].

Service Innovation: Wearable devices can collect real-time physiological data from patients with chronic diseases, such as blood sugar and blood pressure, and transmit this data to a medical platform. Doctors can use this real-time data to promptly adjust treatment plans, increasing the control rate of chronic disease patients by 25% and reducing the number of acute exacerbations.

2.Institutional Changes in Medical Digitalization: From Technology-Driven to Institutional Innovation

2.1Phased Characteristics of China’s Medical Digitalization Process

Informatization Stage (2000-2015): Marked by the widespread adoption of HIS systems, the electronicization of medical processes took hold. For example, the application of HIS systems computerized processes such as registration, billing, and medication management. This improved outpatient efficiency by 30%, reduced manual errors, and increased the accuracy of medication inventory management from 85% to 98%[9].

Interconnected Phase (2016-2020): The development of regional health information platforms promoted data interconnection and interoperability. For example, the completion of one regional health information platform enabled data sharing among over 200 medical institutions within the region. This enabled instant access to medical information when patients were referred within the region, reducing average referral time by 40%[10].

Intelligent Phase (2021-Present): AI diagnosis and treatment and 5G remote surgery have entered clinical application. The use of AI-assisted diagnosis systems in primary care hospitals has increased the accuracy of diagnosing common diseases by 25%. 5G remote surgery allows patients in remote areas to receive surgical treatment from specialists in larger cities. A successful 5G remote orthopedic surgery saved a patient approximately 20,000 yuan in travel and accommodation costs.

2.2.Driving factors of institutional change

The drivers of institutional change are multifaceted. Technologically, the development of cloud computing has eliminated the need for medical institutions to invest heavily in building and maintaining local IT infrastructure. This has reduced IT costs for small and medium-sized hospitals by over 50%, overcoming the previous barriers to digitalization faced by medical institutions due to insufficient funding and technical expertise. This has enabled more institutions to participate in the digitalization of healthcare. Regarding policy support, the 14th Five-Year Plan for National Health Informatization clearly defines goals for new digital health infrastructure, providing policy support and direction for healthcare digitalization. Local governments have responded with supporting financial support and talent recruitment policies, accelerating the advancement of healthcare digitalization. Demand is also a significant factor. With the aging population and the increasing prevalence of chronic diseases, traditional healthcare service models are struggling to meet people's growing health needs. For example, patients with chronic diseases require frequent follow-up visits, which is time-consuming and expensive under traditional models. Digital remote follow-up models address this issue, driving the digital transformation of healthcare services.

Path dependence manifests itself in regulatory lags and data barriers. This lag is reflected in the mismatch between the cross-regional nature of internet hospitals and traditional medical regulatory systems, resulting in some internet medical services being placed in a regulatory limbo and uneven service quality. Data barriers also hinder the effective sharing of data between medical institutions, rendering each hospital's data like "information silos," preventing efficient information flow and hindering the optimal allocation of medical resources. Breakthroughs should focus on legislative innovation and standardization. The "Medical Data Security Management Regulations" should be formulated to clarify the regulations for the collection, use, and sharing of medical data. Furthermore, the promotion of medical information exchange standards such as FHIR should ensure seamless data integration across different medical institutions.

3.Practical Challenges and Optimization Paths of Medical Digitalization

3.1.Practical Results of Medical Digitalization

In terms of improved efficiency, after implementing an AI imaging system at a tertiary hospital, the lung nodule detection rate increased from 70% to 90%, and the diagnosis time was reduced from an average of 30 minutes to 10 minutes. This not only improved diagnostic accuracy and reduced missed and misdiagnoses, but also significantly improved physician efficiency, increasing the number of images they can process daily by 50%, enabling them to serve more patients, demonstrating this improved efficiency. Regarding cost savings, the DRG payment system reduced average case costs at one hospital by 15%, while also lowering operating costs by 10%. This was because the

DRG payment system enabled the hospital to optimize diagnosis and treatment processes and reduce unnecessary medical expenses. Regarding improved accessibility, telemedicine has expanded to remote areas, enabling patients in these areas to access high-quality medical resources. In one remote county, telemedicine has increased patient visits by 30% and reduced referrals for critically ill patients by 20%.

3.2.Existing Institutional Barriers

The medical insurance payment system is lagging behind: The fee-for-service model was developed under the traditional medical service model, which primarily focused on offline, individual services. However, digital services are comprehensive and continuous, and a fee-for-service model cannot accurately measure the value of digital services. This has inhibited medical institutions' enthusiasm for digital service innovation. Many promising digital service projects have been hindered from being promoted due to a lack of reasonable medical insurance coverage.

A talent gap exists: A multidisciplinary "digital doctor" requires both solid medical knowledge and the ability to apply digital technology. However, the current medical education system still primarily focuses on traditional medical knowledge and lacks courses related to digital technology, making it difficult for medical institutions to recruit suitable multidisciplinary professionals. This talent shortage hinders the full utilization of many advanced digital medical devices and systems, hindering the advancement of medical digitization.

Ethical Risks: The lack of legal regulations governing the determination of liability for AI-based diagnosis and treatment stems from the complexity and unique nature of AI-based diagnosis and treatment[11]. Decisions made by AI-based diagnosis and treatment systems are based on extensive data training, and their decision-making process is difficult to fully explain. When medical disputes arise, it's difficult to clearly determine who is responsible: the physician, the AI system developer, or the medical institution. This ambiguity in determining liability makes physicians and medical institutions cautious about using AI-based diagnosis and treatment systems, limiting their widespread adoption.

3.3.Optimization Path: Collaborative Innovation of Institutions and Technologies

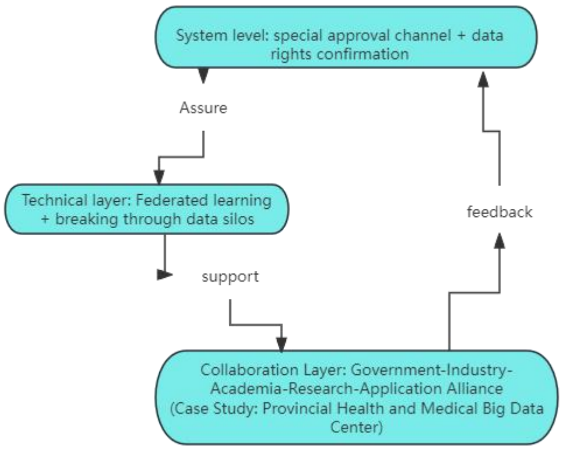

Fig.1. Framework focuses on three core elements and their linkage relationships

This framework takes "institutional layer - technical layer - collaborative layer" as its core dimensions and presents a three-layer linkage mechanism: the institutional layer provides rule guarantees for technological innovation and collaborative practice through special approval channels and data ownership confirmation systems; the technical layer provides technical support for resource integration in the collaborative layer through federated learning technology research and development and breakthroughs in data silos; the collaborative layer, through the practice of "government, industry, academia, research and application" alliances and specific cases (a provincial health and medical big data center), reversely promotes the dynamic optimization of the institutional layer and forms a closed-loop collaborative system.

Conclusion

Drawing on the theoretical framework of new institutional economics, this article systematically explains the logic and practical path of institutional change in healthcare digitalization. The study concludes that healthcare digitalization requires transcending path dependence and achieving a dual breakthrough through institutional innovation and technological synergy. Future research could further focus on governance mechanisms for the healthcare digital divide and cross-national comparisons, offering a Chinese approach to the global healthcare digital transformation.

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Research on the Iterative Path of Personnel Management Systems in Chinese Enterprises Driven by AI Development

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Digital economy;
Personnel management system;
Digital transformatio;
Human resource management;
AI technology;

ABSTRACT

In the context of the digital economy, the experience-based decision-making and process fragmentation limitations of traditional personnel management systems are difficult to adapt to the needs of agility and precision. The research focuses on the inherent logic and practical path of system iteration, and proposes a collaborative transformation framework through three-dimensional analysis of technology, process, and organization and verification of state-owned enterprise cases. The technical dimension integrates big data and AI to achieve intelligent decision-making, the process dimension reconstructs full life cycle management, improves efficiency and experience, and the organizational dimension promotes the transformation of HR into a strategic partner.

INTRODUCTION

In the context of the digital economy, the core characteristics of data assetization, technological intelligence and scenario ecology have had a systematic impact on traditional personnel management systems. The limitations of traditional systems that rely on empirical decision-making and process fragmentation have made it difficult to adapt to the digital age's demand for agility, precision and strategy in human resource management. Data assetization promotes the transformation of human resources data from static records to dynamic value carriers, requiring the system to have the ability to integrate and analyze multi-source data in real time to support talent strategic decision-making[1]. Technological intelligence reconstructs core processes such as recruitment, performance, and training through technologies such as AI and big data, improving management efficiency and scientific decision-making[2]. Scenario ecology further requires the deep integration of personnel systems and business scenarios to achieve dynamic synergy between human resource management and organizational strategy.

External drivers of system iteration include policy orientation and competitive market pressures. At the policy level, the national digital transformation strategy clearly requires enterprises to deepen the digitalization of human resource management. As reform pioneers, state-owned enterprises need to take the lead in promoting the digital reconstruction of personnel systems to respond to policy calls[3]. At the market competition level, the digital economy has intensified the competition for talent. Enterprises need to improve their ability to attract, cultivate and retain talent through intelligent personnel systems to build core competitiveness[4]. Internal requirements focus on efficiency improvement, employee experience optimization and strategic coordination. In terms of efficiency improvement, a large amount of repetitive work in traditional personnel management can be handled automatically through digital

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systems, freeing up HR energy to invest in high-value work[5]. Employee experience optimization requires the system to provide convenient and personalized services, such as self-service inquiries, intelligent question-and-answer functions, etc., to improve employee satisfaction and sense of belonging[6]. Strategic collaboration emphasizes that personnel systems need to be aligned with corporate strategic goals and support organizational change and business development through data insights[7].

1.Core dimensions of personnel management system iteration

1.1.Technical dimension: the integrated application of big data and AI technology

Driven by the digital economy, the integrated application of big data and AI technology has become the core technical engine for the iteration of enterprise personnel management systems. Its value is not only reflected in efficiency improvement, but also in achieving intelligent decision-making and precise management through data drive. By integrating multi-source human resources data (such as recruitment records, performance data, employee behavior data, etc.), big data technology provides a data foundation and analytical framework for talent supply and demand forecasting, employee portrait construction, and turnover risk warning. For example, based on historical data and external labor market information, companies can build forecasting models to identify talent gaps in key positions in advance and optimize recruitment plans. At the same time, by constructing multi-dimensional employee profiles (covering skills, performance, career development tendencies, etc.), they can provide a basis for personalized training and career planning. In addition, big data analysis can also achieve early warning of turnover risks by identifying turnover risk factors (such as decreased job satisfaction, performance fluctuations, etc.), help companies take targeted retention measures, and reduce the cost of talent loss.

The in-depth application of AI technology has further promoted the intelligent transformation of personnel management processes, and has shown significant value in natural language processing (NLP), machine learning and computer vision. In the recruitment process, AI-powered tools (such as intelligent resume screening systems and chatbot interviewers) can quickly process massive resumes, identify candidate characteristics that match the position, and improve recruitment efficiency and accuracy; in performance evaluation, machine learning algorithms can integrate multi-source performance data (such as task completion, colleague feedback, project contributions, etc.) to achieve more objective, Comprehensive performance analysis to reduce human bias; computer vision technology empowers intelligent attendance systems to achieve contactless and efficient attendance management through facial recognition and other methods, improving employee experience and management efficiency. However, the application of AI technology also faces challenges, such as algorithmic bias, data privacy protection and other issues. It requires companies to pay attention to ethical norms and risk management in the process of technology selection and implementation to ensure the fairness and compliance of technology application.

The key value point of technological integration lies in realizing the transformation from “experience-driven” to “data-driven” management model, and improving the foresight, accuracy and personalization level of personnel management. Through the synergy between big data and AI technology, companies can gain a deeper understanding of the matching between employee needs and organizational needs, optimize human resource allocation, and provide employees with more personalized career development support, ultimately achieving a dual improvement in organizational effectiveness and employee experience. This iteration of technical dimensions is not only an upgrade at the tool level, but also a fundamental change in personnel management concepts and methods, providing important support for enterprises to build talent competitive advantages in the digital economy era.

1.2.Process dimension: digital reconstruction of personnel management throughout the life cycle

Driven by the digital economy, the process dimension iteration of the personnel management system focuses on the digital reconstruction of employees throughout their life cycle, and achieves end-to-end optimization from recruitment to resignation through technological empowerment. In the recruitment process, the application of

AI resume screening and virtual interview technology has significantly improved efficiency and accuracy. According to research, about 49% of companies invest digital human resources in human capital management software, among which digital recruitment tools account for an important proportion. The digital reconstruction of the training process is reflected in the design of personalized learning paths and the development of VR training scenarios. By analyzing the shortcomings of employee capabilities through data, adapted training plans are dynamically generated. This model has been proven to effectively improve the skills matching of employees in the digital reform of state-owned enterprises. The digital transformation of the salary performance dimension has broken through the limitations of traditional periodic accounting. Real-time data collection and the establishment of dynamic incentive mechanisms have enabled immediate linkage between salary adjustments and performance performance. The case of an education technology company shows that such a system can shorten the performance accounting cycle from monthly to weekly, while improving employee satisfaction by 23%. The digital reconstruction of the resignation management link uses intelligent analysis tools to explore the reasons for resignation and provide data support for talent retention strategies. This full-process data closed-loop management has become a trend among large enterprises. About 32% of enterprises plan to increase investment in cloud computing services to strengthen resignation data analysis capabilities. The core goal of process reconstruction is to achieve a dual improvement in efficiency and experience, reduce operational errors by reducing manual intervention, and optimize employee interaction experience by utilizing mobile and self-service functions. For example, a state-owned enterprise reduced employee onboarding time from 3 days to 4 hours through a digital system, significantly improving the experience for new employees. It is worth noting that HR needs to be deeply adapted to the organizational structure and employee behavior habits to avoid technological waste. This requires companies to fully consider the matching degree between user needs and operating scenarios during the system design stage.

1.3.Organizational Dimension: HR Role Transformation and Organizational Architecture Adaptation

Driven by the digital economy, HR roles are undergoing a multidimensional transformation from traditional affairs executors to strategic partners, data analysts and experience designers. This transformation is first reflected in the upgrading of strategic positioning. HR needs to be deeply involved in corporate strategic planning and support the realization of business goals through human resources strategies. For example, in terms of talent allocation, HR needs to formulate forward-looking talent reserve plans based on business expansion needs to ensure that the talent supply in key positions matches the pace of business development. At the same time, the role of data analyst requires HR to have data interpretation capabilities and provide decision-making support to management by analyzing employee performance data, turnover rate and other indicators. The role of experience designer focuses on optimizing the entire life cycle experience of employees, from the digital transformation of the recruitment process to the personalized design of employee training, to improve employee satisfaction and sense of belonging.

The adaptation and adjustment of organizational structure is an important guarantee for the transformation of HR roles. It has become a trend to establish digital HR departments, which integrate professional talents such as data analysis and system development to promote the digital upgrade and maintenance of personnel management systems. The establishment of cross-departmental data collaboration groups promotes information sharing and collaborative decision-making. For example, HR departments and business departments jointly analyze talent demand data and develop more accurate recruitment strategies. In addition, the construction of a flexible organizational structure enhances the organization's ability to respond to market changes and quickly deploy human resources to meet business challenges through project-based teams and other forms. This adjustment of the organizational structure not only optimizes internal processes, but also provides practical scenarios for the transformation of HR roles and promotes the coordinated evolution of the organization and the system.

2.Transformation of personnel systems in large state-owned enterprises

Large state-owned enterprises have shown clear compliance priority characteristics in the transformation of AI technology in personnel systems, which stems from their special positioning as policy response subjects.

1) State Grid Corporation of China: Its personnel system iteration strictly follows the requirements of the “Action Plan for Digital Transformation of State-owned Enterprises” and establishes a three-level review mechanism in the data governance link to ensure that core processes such as cadre appointment and removal, salary accounting, etc. comply with regulatory standards. The system realizes the immutable storage of personnel files through blockchain technology. While meeting the legal validity requirements of the Archives Law for electronic files, it compresses the file query response time from 3 working days to 15 minutes, significantly improving management efficiency.

2) Sinopec adopts a step-by-step digital transformation strategy, first verifying the intelligent recruitment system at its East China branch through a "pilot-promotion" model, and then gradually covering it to the entire group. Its system integrates resume analysis, AI interview and background check functions, shortening the recruitment cycle by 40%. At the same time, it reduces employment risks through a multi-dimensional compliance verification module. This practice is highly consistent with the reform logic of "steady progress" in the digital transformation of state-owned enterprises.

The two types of enterprises present differentiated paths in terms of system integration and organizational adaptation:

1) State Grid Corporation of China has built a “dual-mode IT architecture”. While retaining the traditional SAP-HR core module, it connects to new functions such as intelligent performance analysis and talent inventory through a microservices architecture to achieve a smooth transition between the old and new systems. This fusion model not only ensures the integrity of historical data, but also provides a data foundation for the application of AI algorithms. Its experience shows that technical iteration needs to be balanced with organizational inertia[8].

2) Sinopec emphasizes the supporting role of HR's role transformation. Through the "Talent Heat Map" tool developed by HR, it integrates employee skills, performance and project experience data to provide decision-making support for talent allocation in the refining and chemical sectors, reflecting the leap of HR functions from the operational level to the strategic level.

Therefore, we can see that the two types of cases jointly reveal that the digital transformation of state-owned enterprise personnel systems requires seeking a dynamic balance between technological innovation and institutional constraints, reducing resistance to change through gradual transformation, and consolidating transformation results through organizational capacity building.

Table.1.Comparison of the characteristics of digital transformation of personnel systems in large state-owned enterprises

Contrastive dimensions	**State Grid**	**Sinopec**
Core Features	Compliance first, strictly follow policy requirements	Step-by-step transformation, steady progress
Key technology applications	Blockchain technology enables immutable storage of personnel files	Intelligent recruitment system (resume analysis, AI interviews, background checks)
System Convergence Strategy	Build a "dual-mode IT architecture", retain the SAP-HR core module, and access new functions for microservices	-
Organizational adaptation measures	Smooth transition between old and new systems, balancing technical iteration and organizational inertia	Establish a "Digital HR Special Group" where 85% of HRs master basic data analysis skills
Transformation results	File query response time reduced from 3 working days to 15 minutes	Recruitment cycle shortened by 40%; "Talent Heat Map" supports talent allocation in refining and chemical sectors
Core Revelation	Technological iteration needs to be balanced with organizational inertia	The HR function leaps from the operational to the strategic level

Table.1. Comparison of the characteristics of digital

transformation of personnel systems in large state-owned enterprises

In the next 3-5 years, the iteration of personnel management systems will show four core trends, and the deep coupling of technological innovation and organizational needs will reshape the human resource management paradigm. AI will be upgraded from an auxiliary tool to a core carrier of employee services. Through natural language processing and multimodal interaction, it will achieve intelligent coverage of scenarios such as recruitment rhetoric generation, performance feedback optimization, and personalized training plan customization, promoting the transformation of HR from a rule enforcer to a value co-creator.

It is worth pointing out that data-driven dynamic organizational structure adjustment will become a key capability for enterprises to cope with uncertainty. By integrating employee skills, project experience and business demand data in real time, AI algorithms can automatically generate optimal team configuration plans, supporting agile organizational structure reorganization and dynamic talent allocation[9]. This trend requires personnel systems to have stronger data integration capabilities and interpretability of algorithmic models. The popularization of privacy computing technology provides a balanced path for the release of data value and security protection. Through technologies such as federal learning and multi-party secure computing, cross-departmental and cross-enterprise talent data collaborative analysis can be achieved without exposing the original data[10]. This not only meets the compliance requirements of laws and regulations, but also provides data support for precise talent decision-making. These intertwined trends will drive the evolution of personnel management systems from process digitalization to value intelligence, ultimately achieving dynamic synergy between human resource management and organizational strategy.

CONCLUSION

Promoting the iteration of China's enterprise personnel management system requires building a four-dimensional strategic system that integrates technology, talent, systems and culture, especially for large state-owned enterprises, which needs to balance innovation and stability within a compliance framework. At the technical selection level, it is recommended to adopt a hybrid model of “open source framework + customized development”: open source frameworks such as microservices architecture can reduce development costs and improve system flexibility, while customized modules can meet the compliance needs of cadre management, salary systems, etc. unique to state-owned enterprises. This model not only ensures a smooth transition between the old and new systems, but also provides a data foundation for the application of AI algorithms.

Talent cultivation and organizational adaptation are key supports for system iteration. Enterprises need to establish “Digital HR Capacity Enhancement Program”o enable HR to master basic data analysis skills through certification training and promote its transformation from operational to strategic levels.

In addition, in terms of cultural construction, it is necessary to create consensus on digital transformation through demonstrations by senior leaders and sharing of cross-departmental collaborative cases to reduce the resistance to change brought about by organizational inertia. Therefore, for state-owned enterprises, we can learn from the experience of the State Grid Corporation of China “dual-mode IT architecture”, connect intelligent functions on the basis of retaining traditional core modules, and achieve a dynamic balance between technological innovation and organizational inertia. These strategies need to be flexibly adjusted according to the size of the enterprise, industry characteristics and digital maturity to ensure that personnel system iteration and organizational strategy are deeply coordinated.

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Research on Obstacles and Optimization Paths of Emotional Connection between Virtual Anchors and Consumers

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KEYWORDS

Virtual anchor;

Emotional connection;

Human-Computer interaction;

Optimization path

ABSTRACT

With the deep integration of artificial intelligence and virtual reality technology, virtual anchors have become an important media form in e-commerce platforms, news communication, and other fields. This article systematically analyzes the three core obstacles of technology, cognition, and operation in the emotional connection between virtual anchors and consumers, as well as the deep-seated causes. The research found that the rigid human-computer interaction at the technical level stems from the ceiling of motion capture simulation technology, the lack of trust at the cognitive level is rooted in the perception of emotional commodification, and the homogenization at the operational level is attributed to security dependence; the three-dimensional optimization path can effectively solve the above obstacles by strengthening sensory immersion, balancing real perception. This research addresses fragmented studies and offers theoretical and practical support for the industry's sustainable, high-quality development.

INTRODUCTION

With breakthroughs in key technologies including generative artificial intelligence (AIGC), virtual reality (VR), and real-time rendering, virtual anchors have rapidly advanced from the conceptual experimental stage to large-scale commercial application and have been widely deployed in various highly interactive scenarios. To illustrate, live e-commerce, brand marketing, news broadcasting, online education, and customer service, aiming to meet the diverse needs of enterprises and consumers for novel interactive forms in digital survival. However, behind the prosperity of the industry lies a core contradiction: the high-tech interactive medium itself is not equivalent to an effective emotional bond. A large amount of market feedback and preliminary research show that while virtual anchors achieve information transmission and visual attraction, they often find it difficult to establish a continuous, stable, and deep emotional connection with consumers[1]. This lack of emotional connection has become a key bottleneck restricting virtual anchors from upgrading from attracting attention to winning hearts, and from traffic tools to brand assets.

Continuous policy support empowers the industry. However, behind the technological iteration, insufficient emotional interaction has become a core bottleneck for the high-quality development of the industry. Although virtual anchors boast numerous advantages including 24/7 availability and customizable images, their user experience and emotional connection with consumers are significantly weaker than those of real anchors. Among them, the proportion of young Generation Z groups is relatively high. Emotional connection has become a key element for virtual anchors to break through homogeneous competition and build core barriers, and it is also the core starting point for their upgrade from tool attributes to value attributes. Academic research confirms the importance of this pain point. Existing research has confirmed that the emotional connection and trust between consumers and anchors are key variables affecting purchasing decisions and brand loyalty. Emotional computing theory and quasi-social interaction theory point out that the core value of human-computer interaction lies in emotional resonance, and natural emotional expression and accurate emotional response are the keys to emotional

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connection in virtual scenarios. However, in practical applications, virtual anchors still face multiple dilemmas: technically, interaction delays and rigid micro-expressions lead to emotional expressions that are similar in form but different in spirit; cognitively, consumers' psychological barriers to virtual identities form trust barriers; in terms of experience, standardized responses and homogeneous personas cannot meet personalized emotional needs.

Academic research has confirmed the importance of this practical pain point from multiple dimensions. Studies based on emotional computing theory, quasi-social interaction theory, and social presence theory generally point out that the ultimate value of human-computer interaction is not pure functional efficiency, but whether it can trigger emotional resonance. Consumers' purchasing decisions, brand attitudes, and long-term loyalty are largely influenced by the emotional connection and trust relationship they establish with interactive media. However, when mapping the theory to the specific scenario of virtual anchors, multiple real dilemmas can be found: in terms of technical performance, problems.To illustrate, interaction delays, rigid micro-expressions, and uncoordinated multi-modal information lead to emotional expressions that are similar in form but not in spirit; in terms of consumer cognition, a clear understanding of the essence of virtual identity forms a natural psychological barrier and trust barrier, and emotional expressions are often attributed to algorithm-driven mechanical performances; in terms of operational experience, standardized response scripts, homogeneous role settings, and utilitarian content design cannot meet consumers' growing personalized and deep emotional needs. These dilemmas are intertwined and jointly hinder the establishment of deep emotional connections.

Therefore, systematically sorting out the core obstacles in the process of emotional connection between virtual anchors and consumers, deeply analyzing the technical limitations, cognitive psychology, and operational logic behind them, and exploring collaborative and operable optimization paths on this basis is not only an urgent need to solve the current industry's pain point of advanced technology but insufficient experience, but also a response to the trend of cross-disciplinary integration of human-computer interaction, communication, and other disciplines, and promotes the transformation of artificial intelligence technology from functional realization to emotional and humanized value creation. Important theoretical topic.

1.Research Significance

1.1.Theoretical Perspective

Firstly, it helps to fill the core gap in the fragmented research on emotional connection of virtual anchors. Existing studies are mostly scattered in isolated discussions of technology implementation, user acceptance, or short-term marketing effects, lacking a unified analysis framework. This study focuses on the dynamic emotional interaction between virtual subjects and consumers, integrates multidisciplinary perspectives of computer science, psychology, and communication, and constructs a closed-loop analysis framework covering obstacle identification, cause analysis, and path optimization, aiming to incorporate scattered issues into a coherent logical system and provide structured analysis tools for subsequent research. Secondly, it breaks through the boundary of traditional emotional connection research relying on real subjects, extends the theory to virtual scenarios, analyzes the synergistic mechanism of technology and emotional attributes empowered by digital technology, clarifies the unique evolution path of emotional connection from technical interaction to emotional resonance, and enriches the theoretical application scenarios and connotations. Thirdly, it verifies the cross-disciplinary theoretical crossover adaptability and proposes a three-dimensional analysis framework of social presence enhancement, authenticity balance, and quasi-social relationship construction, providing a new paradigm for subsequent research. At the same time, it guides the industry to transform from traffic competition to emotional value competition model, reduces the waste of homogeneous resources, and improves the overall development quality of the industry. Fourthly, it promotes the industry to transform from technology accumulation to value cultivation, extending the core research logic of human-computer interaction from early video conferencing and virtual game scenarios to the emerging scenario of e-commerce platform with high dynamics and high commercial attributes, exploring the particularity of emotional interaction between virtual subjects and consumers, and guiding resources to high-quality directions. To illustrate, user emotional needs mining and original content design.

1.2.Practical Perspective

This research empowers multiple subjects and industrial development: Firstly, it provides precise guidance for all parties in the industrial chain - technology research and development institutions clarify key research directions, operators avoid pitfalls. To illustrate, homogenization of persona, and brand owners obtain collaborative implementation paths. Secondly, the emotional connection between virtual anchors and consumers is not only a basic challenge in technical practice and commercial application, but also an important topic in user experience research in the digital economy era. First, the research on this topic helps to deeply understand the role of emerging technologies in human emotional interaction, which can not only provide enterprises with strategies to optimize consumer experience, but also strengthen consumers' brand identity, which has been verified by multiple cross-level studies[1]. The optimization of emotional connection is also related to the future expansion of virtual anchor application scenarios. By solving the existing obstacles, enterprises can further stimulate user loyalty and participation and bring more far-reaching economic benefits to the digital market[2]. It helps the industry to transform its development strategy, and the research guides the industry to shift from the competition mode of simply pursuing traffic growth and short-term conversion to a healthy mode of cultivating emotional value and long-term user relationship. By optimizing emotional connection, it can reduce the waste of resources caused by low-level homogeneous competition, improve the life cycle value of users, and thus promote the transformation of the entire virtual marketing industry to high-quality and sustainable development. At the same time, it provides inspiration for enterprises to build innovative business models. For example, by introducing immersive shopping experience and virtual spokesperson operation mode through virtual anchor technology, enterprises can effectively integrate online user resources and create sustainable commercial value[3].

Thirdly, it responds to the policy requirements of the digital economy, proposes an optimization framework based on China's market practice, provides reference for the global virtual industry, enhances international discourse power; at the same time, it helps consumers establish rational cognition, enhance emotional interaction experience, and realize the coordinated development of technological progress and humanistic care, providing practical guidance for the transformation from technology accumulation to value cultivation. Fourthly, it responds to the core controversies. To illustrate, whether virtual subjects can trigger real emotional resonance, clarifies the dialectical relationship of virtual emotional expression, and enhances consumers' virtual interaction experience. By optimizing the emotional response quality and personalized interaction ability of virtual anchors, it alleviates consumers' trust crisis in technology-simulated emotions and reduces the experience loss caused by emotional alienation - for example, allowing virtual anchors to have a full-chain dynamic ability of emotion recognition, empathetic response, and solution, and can not only express understanding for consumers' product anxiety, but also give personalized suggestions based on product characteristics to avoid the resistance caused by mechanical promotion rhetoric; at the same time, it reduces consumers' cognitive defense through transparent operation, and ultimately achieves a win-win situation for enterprise commercial value and consumer emotional needs.

2.Literature Review

2.1.Technology Development and Emotional Computing Research

As an emerging media form, technological iteration is the core support for virtual anchors to establish emotional connections with consumers, and its enabling role runs through the entire dimension of interaction form, response efficiency, and experience immersion. Early graphic rendering and motion capture technology realized the basic image concretization of virtual anchors, making them have the basic function of information transmission, but at this time, emotional transmission only stayed at the level of text and simple voice, and it was difficult to form effective emotional resonance. With the integrated application of AIGC technology and multi-modal interaction technology, virtual anchors have realized the coordinated synchronization of voice, expression, and body movements, which has significantly improved the simulation and adaptability of interaction. Wolter et al. proposed that Consumer-Company Identification (CCI) is one of the core mechanisms for building emotional connections, which is driven by consumers' interpretation of brand symbolic value, identity, and social significance[1].As an interactive medium between brands and consumers, virtual anchors can enhance consumers' social identity through customized image design and emotional interaction. However, research also points out that if consumers are skeptical about the authenticity of virtual anchors, it may weaken this identity, thereby affecting brand loyalty and user engagement.

Today's artificial intelligence is still data-driven intelligence, and Machines' emotional expressions essentially stem from extensive data training. Emotional computing technology equips machines with the ability to recognize, understand, and express emotions, allowing them to respond to human emotional states in an anthropomorphic manner—providing corresponding emotional guidance, encouragement, or comfort to help people adjust their cognitive and emotional states[4]. It clarifies the core function of emotional computing technology, realizes anthropomorphic feedback through identifying, understanding, and expressing emotions, and helps humans adjust cognitive and emotional states; at the same time, it warns of technical limitations, and one-way emotional output may constitute potential manipulation, weakening human's autonomous control over their own emotional occurrence. However, scenario differentiation remains insufficient, risk argumentation lacks clarity, and a balanced perspective is missing — details like interaction modes, risk boundaries, and optimization paths tailored to application scenarios need supplementation.

2.1.Consumer identification and emotional connection mechanism

Nagy et al. once proposed the concept of imagination affordance, pointing out that people may have certain expectations for technology, and then shape the way they use and perceive technology, thus describing how technology mediates emotional experience. Imagination affordance regards certain characteristics of technology as emotional clues for users and regards technology as an emotional relational entity or social actor[5]. However, it does not define which technical features can be regarded as emotional clues, which makes it difficult to accurately locate key influencing factors in practice; secondly, it does not explain in which scenarios and cognitive states users develop emotional expectations for technology or whether differences exist in users' imagination affordance, and it overlooks scenario differentiation considerations. Two core conclusions have been formed around the marketing value of emotional connection: First, Emotional connection yields scenario-specific marketing effects, with stronger conversion in emotion-oriented product categories; second, the strength of emotional connection is positively correlated with the marketing effect, but excessive emotional marketing is easy to cause consumer resistance and form emotional fatigue. A quantitative relationship model between emotional connection and marketing effect remains absent, research on differentiated effects across age groups and consumption levels remains inadequate, and discussions on the long-term impact mechanism of emotional connection on brand asset accumulation remain scarce, and more focus is on short-term purchase conversion, ignoring the long-term marketing value of emotional connection, and failing to deeply reveal how this connection is constructed or hindered in a dynamic and contextualized interaction process,

To summarize, current research exhibits a clear gap: technology and effect-oriented studies dominate, with no in-depth qualitative description of consumers' subjective experiences and no systematic focus on the specific process of emotional connection. Therefore, it is urgent to deeply explore the specific emotional obstacles and their socio-psychological roots perceived by consumers when interacting with virtual anchors.

3.Core Obstacles and Cause Analysis of Emotional Connection between Virtual Anchors and Consumers

The construction of emotional connection between virtual anchors and consumers is essentially a collaborative process of technical interaction, cognitive identity, and operational adaptation in multiple dimensions. However, in actual scenarios, the emotional connection between virtual anchors and consumers still faces obstacles in three core levels: technology, cognition, and operation, and its causes are closely related to technical limitations, consumer psychological characteristics, and operational defects, and the specific analysis is as follows:

3.1.Technical Level Obstacles and Cause Analysis

The core technical obstacle is the fundamental bottleneck in establishing emotional connection. Firstly, the technical traces of virtual anchors may make it difficult for consumers to experience real emotions, increasing the psychological distance for users. Studies have shown that consumers' emotional acceptance of virtual characters largely depends on their perception of technical authenticity[6]. In addition, the behavior patterns and emotional expressions of virtual anchors cannot currently fully reach the level of human interaction subtlety, thus limiting the possibility of deep emotional interaction. Secondly, the shortcomings in realistic expression lead to incomplete transmission of non-verbal cues, to illustrate, stiff facial expressions, asynchronous lip movements and speech, and mechanical body movements. When expressing apology, a few virtual characters can only complete the action of bowing their heads, but cannot present accompanying emotional signals, to illustrate, frowning and slowing down their tone; when expressing joy, they can only complete the switching of smiling expressions, but lack details, to illustrate, bright eyes and slight body shaking. These details are the core elements of conveying real emotions and building social presence, and their incompleteness will directly reduce consumers' emotional involvement.

The social presence of virtual anchors plays a crucial role in emotional connection. However, due to technical limitations, the facial expressions, vocal tones, and multimodal emotional coordination of virtual anchors still need further optimization. For example, one study pointed out that virtual anchors appear relatively stiff in emotional performance, which leads to consumers questioning their authenticity, weakening emotional resonance and interaction effects[7]. From the perspective of cognitive bias in realism, a few technology research and development excessively pursue objective realism. When the realism reaches a certain threshold, it exposes the mechanical nature of emotional expression due to over-realism — for example, the facial details of a certain high-realism virtual anchor can clearly show pores, but when responding to consumers' emotional appeals, the expression switching is stiff and lacks transition. This contrast between high-realism form and low-realism emotion triggers a strong sense of incongruity in consumers, making emotional responses superficial and difficult to resonate with.

The deep-seated causes of technical obstacles stem from multiple constraints of R&D orientation, technical bottlenecks, and market reality. Firstly, technological R&D direction suffers from deviations. The goal setting of abundant technical breakthroughs is to improve hard indicators. To illustrate, graphics rendering resolution and increase the capacity of the action database, rather than focusing on optimizing the ultimate user's social presence and subjective perception of authenticity. This technology-for-technology's-sake orientation leads to a mismatch between technological upgrades and the need for real emotional connection. Secondly, core technical bottlenecks restrict the implementation of theories. Micro-expression capture technology remains immature and cannot accurately capture consumers' emotional fluctuations to deliver matched emotional responses. The current mainstream emotional computing algorithms have insufficient accuracy in identifying complex emotions (anxiety with anticipation, satisfaction with hesitation), and micro-expression capture technology is also difficult to restore key emotional signals. To illustrate, human eye micro-movements and subtle upward movements of the corners of the mouth, which makes it difficult to supplement the authenticity of interaction and to crack the cognitive bias of realism. Thirdly, cost restricts the popularization of high-quality technologies. Building a virtual anchor that can conduct high-naturalness emotional interaction requires huge capital investment in hardware equipment, algorithm research and development, and content production, which is far beyond the affordability of small and medium-sized businesses and individual creators. As a result, the market is filled with many virtual anchors that use low-cost, templated technical solutions, which have limited interaction capabilities and further solidify consumers' negative perception of virtual anchors' emotional dullness.

3.2.Cognitive Obstacles and Causes

The essence of cognitive obstacles is the lack of real sense of identity and the emotional involvement obstacles caused by insufficient social presence. Firstly, questioning the sincerity of emotions is the core pain point. Consumers generally attribute the emotional expression of virtual anchors to technical simulation, believing that they lack a real emotional core. This denial of subjective authenticity makes it difficult for them to generate emotional resonance. Consumers' trust in virtual anchors largely depends on their anthropomorphic characteristics and the naturalness of emotional expression. For example, if consumers feel a mechanical response after confiding their consumption confusion to a virtual anchor, they will feel a sense of loss from talking for a long time, and then completely give up emotional interaction; secondly, the designed attribute of virtuality strengthens cognitive defense, and the low willingness to connect emotionally is a direct manifestation of insufficient emotional involvement. Consumers know that their words and deeds are driven by algorithms, and behind them is the commercial purpose of enterprises, which further questions the sincerity of emotional expression. Virtual anchors usually rely on facial expressions, voice content, and text information to convey emotions, but mismatches in cross-modal emotional elements may trigger emotional cognitive conflicts in the user experience.

Research has found that when the voice tone of virtual anchors is inconsistent with the text emotional information, consumers' sense of participation in their interaction decreases significantly [8]. They believe that the care and empathy shown by virtual anchors to consumers are all to promote sales, rather than real emotional care. This cognitive defense directly hinders the establishment of emotional connection, especially in scenarios with strong emotional needs. To illustrate, emotional expression, personalized consultation, this sense of rejection is more obvious. Consumers believe that virtual anchors cannot replace the genuine emotional interaction offered by real anchors and thus naturally resist establishing deep emotional connections with virtual influencers. At the same time, in the context of globalization, consumers of different cultures have significant differences in the emotional expression of virtual anchors. For example, Eastern consumers tend to accept gentle and polite interaction styles, while Western consumers prefer humorous or direct expressions. If virtual anchors fail to integrate different cultural symbols in the design and interaction process, it may reduce their cross-cultural emotional connection ability[9].

The deep-seated causes are highly related to the essential characteristics of virtual interaction and the current situation of the industry: First, emotional connection depends on the perception of the presence of real subjects, while virtuality lacks autonomous emotional experience and initiative, and cannot meet the human need for real emotional communication; The essential need for human emotional connection has a natural contradiction with virtual attributes. The establishment of emotional connection depends on two-way real emotional resonance, while virtuality lacks autonomous emotional experience and initiative, and cannot generate real emotional resonance like humans, and can only simulate emotional expression through algorithms. This one-way simulation interaction mode is difficult to meet the human need for real emotional communication.Secondly, the stronger the perception of high fidelity but non-realness among digital consumers, the lower the subjective authenticity score and the more difficult it is to establish emotional trust. In addition, industry chaos intensifies cognitive biases, and several merchants engage in deceptive virtual promotions — for instance, one merchant's virtual anchor concealed its virtual nature and recommended products under the guise of real-person reviews, which triggered an industry trust crisis after being exposed, leading more consumers to question the virtual emotional expression, and further strengthened consumers' cognitive labels of virtual non-realness and utilitarianism.

3.3.Operational Obstacles and Causes

Operational obstacles make it difficult to continuously deepen emotional connection. First, the homogenization of personality is serious, and it is impossible to build differentiated emotional involvement points. In practical applications, virtual anchors usually adopt standardized image design and operation strategies to achieve scale and economic benefits. However, this templated design is difficult to meet consumers' needs for personalized interaction. Studies have shown that content homogenization reduces long-term consumer interest and weakens the depth of emotional connection[10]. The same young and lively personality is difficult to match the emotional preferences of different consumer groups - for example, for the health category live broadcast for middle-aged and elderly groups, it is difficult to establish a sense of trust by adopting a young and lively personality; for the trendy play category live broadcast for Generation Z, the use of a serious expert personality lacks appeal and cannot form a continuous emotional resonance. Overly focusing on the content design of product promotion makes emotional expression a marketing tool, which is difficult to match the emotional preferences of different consumer groups and cannot form a continuous sense of emotional presence.

Secondly, personalized interaction design, emotional depth, and customization are lacking — quantities of operation teams rely on fixed rhetorical templates, leading to mechanically repetitive interaction modes. It is impossible to adjust emotional expression according to consumer behavior. The operation team has insufficient professional ability and lacks relevant experience in emotional interaction design. The emotional expression in the script is often rigidly spliced with product introduction, lacking natural transition and narrative, which seems utilitarian and insincere. A deeper problem is that the operation lacks the ability to dynamically adjust interaction strategies and emotional responses based on user real-time feedback and historical behavior data. The interaction is always a "one-to-many" broadcast mode, rather than a "one-to-one" dialogue mode. The use of the same welcome rhetoric can neither make old users feel exclusive, nor can it make new users feel guiding, and the interaction effect is greatly reduced, and the abrupt expression of emotional expression and product introduction in a few scripts further weakens the emotional authenticity.

Operational obstacles stem from systemic problems in strategic orientation, capability system and resource allocation. First, corporate operating goals are generally short-sighted. The assessment of virtual anchors is mostly focused on immediate conversion indicators, the number of viewers, click-through rate, and sales of the live broadcast, while insufficient attention is paid to long-term indicators related to the quality of emotional connection. To illustrate, emotional trust, user stickiness, and long-term repurchase rate. This KPI baton leads to the natural inclination of operating resources towards promotional activities that can quickly drive sales, ignoring the emotional content design and relationship maintenance that require long-term investment and patient cultivation, making the operating strategy run counter to the long-term goal of emotional connection. Second, the ability of emotional operation is insufficient. The operation team lacks the professional ability of virtual anchor personality shaping and emotional interaction script design, and it is difficult to effectively combine product information with emotional needs. They have not mastered the design method of continuous emotional involvement, nor do they have the skills to shape emotional authenticity. It is difficult to effectively combine product information with emotional needs. Most operation teams are transformed from traditional e-commerce operators, lack relevant experience in virtual subject interaction design, and do not consider the virtual characteristics and consumer cognitive differences. Third, the uneven distribution of resources exacerbates the imbalance of operations. Head platforms and brands can rely on sufficient funds and talents to form a professional emotional operation team responsible for virtual personality polishing, script refined design and data monitoring optimization; while small and medium-sized businesses are limited by funds and talents, and cannot carry out refined emotional operation, and mostly adopt templated scripts and homogeneous personalities, which further magnifies the negative impact of the lack of authenticity and insufficient emotional involvement.Fourth,an effective evaluation system for operational effects remains absent. Enterprises mostly evaluate operational effects based on indicators traffic and conversion and have not established evaluation indicators related to emotional connection, which cannot accurately perceive the effect of emotional connection, and it is difficult to optimize operational strategies in a targeted manner.

3.4.Core Obstacles and Causes Thinking Flow Chart

To present the obstacle configurations and interaction mechanisms of the technical, cognitive and operational dimensions of the system, this paper constructs the following thinking flowchart. This chart aims to condense the core representations and underlying causes at each level and reveal the element correlations and logical transmission paths among them, thereby providing a structured analysis framework for comprehensively grasping the obstacle spectrum of the emotional connection between virtual hosts and consumers.

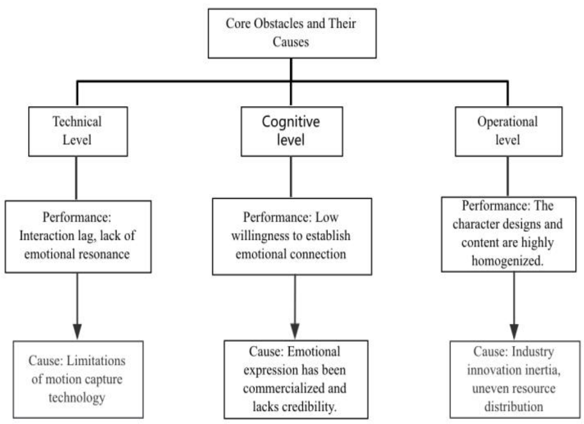

Fig.1. Core Obstacles and Causes Thinking Flow Chart

4.Construction of Optimization Path for Emotional Connection between Virtual Anchors and Consumers

In response to the three major obstacles of technology, cognition, and operation, combined with the requirements of quasi-social interaction theory for emotional resonance, an optimization path is constructed from the three dimensions of technology upgrade, cognitive guidance, and operational innovation to help establish and deepen the emotional connection between virtual anchors and consumers. A multi-dimensional collaborative optimization framework is an effective paradigm for improving the emotional connection effect of virtual subjects.

4.1.Technical Upgrade Path

The lack of social presence is the core problem of the technology, it is necessary to strengthen the sense of immersion and naturalness through technological iteration. On the one hand, upgrade multi-modal perception and expression technology, introduce high-precision capture equipment and generative AI models, focus on optimizing micro-expression dynamic simulation algorithms, and build a multi-modal emotional database covering different scenarios and different emotional types to improve the accuracy and timeliness of emotional recognition, so that consumers can intuitively feel the instant feedback and emotional synchronization of virtual anchors. On the other hand, Virtual anchor design can integrate additional features — machine learning can enhance humorous expression, emotional care, and personalized voice templates to narrow the perceived human-machine distance. Anthropomorphism can significantly improve the emotional credibility of virtual characters and users' willingness to accept[11]. Build a multi-modal emotional database covering rich scenarios, diverse groups of people, and complex mixed emotions, dynamically generate matching emotional responses with personal style imprints, and achieve a leap from response to echo. Sort out the types of emotional appeals in different consumption scenarios, and reverse deduce the key technical parameter standards. To illustrate, interaction response speed and non-verbal cue transmission accuracy to ensure that technical optimization accurately matches emotional transmission needs. At the same time, expand the non-verbal cue database of facial micro-expressions and body movements, and enhance the collaborative improvement of emotional presence and cognitive presence.

Secondly, break through the bottleneck of core technologies. Aiming at the shortcomings of emotional computing and micro-expression capture, adopt the AIGC and emotional big data fusion training mode, relying on the mature algorithm framework in emotional interaction technology research, so that virtual anchors can dynamically adjust emotional response strategies according to consumers' tone and comment mood fluctuations to avoid templated expressions. Thirdly, optimize the cost supply model, draw on the application experience of technical modularization, and reduce the virtual development threshold for small and medium-sized businesses through open source algorithm integration and basic function standardization, and build a tiered technical solution from the basic version to the advanced version: the basic version covers core emotional interaction functions (simple emotion recognition, standardized emotional response, and basic non-verbal cue transmission) to meet the basic needs of small and medium-sized businesses; the advanced version provides personalized emotional interaction functions, Augmented Reality (AR) and Virtual Reality (VR) technologies can build more immersive interactive scenarios for virtual anchors, thereby strengthening consumers' sense of social presence when participating. For example, adding real-time dynamic feedback technology can make the emotional performance of virtual anchors closer to real people[12]. At the same time, reduce the technical access cost for small and medium-sized businesses to ensure that basic interactive realism can be achieved under different resource conditions.

4.2.Cognitive Guidance Path

The core of cognitive guidance is to transparentize virtual identities and build emotional real cognition to eliminate consumers' trust barriers. First, actively inform the virtual attributes and operating entities through opening introductions, interface annotations, to avoid cognitive confusion; at the same time, design sincere interaction scripts that are close to daily life, reduce rigid promotion rhetoric, and increase emotional listening, empathetic responses, and enhance the anthropomorphic personality of virtual anchors by adding humorous expressions, emotional care, and interactive micro-expressions. Research shows that the improvement of credibility can effectively enhance consumers' willingness to purchase and the intensity of emotional connection[10];based on the research conclusions in the field of human-computer interaction on the transparency and trust construction of virtual subjects, abandon the single identity notification mode and adopt a layered strategy of basic disclosure and in-depth interpretation: the basic layer clarifies its virtual attributes and core functions through the top announcement of the live broadcast room and the 30-second self-introduction of the virtual opening to avoid consumers' excessive expectations of objective authenticity due to identity confusion. This transparent disclosure will not weaken emotional involvement but can enhance the perception of subjective authenticity through sincere communication and lay the foundation for emotional connection.

Secondly, build a precise matching system of group portraits, emotional needs, and scenario design to strengthen differentiated emotional involvement experiences. Design customized interactive scenarios for the cognitive characteristics and emotional appeals of different consumer groups: for example, for young consumer groups, create trendy companion-type interactive scenarios, combine hot topics to carry out relaxed emotional communication, and enhance the sense of companionship based on the theory of social presence; for middle-aged and elderly consumer groups, build professional assistant-type scenarios, reduce cognitive defense through clear information transmission and patient problem solving, and enhance emotional trust. For groups seeking professional advice, they should create a stable, reliable, and knowledgeable personality and provide logical and caring answers. Through precise matching, effectively penetrate cognitive defenses and establish emotional closeness. At the same time, incorporate low-pressure interaction principles into scenario design, allowing consumers to independently control the interaction rhythm and avoid excessive emotional guidance causing resistance. Build a trust endorsement system of industry norms, corporate self-discipline, and third-party supervision to break the cognitive prejudice caused by industry chaos. Carry out hierarchical evaluation of the authenticity of emotional expression and the accuracy of information transmission, introduce authoritative institutions to carry out virtual trust rating, and strengthen consumers' cognition of virtual reliability and sincerity through external endorsement to clear cognitive obstacles for the construction of social presence.

4.3.Operation Innovation Path

Operation innovation should be guided by enhancing social presence and balancing authenticity to create differentiated emotional resonance. First, deeply cultivate differentiated persona shaping to strengthen the sustainability and uniqueness of emotional involvement. Abandon the homogeneous label-based persona design and adopt the positioning logic of emotional pain point matching and personality trait segmentation: first, lock the core emotional appeals of the target group through user portrait analysis, and then design personality traits that are both recognizable and emotionally warm. To illustrate, creating a best friend-type beauty consultant for young female groups, combining professional answering ability and empathetic sharing attributes; create a technical house partner for male groups, and establish resonance with a rigorous, professional and interesting style. At the same time, design scenario-based interactive sessions, encourage user co-creation, naturally integrate brand value into the interaction, and realize the synergistic improvement of emotional resonance and brand recognition. Establish a management system for persona consistency, clarify the normative standards for the virtual anchor's language style, facial expressions, value propositions, and other core elements, and effectively enhance social presence.

Secondly, upgrade the interactive script design, weaken utilitarian perception, and enhance subjective authenticity. Construct a three-dimensional script framework encompassing scenario-specific, emotional, and personalized elements: at the scenario-specific level, break free from the constraints of a single promotional scenario and expand into diverse scenarios—product usage simulation, consumer pain point resonance, and industry knowledge popularization, adding a scenario of answering parenting questions for novice mothers in the maternal and infant product live broadcast, and enhance emotional substitution through real scenario restoration; at the emotional level, reduce rigid sales rhetoric and increase empathetic expressions,sharing the story behind product development, real user feedback, to weaken the mechanical sense driven by algorithms and alleviate the authenticity paradox through sincere narration; at the personalized level, establish a user tag system, accurately match script content according to users' consumption history, interaction preferences, emotional tendencies, and other dimensions, and explore the application of virtual anchors in emerging fields, to illustrate, education and medical care, serving as an interactive assistant for online courses or providing emotional support in mental health counseling. Multi-scenario not only expands the coverage of virtual anchor applications but also helps to deepen emotional connections with consumers in different fields[13]. Dynamic update mechanism, optimize content every week based on hot topics and user feedback.

Thirdly, improve the assessment and resource allocation system to provide guarantee for long-term emotional operation. In terms of the assessment mechanism, establish a dual-oriented assessment system of emotional value and short-term transformation, and incorporate indicators. To illustrate, user stay time, emotional interaction frequency, emotional trust score, repurchase rate, and user recommendation willingness into the assessment to guide operational resources to emotional connection construction. In terms of resource allocation, build a hierarchical empowerment system: head platforms and brands can form professional emotional operation teams to be responsible for virtual persona polishing, script refined design, data monitoring and optimization, user emotional needs analysis; for small and medium-sized businesses, launch low-cost operation toolkits, including standardized emotional interaction templates, persona positioning tools, user tag management systems, script optimization guidelines, to reduce the threshold for refined operation. At the same time, establish an operation effect feedback closed loop, and regularly evaluate the emotional connection effect through user questionnaires, comment sentiment analysis, interaction data tracking, emotional trust evaluation, and other methods to form a closed-loop mechanism of data collection, effect analysis, strategy optimization, landing execution, and then re-evaluation to ensure that operation measures always fit the emotional needs of consumers and the goal of shaping authenticity, and dynamically adjust operation strategies.

In summary, technology upgrade is the basic guarantee for enhancing social presence, providing underlying support for natural interaction; cognitive guidance is the key to balancing real perception and helping to establish deep trust; operation innovation is the core path to deepen emotional resonance and strengthen connection stickiness. The three work together and advance together to fully solve the core obstacles, realize the harmonious unity of virtual identity and real emotion, promote the stable establishment and long-term deepening of emotional connection between virtual anchors and consumers, and ultimately achieve a win-win situation of commercial efficiency and humanistic care, leading the virtual anchor industry to a new stage of high-quality development with emotional value as the core.

Conclusions

Core Conclusions

This study systematically explores the core obstacles, causes, and optimization paths of emotional connection between virtual anchors and consumers. The core conclusions are as follows: First, the core obstacles to emotional connection between virtual anchors and consumers present a synergistic constraint of technology, cognition, and operation. Among them, the lack of presence maintenance and insufficient shaping of authenticity at the operational level are the key bottlenecks for the emotional connection to continue to deepen, specifically manifested in problems. To illustrate, homogenization of persona, utilitarian scripting, and short-sighted assessment, which are essentially that the operational strategies have not effectively matched the core guidance of the two major theories. Second, the optimization path at the operational level needs to build a three-dimensional long-term mechanism of persona cultivation, script upgrading, and system guarantee. It strengthens social presence through the differentiated persona shaping of emotional pain point matching, alleviates the authenticity paradox by upgrading the script with scenarios, emotions, and personalization, and provides guarantee for emotional operation by relying on dual-oriented assessment and hierarchical resource allocation. These three paths form synergy with technical and cognitive level optimization measures to jointly solve the emotional connection obstacles. It ensures that the operational measures are precisely directed to the core needs of emotional connection.

Research Limitations and Future Directions

This study still has several limitations: first, research primarily focuses on three dimensions — technology, cognition, and operation — and fails to fully consider how differences in emotional needs across consumer groups impact obstacle perception and optimization path adaptability; For example, the younger Generation Z and middle-aged and elderly groups have significant differences in the emotional perception threshold and interaction preferences of virtual anchors, which leads to the limited universality and precise adaptability of the research conclusions; Secondly, external environmental variables associated with policy supervision have not been considered.

At present, the relevant laws and regulations of the virtual live broadcast industry are still not sound, and the regulatory guidelines have not been refined, and policy orientation and regulatory requirements may directly affect the operational strategies of enterprises and then act on the emotional connection construction process. The existing research does not explore the potential impact of this external constraint on the emotional connection effect; Thirdly, the dynamic mechanism of emotional connection is not fully explored. The existing research focuses on the static obstacles and optimization paths of emotional connection and does not pay attention to the long-term dynamic change process of emotional connection from establishment, deepening to attenuation, and it is difficult to reveal the core influencing factors and stability laws of emotional connection in different stages.

Future research can carry out differentiated research on sub-groups, focusing on the emotional needs differences of different groups (teenagers, middle-aged and elderly), different industries (FMCG, durable goods) and different live broadcast modes; By expanding multi-scenario comparative research, explore the obstacle differences and adaptive optimization paths of virtual anchor emotional connection in different application scenarios, and explore the differentiated adaptation strategies of operational optimization paths to improve the scenario pertinence of research conclusions. Longitudinal tracking, case historical analysis and other methods can be used to explore the key influencing factors in different stages, the stability mechanism of emotional connection and repair strategies, so as to provide more forward-looking management insights.

In combination with the continuous development of AIGC and real-time interaction technologies, the operation mode of virtual anchors will usher in new changes, and explore generative AI's application in dynamic script generation and intelligent persona optimization, along with the balance mechanism between operational efficiency and emotional connection effects under technological empowerment. Proactively explore how these new technologies will reshape the possibilities and paradigms of emotional connection, for example, what new challenges and optimization opportunities will highly autonomous AI personalities and immersive holographic interaction bring. Through interdisciplinary research perspectives, deeply explore consumers' emotional cognitive mechanisms of virtual anchors, further enrich the theoretical connotation of operational optimization paths, and provide more comprehensive theoretical support for the deep construction of emotional connection between virtual anchors and consumers.

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Explainable AI Prevention Pathways for Employee Turnover in Digital Transformation Enterprises: Model Construction and Strategy Optimisation Based on Ensemble Learning + SHAP

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KEYWORDS

Digital transformation;
Human resource risk management;
Employee attrition prediction;
Explainable AI;
SHAP method

ABSTRACT

In the context of digital transformation, employee turnover has become a critical risk for corporate development. Traditional human resource management and purely machine learning models have limitations in prediction or face 'black box' issues. This study constructs an Ensemble Learning + SHAP dual-track framework, using digital enterprises as a case study. It's trying to achieve a high-precision turnover prediction through Random Forest, while leveraging SHAP to reveal key influencing factors,most notably a U-shaped relationship between tenure and attrition risk,and proposes targeted retention strategies such as a hierarchical career development framework and a closed loop workload optimisation system. This approach effectively addresses the accuracy-interpretability trade off, providing a new pathway for intelligent, proactive human resource risk management in digitally transforming enterprises.

INTRODUCTION

Against the backdrop of deepening digital transformation, employee attrition has emerged as a critical strategic risk, directly constraining corporate sustainability and innovation capacity. Traditional human resource management (HRM) practices, which often rely on managerial intuition and retrospective exit interviews, are theoretically unsound as a mechanism for proactive risk mitigation. They fail to capture the complex, non-linear interactions between myriad factors—such as compensation equity, career trajectory, workload stress, and organisational culture—that collectively drive turnover decisions. Moreover, they suffer from an inherent predictive lag, typically triggering intervention only after an employee has mentally disengaged.

The advent of data analytics and machine learning (ML) promised a change. Algorithms like Random Forests have demonstrably improved predictive accuracy. However, their widespread adoption in HRM has been hampered by a critical barrier which is the black box problem. When a model flags an employee as a high turnover risk, HR practitioners are left in the dark regarding the specific reasons behind this prediction. This opacity hinders the design of personalised retention interventions, undermines managerial trust, and precludes the audit of the model for potential biases related to gender, age, or other protected attributes. Consequently, high precision models often fail to translate into tangible managerial effectiveness.

To bridge this gap, this study proposes and implements a dual track analytical framework that synergistically combines the predictive power of ensemble learning with the explanatory clarity of SHAP . We here by using digital enterprises in Guangzhou, China, as an empirical case study,

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this research aims to: (1) construct a robust, high performance attrition prediction model; (2) employ SHAP to transform model outputs into transparent, actionable intelligence about key risk drivers; and (3) derive targeted, evidence-based retention strategies. By doing so, it offers a novel, integrated pathway for moving HR risk management from a reactive, intuitive function towards a proactive, intelligent, and explainable strategic pillar.

1.Literature Review : From Prediction to Explainable Intelligence

The quest to understand and predict employee turnover has evolved through distinct methodological stages. The first stage relied heavily on traditional statistical methods for example logistic regression and theory-driven models from organizational behavior, such as the Mobley turnover chain. While providing interpretability, these approaches often struggled with the high-dimensionality and complex interactions present in real-world HR data.

The second stage embraced classical machine learning algorithms, including Decision Trees, Support Vector Machines (SVM), and K-Nearest Neighbors (KNN). These models improved handling of non-linear patterns but introduced a trade-off between performance and transparency. Ensemble methods, notably Random Forest (RF) and Gradient Boosting Machines like XGBoost, marked a significant advance in this stage, consistently achieving state of the art predictive accuracy by aggregating multiple weak learners. However, their nature further deepened the black box dilemma[1].

This has ushered in the current, third stage, focused on Explainable AI (XAI). The core challenge is no longer solely predictive accuracy but achieving interpretability without sacrificing performance. Techniques like LIME (Local Interpretable Model-agnostic Explanations) and SHAP have been adapted to HR analytics. SHAP, grounded in cooperative game theory, is particularly powerful as it provides a unified, theoretically sound measure of feature importance that is both consistent and locally accurate.

Despite these advances, a critical gap persists in the literature. Most studies conclude with model explanations or instance-level insights but stop short of systematically translating these data-driven discoveries into comprehensive, actionable management strategies that are integrated with established HR theories. Furthermore, there is limited research focusing specifically on the unique attrition dynamics within digital transformation enterprises, which operate at a faster pace and under different pressures. This study aims to fill this gap by not only applying the RF+SHAP framework but also using its outputs to construct a theoretically grounded, strategic retention toolkit for this specific context.

2.Research Methodology : A Dual-Track Framework

2.1.The Dual-Track Framework: Ensemble Learning + SHAP

To simultaneously achieve high predictive accuracy and essential interpretability, this study constructs a dual-track analytical framework. The Predictive Track employs Random Forest (RF) as its core engine, chosen for its robustness against overfitting and superior ability to model the intricate, non-linear interactions characteristic of HR data. The Explanatory Track utilizes the SHAP (SHapley Additive exPlanations) framework post-hoc to attribute model predictions to individual input features, transforming opaque outputs into intelligible insights. This is not a sequential application but an integrated design where the predictive model's output becomes the direct input for explanatory analysis.

2.2 Data and Preprocessing

The analysis is grounded in a multi-dimensional human resources dataset from digital enterprises. A rigorous preprocessing pipeline was executed, involving the encoding of categorical variables, treatment of outliers in key numerical features like monthly income and overtime hours using robust statistical methods, and the critical removal of variables that could lead to target leakage, ensuring the model learned genuine predictors of attrition risk rather than procedural artifacts[2].

2.3 Model Optimisation and Integrated Evaluation

The RF model was optimized via a 5-fold cross-validated grid search to tune hyperparameters such as the number of trees (n_estimators) and maximum depth (max_depth), seeking to maximize the area under the ROC Curve (AUC). Model efficacy was assessed through a tripartite framework: (1) Predictive performance using standard metrics; (2) Interpretability fidelity by checking SHAP explanations against domain knowledge; and (3) Operational stability by testing the consistency of outputs across different data

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SHAP-Based Insight	Theoretical Correlate	Implication for HR Practice
U-shaped tenure-risk relationship	Career Stage Theory; Social Exchange Theory	Retention strategies must be phased and tailored to employee lifecycle stages (new hire, core, veteran).
Overtime as a primary risk driver	Job Demands-Resources (JD-R) Model; Conservation of Resources Theory	Workload and well-being are not just some soft issues but quantifiable risk factors requiring systemic management.
Job level and income as stabilizers	Equity Theory; Human Capital Theory	Competitive compensation and clear advancement paths are validated as foundational retention tools.

samples.

3.Result and Interpretation： From Data to Insight

3.1.Predictive Performance

The comparative model evaluation yielded decisive results. The Random Forest model demonstrated superior and robust performance, achieving an AUC of 0.9998 and maintaining a precision-recall balance above 0.97. This indicates an exceptional ability to discriminate between employees at risk of departure and those likely to remain. The failure of other models like SVM underscores the importance of aligning algorithmic choice with data characteristics in HR analytics[3,4].

3.2.Explainable Insights via SHAP

The application of SHAP provided the crucial link between prediction and understanding. Global analysis identified the three most influential predictors of turnover: Resignation status (administrative indicator), Total working years (Tenure), and overtime patterns. The most significant finding was the non-linear, U-shaped relationship between tenure and attrition risk. SHAP dependence plots clearly illustrated elevated risk for new employees (<3 years), decreased risk for core employees (3-10 years), and a resurgence of risk for veteran employees (>10 years). Furthermore, SHAP confirmed a strong positive relationship between overtime frequency and attrition probability, while higher job level and income acted as stabilizing factors.

Table.1. Strategic Insights Derived from SHAP Explainability Analysis

4.Theoretical Integration： Explain the WhyBehind the Data

The empirical findings necessitate integration with organizational theory to move from correlation to causal understanding. The U-shaped tenure-risk curve empirically validates the progression of psychological contracts and career stages. The high initial risk mirrors the fragility of early social exchange; the mid-career stability reflects fulfilled exchanges and growth per career stage theory; the late-career risk resurgence aligns with career plateau and conservation of resources theory, where challenge resources deplete. Similarly, the strong link between overtime and attrition provides quantitative validation for the health impairment pathway in the JD-R Model, where excessive demands deplete energy reserves. This synthesis allows us to posit that attrition risk in digital enterprises is a function of the dynamic equilibrium between structural resources and psycho-physiological demands across the career lifecycle which is a proposition made measurable by our framework.

5.Core Strategy Recommendations

Integrating the SHAP-derived insights with the context of digital enterprises, here we proposed a targeted, dual-core strategic framework.

5.1.Phased Career Development Framework

Based on the U-shaped tenure-risk insight, a differentiated approach is mandated:

For new hires (<3 years): Implement structured onboarding and early career navigator programs to accelerate role clarity and social integration, fortifying the initial psychological contract.

For Core Employees (3-10 years): Sustain engagement through Dual-career pathway initiatives, combining transparent vertical promotion with formal lateral rotation programs to provide continuous growth and prevent stagnation.

For veteran employees (>10 years): Mitigate plateau risks by creating formal Senior Expert roles, leveraging their institutional knowledge through mentorship and strategic advisory duties to facilitate value reconstruction.

5.2.Closed-Loop Workload Optimisation System

Addressing the overtime-driven risk requires a systemic JD-R-informed approach:

Assess: Institute an Overtime Necessity Audit to eliminate non-essential overtime.

Compensate and Recover: Enforce a Time-off in Lieu + Premium Subsidy policy to fairly compensate and mandate recovery.

Optimise at Source: Deploy process automation and AI tools to streamline workflows, reducing the root cause of excessive demands.

SHAP Insight	Proposed Intervention	Responsible Function	Success Metric (KPI)
U-Shaped Tenure Risk	1. Launch Early Career Navigator program. 2. Establish Internal Talent Marketplace for lateral moves. 3. Create Senior Fellow roles.	Talent Development HR Business Partners Strategy andOps	Attrition rate by tenure cohort.
Overtime as Key Driver	1. Implement Overtime Transparency Dashboard. 2. Policy: Mandatory Time-off in Lieu. 3. Audit projects for Sustainable Workload Design.	Team Leads / HR HR / Finance Project Management Office	Avg. monthly overtime hours; Well-being survey scores.
Job Level andIncome as Stabilizers	1. Review compensation equity for high-risk cohorts. 2. Accelerate promotion cycles for high-potentials in risk groups.	Compensation andBenefits Leadership Committee	Attrition rate of high-potentials; Pay equity ratio.

Table.2. Actionable Retention Strategy Matrix

6.Ethical Considerations and Implementation Roadmap

Deploying predictive analytics in HR demands ethical vigilance and structured change management.

6.1.Ethical Guardrails

To ensure responsible use, deployment must be governed by principles of transparency and consent (informing employees about analytic purposes), human-in-the-loop decision making (using outputs for supportive dialogue, not automated punishment), and continuous bias auditing (using SHAP to check for unfair disparities across demographic groups).

6.2.A Phased Implementation Roadmap

Transitioning from prototype to practice requires a structured approach:

Phase 1: Pilot and Validation (Months 1-3): Test in a single business unit to refine predictions and explanations.

Phase 2: Process Integration and Training (Months 4-6): Train managers on interpreting risk reports and SHAP insights for coaching conversations.

Phase 3: Full Deployment with Ethics Board (Months 7-12): Enterprise-wide rollout overseen by a cross-functional ethics board.

Phase 4: Continuous Learning (Ongoing): Integrate intervention outcomes to learn which actions are most effective, evolving from predictive to prescriptive analytics.

Conclusion

This study successfully demonstrates that the Ensemble Learning + SHAP framework effectively bridges the accuracy-interpretability divide in employee attrition prediction. By integrating data-driven insights with organizational theory, it provides not just a predictive tool but a diagnostic system for understanding the underlying mechanisms of turnover. The proposed phased career framework and workload optimization system offer a concrete pathway for proactive retention.

Limitations include the cross-sectional nature of the data and the specific cultural context. Future research should pursue longitudinal studies to establish causality, integrate external pull factor data, and replicate the framework across diverse cultural and industrial settings. Ultimately, the goal is to deeply integrate this explainable intelligence into corporate HR systems, creating a closed-loop ecosystem for strategic human capital management that is both empirically grounded and ethically sound[5].

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A Study on the Dual-Role Conflict and Integration of Design Managers As Creative Advocate and Project Constraint Controller

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KEYWORDS

Design manager;
Role conflict;
Sustainable development;
Project management;
Integration strategy;
Green construction;
Creative management;

ABSTRACT

The green transition in the architecture and interior design industry is being put under pressure by the global trend of pursuing Dual Carbon goals and ESG principles. The key players in this process are design managers. They have been struggling with a dilemma between dual roles: creative vision protection and project constraint control. Sustainable development has exacerbated this inherent conflict [1]. It becomes a powerful new agenda, tightening even further the traditional tension between creativity and commercial reality. This paper examines the new features of this conflict in the modern context. We believe that effective managers must not make binary decisions but become efficient translators and coordinators. Their main objective is to convert sustainable ideas into feasible designs and budgets which can be accepted by all stakeholders. This article offers fresh perspectives and practical methods for design managers who find themselves in this new age.

INTRODUCTION

Design managers are in a special and sometimes difficult middle ground in the design and construction industry. On one hand, they need to be the Creative Advocate, defending the design's integrity, innovation, and the pursuit of superior aesthetics, functionality, and user experience. On the other hand, they must be the Project Constraint Controller, strictly controlling budgets, timelines, scope, and commercial objectives to ensure successful project delivery. The fundamental tension between these two roles is well-documented [2].

Now, the need to develop in a sustainable way has become an industry requirement because of the global climate issues and national policies such as the Dual Carbon targets of China. This change has changed the working environment of design managers fundamentally. They are now required to balance not only the traditional creativity-constraint paradox but also meet new requirements of eco-friendly materials, energy-saving technologies and green building certification. This is practically introducing another powerful role: the Sustainability Driver. The introduction of this new duty makes the current dynamic more complex. Sustainable needs tend to imply greater initial expenditures, longer time frames and technical risks, which immediately conflict with cost-cutting and schedule efficiency objectives. At the same time, the constraints of sustainable design can occasionally seem like a constraint on pure creative play [1].

This conflict is expressed in actual terms. As an example, the design team on a high-end office project might suggest a new low-carbon concrete. Although it is consistent with green principles, this material may be 30 percent more costly and available only to a few suppliers. The design manager has enormous pressure: he can either approve it which would lead to budget overruns and delays or reject it which would endanger the green rating of the project as well as the sustainability brand image of the client. The manager is squarely between two fires [1].

Thus, the present study aims at answering a number of important questions: How does the traditional role conflict of design managers manifest and escalate in the new imperatives of sustainable development? What are its underlying causes? Facing this heightened tension, what can design managers do to balance creative excellence,

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commercial viability, and environmental responsibility? Answering these questions will not only help to understand better the real-world challenges that the profession faces but also provide practical recommendations on how to enhance project outcomes and promote green design practices.

1.Literature Revie

1.1.The Role and Identity of Design Manager

Design management is an interdisciplinary discipline, and the practitioners of this field tend to be in a hybrid or in-between position. It has been found out that design managers are always between the designer and manager identities, creativity and business, vision and practicality. This in-betweenness is both a source of their value-allowing them to cross different professional languages and logics-and a source of stress, which causes role ambiguity and conflict [6]. The professional identity of a design manager is not fixed but it is constantly formed by interactions with various stakeholders depending on the tools, skills and personal experiences of the individual.

More specifically, design managers work on a daily basis in the area of translation. They need to transform the technical language of designers into business value that is comprehensible by clients and transform client budget limitations into specific technical limits to designers. Effective design managers tend to be boundary spanners who are able to create connections between various domains. But as sustainability emerges as an important new dimension, this bridge is put under significant pressure increasing the existing strain of their intermediary role.

1.2.Role Conflict Theory and Its Manifestation in Design

The role conflict theory argues that stress is caused by the existence of incompatible or conflicting expectations among individuals. This conflict is especially acute in design project management. Role conflict was found in design supervision early on and organizational changes were proposed as a mitigation strategy [2]. In green building projects, conflicts are even more multifaceted, occurring at various stages due to misalignment between sub-goals, such as energy performance versus cost targets [1].

The recent studies have concentrated on the issue of conflicts in sustainable projects. As an illustration, a 2021 case study following three LEED-certified projects concluded that more than 60 percent of major design modifications and disputes were related to fulfilling certain sustainability credit criteria [1]. These clashes are not only between clients and contractors but also among design teams where architects, structural engineers, and MEP specialists might have different interpretations and priorities concerning the implementation of green. The choice of design leaders in such situations is complicated by external factors (such as cost perceptions) and internal drivers (personal values and environmental ethos). This complexity is one of the fundamental forms of internalized role conflict; surveys show that most design managers experience considerable stress when their personal sustainability beliefs are in conflict with strict project cost controls [5].

1.3.The New Demands of Sustainable Development

Sustainable development has shifted to become a central force of design practice instead of a peripheral concern. Multi-level, systems-thinking is now recommended in scholarly frameworks regarding sustainable design [3]. As a result, the designer is becoming a change agent [5]. Studies have classified different roles that designers play in promoting sustainability in organizations as internal advocate, practical expert, and systems thinker, indicating that varying capabilities are needed at various organizational maturity levels [4].

This means that design managers should not only promote sustainability but also create the appropriate capabilities in their teams and organizations. This certainly adds to their workload and managerial complexity, with activities such as training teams on new green material standards or developing new sustainable supplier assessment protocols being tasks that go beyond traditional design management duties [3]. Global rating systems like WELL further compound this by expanding the focus from energy to holistic human health factors, requiring design managers to engage with a broader range of scientific parameters and specialist consultants, thereby increasing the interfaces and knowledge domains they must coordinate [1].

To recap, the current literature has looked into design manager identity, role conflict and sustainable design separately. Nevertheless, only a few studies combine all three to systematically examine how sustainability becomes an important contextual variable that transforms and amplifies the traditional role conflict of design managers. This study is aimed at filling that gap.

2.New Manifestations of Dual-Role Conflict Intensified by Sustainability

In the face of sustainable development requirements, the traditional conflict between creativity and constraint is gaining new aspects. The circumstances that cause a conflict, its strength, and complexity have been dramatically increased to become an ever-present and overt theme in all projects [1].

To begin with, conflicts are becoming more and more focused on sustainability-related decisions that require complex and specialized information. A good example is material selection. Low-carbon materials tend to have a cost premium and longer lead times, which directly conflict with budget and schedule goals [1]. The decision is no longer a simple price comparison. Managers need to evaluate "embodied carbon," compare Life Cycle Assessment reports, and consider supply chain locality for certification points. This specialized data requires time to digest, yet clients often demand immediate answers on best value, creating conflict through information asymmetry and time pressure [1].

In the same way, design reviews of improved energy or health standards can also be associated with new technologies that have uncertain risks and maintenance expenses. In this case, the drive to innovate by the Creative Advocate collides head-on with the need to mitigate risk by the Constraint Controller. An example is the choice to implement a new smart shading system to save energy which usually causes controversy because clients are concerned about long term support and maintenance liabilities of software. As one of the design directors interviewed said, we promoted an advanced algorithmic shading system in terms of energy objectives, but the client was busy worrying about the possibility of the software company failing within five years. The negotiations were drawn out as a result of the technological risk being balanced against our sustainability goals.

Second, the cause of conflict has changed into "temporal trade-offs" with inconsistent measures instead of differences in opinion. In traditional conflicts, there was a focus on varying perspectives regarding the immediate value of projects (e.g., aesthetics vs. cost). Sustainability brings about conflicts between short-term project expenditure and long-term environmental/social benefits [3]. It is very difficult to convince a client to invest in a measure that takes 20 years to pay back, as it tests the manager's communication and value-articulation skills.

The main problem is that it is hard to measure the long-term benefits of green certification such as better health of occupants or brand improvement. Although there are tools to compute financial returns, most of the sustainability advantages are considered intangible. Studies have shown that design leaders make their decisions based on a personal evaluation of costs and these long-term values [1]. This value perception gap increases when clients are developers who care about short term rental yields, and the manager becomes a value translator selling a future oriented story to a present focused stakeholder.

Lastly, conflict entails more stakeholders and criteria of evaluation that require new knowledge and challenge the traditional authority. The client-designer-contractor triad is no longer the only one; environmental consultants, certification bodies (e.g., LEED AP), and even the wider society become significant participants. Conflict resolution has to meet changing regulations, certification standards, and social norms instead of merely technical or business sense. Choosing a flooring material, such as checking VOC emissions in order to get WELL certification, and using materials from sustainably managed forests are examples of knowledge areas that might be outside the scope of a typical designer or project manager [1].

Therefore, design managers have to strike a balance between technical, economic, regulatory and social acceptability. This is very hard. They can experience their traditional professional authority being questioned because they will need to depend on and integrate the advice of new sustainability experts yet make final decisions about feasibility and cost impact. This slight change in their role contributes to the load [6].

3.Pathways to Integration: Triadic Synergy Strategies for Design Managers

When faced with the increased demands of sustainability, high-performing design managers do not just pick one or the other. They come up with plans to systematically incorporate the three goals of creativity, constraint and responsibility [5]. This integration is not a static compromise but a dynamic, creative management process.

First, Be a Sustainable Value Translator to combine creativity and responsibility in new communication languages. Good integrators are good at translating abstract green ideas into concrete design language and persuasive business value [3]. They go beyond generic eco-friendly claims, using data (energy simulations, carbon calculations) and experiential demonstrations (showing how healthy materials improve space quality) to convert long-term environmental benefits into immediate user advantages or brand equity.

As an illustration, when suggesting a high-end low-formaldehyde panel they can offer comparison samples to customers so that they can feel the air quality difference or reference studies which associate enhanced indoor air with fewer sick days among employees and related cost savings. This strategy at once gains the support of the Creative Advocate (looking for healthy spaces) and the Constraint Controller (concentrating on total cost-benefit). This requires not only knowledge of sustainability but also the ability of managers to translate it into persuasive stories, skills in interpreting Life Cycle Assessments and communicating technical results in layman terms [1].

Second, Engage in Dynamic Contextual Trade-offs, setting phase-specific decision rules instead of rigid either-or choices. Integration involves dynamically prioritizing the three goals depending on project phase, specific tasks, and stakeholder concerns [1]. Proactive managers establish a clear decision priority framework with key stakeholders at the project outset. In the conceptual design phase, exploration of creative and sustainable vision may take precedence with a more flexible budget. During detailed design, the focus shifts to lock-down, strict control of technical implementation and cost. In procurement, balancing environmental performance, price, and supply stability might involve a weighted sustainability-cost scoring matrix for vendor selection.

This contextual flexibility is an advanced management acumen. It entails the full knowledge of the whole project life cycle and the capacity to assume various lead roles: Explorer/Advocate at the beginning, Controller/Arbiter in the middle, and Coordinator/Ensurer towards the end. Studies indicate that a design manager's identity is formed exactly by passing through such contextual challenges [6]. Explicit phase rules can prevent numerous possible conflicts prior to their occurrence during meetings.

Third, Create a Systematic Collaborative Governance model that would encourage organizational change based on individual dependence to institutional support. The efforts of individuals need to be supported by the organization. Design managers may serve as catalysts towards institutionalizing support in several ways:

Promote cross-functional green project teams that bring together design, cost, engineering, procurement and sustainability consultants right at the start, with set collaboration mechanisms.

Measure sustainability goals and incorporate them into the terms of a contract, e.g. design fee structure based on levels of certification achieved or provisions requiring certain proportions of recycled materials in construction contracts [1].

Create project performance evaluation systems with environmental measures that will make sure that internal KPIs measure energy/water savings and carbon reduction in addition to profit and schedule, thus encouraging sustainable results since the beginning [5].

By streamlining the organizational processes and incentive systems, individual role conflict can be turned into institutionalized collaboration. This is in line with the conventional methods of solving role conflict by organizational adjustment but it has been injected with the new imperative of sustainability [2]. The design manager ceases to be a solitary advocate when sustainability is incorporated into the normal operations of the system and becomes an executor and beneficiary of the system thereby reducing personal pressure.

Conclusion

The research has discussed the conflict and integration of the roles of design managers as the Creative Advocate and Project Constraint Controller in the imperative of sustainable development. The results indicate that sustainability is not an extra role but a major aspect that dramatically transforms the traditional conflict pattern [1]. It renders conflict situations more concrete (based on green decisions), roots deeper (based on trade-offs between temporal values), and solutions more complicated (with the need to coordinate more heterogeneous stakeholders). Design managers are able to work in a triadic force field of creativity, constraint and responsibility with all three vectors pulling at every decision.

To overcome this challenge, design managers need to undergo a fundamental cognitive shift: from a binary either-or mindset to a systemic triadic synergy approach. They must become Translators of Sustainable Value, Masters of Dynamic Contextual Trade-offs, and Architects of Systematic Collaboration. The future core competency profile for design managers must expand beyond traditional design and project management to include systems thinking, lifecycle assessment, sustainability value communication, and multi-stakeholder mediation [3][5]. Correspondingly, educational frameworks in architecture and interior design must evolve to strengthen training in sustainability knowledge, interdisciplinary communication, and complex system management.

The major contribution of this paper is to incorporate the context of sustainable development into the analytical framework of role conflict among design managers, and to propose a model of triadic force field that provides a more contemporary and explanatory view. Moreover, these three integration strategies, value translation, dynamic trade-offs and systematic collaboration are an integrated answer to individual capability to organizational systems, giving practical directions.

This study has a limitation of depending on theoretical analysis and synthesis of the available literature without any primary empirical data based on large-scale surveys or in-depth case interviews. The conflict manifestations and integration strategies that have been discussed here could be further validated through future research by using detailed case studies, behavioral event interviews, or extensive questionnaires. Further exploration of how these dynamics differ across various organizational cultures (e.g., developer, design institute, government agency) and project types (e.g., commercial, healthcare, educational) would give more nuanced insights. Also, it is an interesting new research direction to explore how digital tools (e.g., BIM, carbon calculation software) might alleviate or exacerbate this role conflict [1]. Such detailed work will offer more scientific and accurate advice on the professional development of design managers, organizational design, and industry education.

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Adding Graphene Materials on The Mechanical Properties And Durability Of Concrete

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KEYWORDS

Concrete; graphene oxide;
Shell powder ;
Mechanical properties;
Durability

ABSTRACT

Cement concrete, with its advantages of easy molding, good integrity, and significant economic benefits, is the most widely used building material in the world. However, the disadvantages of cement-based composites, including their inherent brittleness, low tensile strength, and susceptibility to corrosive environments, have always been major concerns. Within this framework, the application of nanomaterials and nanotechnology in cement-based materials has become the most attractive solution . Graphene, as a nanomaterial with a unique two-dimensional structure, offers new insights into improving concrete performance through its nano-filling effect and interfacial reinforcement. This study focuses on exploring the effects of different graphene oxide dosages on the workability, mechanical properties, and economic efficiency of concrete. This paper aims to provide a scientific understanding of the application of graphene materials in cement-based materials to promote their future practical application . The results show that the incorporation of graphene oxide effectively improves the compactness of concrete, reduces water absorption and dehydration rates, and enhances the compressive strength, splitting tensile strength, impermeability, resistance to chloride ion attack, and resistance to wet-dry cycles. The overall performance of concrete reaches its optimal state when the graphene oxide dosage is 0.050% . This study provides data support and theoretical basis for the application of graphene oxide in concrete.

INTRODUCTION

Cement concrete is widely used in civil infrastructure construction around the world due to its ease of molding, significant economic benefits, and excellent compressive strength. Currently, global concrete consumption reaches 30 GT annually, making it the most consumed synthetic material in the world [1]. However, due to the inherent quasi-brittleness of concrete and its tendency to deteriorate in harsh environments, it has always been a focus of scientific attention [2-3] . Moreover, the environmental hazards caused by concrete production are not to be underestimated. According to statistics, the energy consumption required for cement production accounts for 7% of global industrial energy consumption, and every ton of cement produced emits 1 ton of CO_2 into the atmosphere, accounting for 8% of global anthropogenic carbon dioxide emissions [4-5] . Even more worrying is the unavoidable water consumption caused by concrete production. It is estimated that concrete production consumes approximately 18% of global industrial water consumption annually [6] . Therefore, researchers are committed to improving the performance of cement-based materials to reduce the consumption of concrete components. Different types of fibers (including carbon fiber, jute, steel fiber, etc.) have been used in cement-based materials to improve their mechanical properties and durability by controlling the incubation and propagation of microcracks [7-9] . However, the reinforcement obtained by relying on fibers does not change the structure and toughness of the hardened cement matrix, and brittleness and cracking still occur at the nanoscale [10] .

In recent years, significant progress has been made in the application of nanomaterials in the field of concrete,

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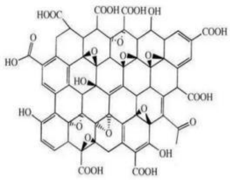
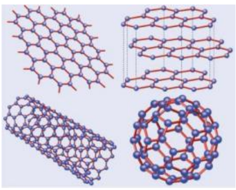
providing new opportunities for improving concrete performance. Graphene's structure can be viewed as a single layer of graphite, with each carbon atom forming covalent bonds with three adjacent carbon atoms through sp^2 hybridization, constituting a hexagonal planar network structure. This structure gives graphene extremely high stability and strength. It is reported that a single layer of graphene is only 0.35 nm thick, yet possesses extremely high mechanical properties (theoretical tensile strength and Young's modulus reach 130 GPa and 1.1 TPa, respectively), thus being considered one of the best nanomaterials for improving the performance of cement-based materials. However, despite the broad application prospects of graphene in concrete, in-depth research is still lacking regarding its specific application in self-compacting concrete with shell powder and its synergistic mechanism with shell powder. Shell powder, as a concrete admixture, can save on concrete costs.[11] Therefore, combining graphene with shell powder and applying it to self-compacting concrete is expected to further improve concrete performance and achieve economic savings. Figure 1 shows graphene.



(a) Chemical bonds in graphene oxide



(b) Graphene structure

Fig.1. graphene

1.Literature Review

At present, graphene nanosheets (GNPs), graphene oxide (GO) and reduced graphene oxide (rGO) are the three main forms that can be used in industrial applications [12]. Related studies have shown that adding a small amount of GNPs can accelerate ion exchange, promote cement hydration reaction, and produce more hydration products; on the other hand, GNPs with high specific surface area can inhibit crack propagation and incubation, so that the cement matrix can obtain better mechanical properties and durability [13]. Wang et al. [14] proved that uniformly distributed GNPs can effectively improve the mechanical properties of cement composites by reducing the stress under external load. Qureshi et al. [15] analyzed and compared the mechanical properties of cement paste with 0.01% to 0.16% of GNPs by weight of cement, and found that 0.02 wt% of GNPs had the best effect on improving the compressive and flexural strength of cement paste, but when the concentration of GNPs in the cement matrix exceeded 0.02 wt%, the improvement effect of cement paste on compressive and flexural strength gradually decreased. Ho et al. [16] studied the effects of different dosages (0.01%, 0.03%, 0.05%, 0.07%, 0.1% and 0.3%) of ultra-large (56±12 mm) GNPs exfoliated by electrochemical peeling on the compressive and tensile strength of cement mortar. The results showed that adding 0.07% GNPs was the optimal dosage, and the compressive and tensile strength of cement-based composites increased by 34.3% and 26.9% respectively after 28 days. This enhancement is mainly attributed to: on the one hand, the incorporation of GNPs increased the hydration degree of cement paste, resulting in the generation of more hydrated calcium silicate gel; on the other hand, the unique barrier effect and filling effect of GNPs increased the penetration path of harmful substances such as water molecules and chloride ions into the cement matrix, which improved the durability of cement-based materials [17-18] . However, due to the strong van der Waals forces between GNPs layers and their own hydrophobicity, GNPs are prone to agglomeration and it is difficult to achieve uniform dispersion in aqueous solutions. Non-uniformly dispersed GNPs not only limit the excellent performance of GNPs, but also cause the deterioration of the performance of cement-based materials.

As a derivative of graphene, graphene oxide (GO) has abundant oxygen groups (hydroxyl, epoxy, etc.) on its basal surface, which makes GO highly hydrophilic. In addition, the high density of oxygen-containing functional groups can promote the activation reaction of mineral components in cement and accelerate the hydration of cement [19]. Studies have shown that the nucleation effect of GO can promote the early hydration reaction of cement, generate more CSH to provide a dense microstructure, and improve the mechanical properties and durability of cement matrix to varying degrees [20-24] . In order to understand the reasons for the improvement of mechanical properties of GO and the strengthening mechanism, researchers have devoted themselves to the study of the hydration process, microstructure and composition of GO-based cement composites. Zhao et al. [25] showed that the compressive strength of GO-reinforced cement mortar increased by 34.1%, 26.9% and 22.6% after 3 days, 7 days and 28 days of hydration, respectively. In addition to the early stage of cement hydration, contradictory microstructure characterization results and various possible strengthening mechanisms of GO in cement composites have also been reported in the literature. The aforementioned scientists' research on graphene materials shows that, when graphene is incorporated into concrete mixtures, it can improve the mechanical properties and durability of concrete, inhibit crack propagation, and significantly reduce the porosity of the cement skeleton.

2.Experimental Design

2.1.Experimental Materials

Cement: P·O R45 cement, main chemical composition shown in Table 1, physical and mechanical properties shown in Table 2; Water: laboratory tap water; Sand: natural river sand, meeting the standard for construction sand, bulk density less than 1.5 g/m3, fineness modulus of 1.9, moisture content less than 1%; Stone: gravel , bulk density not less than 2.6 g/m3, particle size between 5 mm and 7 mm; the graphene oxide used in the research has a spacing of less than 1 nm , as shown in Figure 2. Shell: calcined and crushed, particle size less than 0.5 mm, bulk density less than 2.9 g/m3, fineness modulus of 2.9, moisture content less than 1%, as shown in Figure 3. The water-reducing agent selected is a polycarboxylate-based high-efficiency water-reducing agent that meets the requirements of "Concrete Admixtures" (GB 8076-2008) .

Table.1. Main components of cement (%)

Ca O	SiO_2	Al2O3	Fe2O3	SO3	Na 2 O	K_2O	M gO
6 4.12	2 2.31	6.42	4.37	1.1	0.75	0.56	0.37

Table.2 . Physical and mechanical properties of cement

Standard consistency water requirement /%	Specific surface area / (m^2 / kg)	Condensation time/min		Compressive strength / MPa		Flexural strength / MPa	
		Initial condensation	Final Condensation	3 d	28 days	3 d	28 days
2 8	3 60	1 75	2 35	2 7.5	4 9.0	5.5	8.0

Fig.2. Graphene used in the experiment

2.2.Experimental Proportions

To explore the effects of graphene oxide (GO) on concrete, this study designed a concrete mix proportion as follows : cement :shell powder: water : fine aggregate : coarse aggregate : water-reducing agent = 400 : 100 : 180 : 820 : 1020 : 6 (kg/m³ ）. In the mix design, the cementitious material consisted of cement and mineral powder, with the mineral powder serving as a partial substitute for cement, representing 25% of the total cementitious material. To investigate the effect of GO on concrete performance, four mix proportions were designed with GO dosages of 0% , 0.025% , 0.050% , and 0.075 % of the total cementitious material, corresponding to dosages of 0 , 0.125 , 0.250 , and 0.375 kg/m³ ， respectively defined as GO-00 , GO-25 , GO-50 , and GO-70 . In addition, a fixed water-to-cement ratio of 0.36 is used to achieve the best balance between strength and workability.

2.3.Test Methods

To determine the practical building performance and mechanical properties of graphene oxide concrete, we need to conduct slump, mechanical properties , and durability tests on the specimens to obtain relevant data and analyze its related mechanical properties.

The workability of the concrete mixture is determined according to the "Technical Specification for Application of Self-Compacting Concrete" (JGJ/T 283-2012), with slump flow used to characterize rheology. The operating procedure is as follows: Fresh concrete is poured into a standard slump cone; after vertically lifting the cone, the maximum flow diameter of the static concrete is measured (accurate to 5 mm); the self-compacting grade is determined based on the diameter value (>650 mm is the highest grade, 550-650 mm is suitable for pumping).

For mechanical property testing, compressive strength and splitting tensile strength were conducted according to the "Standard for Test Methods of Physical and Mechanical Properties of Ordinary Concrete" (GB/T50081-2019) .

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Compressive strength testing used 100mm × 100mm × 100mm cube specimens, while splitting tensile strength testing used ∅ 100mm × 200mm cylindrical specimens. After curing under standard conditions for 7, 28 , and 90 days, the specimens were subjected to loading tests using a hydraulic universal testing machine, and the corresponding strength values were recorded.

The water absorption-dehydration test was conducted according to the "Standard for Test Methods of Long-Term Performance and Durability of Ordinary Concrete" (GB/T50082-2009) . After curing, the concrete specimens were sealed with paraffin wax on their top and bottom surfaces, with the sides serving as reserved water absorption surfaces. The specimens were placed in a humid environment and weighed at regular intervals (e.g., 0.5-48 hours) to record the changes in water absorption mass. After the water absorption test, a dehydration test was conducted in a drying oven to observe the changes in mass of the specimens during the drying process. In the wet-dry cycle test, the specimens were placed in a 3% sodium chloride solution and underwent alternating drying and wetting processes. After the wet-dry cycle was completed, the ultrasonic pulse velocity (UPV) test was performed, and the UPV change rate was calculated. The calculation is shown in formula (1) . After the wet-dry cycle was completed , a 0.10 % concentration silver nitrate solution was sprayed onto the surface of the specimens. The silver chloride generation area (white) and the unreacted area (brown) formed a clear boundary line. The penetration depth of chloride ions was determined by measuring the depth of the white area. The rapid chloride ion penetration test adopts the ASTM C1202-12 standard , using a cylindrical specimen of ∅ 100mm × 50mm , with an applied voltage of 60V for 6 hours . The resistance of concrete to chloride ion erosion is evaluated by measuring the total amount of electricity applied (coulomb value).

$$\text{UPV change rate} = \frac{\text{Initial UPV value} - \text{UPV value after cycle}}{\text{Initial UPV value}} \qquad (1)$$

Corrosion resistance testing was conducted using accelerated corrosion testing. The specimen was a 100mm × 200mm cylinder with embedded reinforcing steel bars, immersed in a 3% NaCl solution, and subjected to a 30V DC current. The time it took for the concrete to crack due to steel bar corrosion was recorded. In addition, to assess the concrete's resistance to chloride ion attack, the penetration depth of chloride ions in the concrete was measured by spraying a 0.10 equivalent concentration of silver nitrate solution. Throughout the corrosion process, the half-cell potential of the specimen was measured every 24 hours for further analysis of its corrosion resistance.

3.Results and Discussion

3.1.Performance

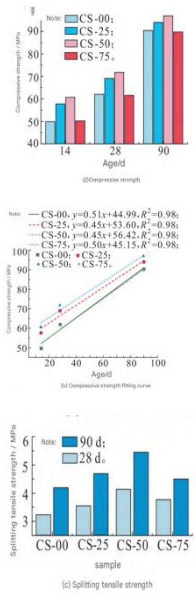
The slump spread test results of concrete with different graphene oxide (GO) dosages are shown in Table 1. With increasing GO dosage, the flowability of the concrete initially increased slightly and then gradually decreased. The flowability reached its maximum value (approximately 720 mm) when the GO dosage was 0.050%, indicating that an appropriate amount of GO can improve the rheological properties of the paste in synergy with water-reducing agents. This is mainly attributed to the dispersing effect of oxygen-containing functional groups on water molecules and cement particles on the GO surface. When the dosage increased to 0.075%, the flowability decreased due to enhanced interactions between GO layers and increased paste viscosity, but it still met the construction requirements for self-compacting concrete (>550 mm).

Group	GO parameters (%)	Collapse spread (mm)	Liquidity rating
G0-00	0	680	SF2
G0-25	0.025	700	SF2
G0-50	**0.050**	**720**	**SF3**
G0-75	0.075	650	SF2

Table.3. Workability of concrete with different GO content

3.2.Mechanical Properties

Figure 3 and Table 2 shows the changes in compressive strength and splitting tensile strength of concrete at 7 days, 28 days, and 90 days under different GO dosages. Overall, the addition of GO significantly improved the early and long-term strength of concrete. When the GO dosage was 0.050%, the 28-day compressive strength increased by approximately 18.6% compared to the control group (GO-00), and the splitting tensile strength increased by approximately 22.4%. The main mechanisms of strength improvement include: filling effect: GO nanosheets can fill the micropores in cement paste, improving matrix density; nucleation effect: the abundant functional groups on the GO surface promote heterogeneous nucleation of hydration products (CSH), accelerating the hydration process; bridging and crack-inhibiting effect: GO forms a two-dimensional network between microcracks, inhibiting crack propagation and enhancing the toughness of the material. It is worth noting that when the GO dosage exceeds 0.050%, the strength growth trend slows down and even slightly declines, which may be related to local defects caused by GO agglomeration.



Group	GO content (%)	Compressive strength (MPa)			
		7 days	28 days	90 days	Remark
GO-00	0.000	32.5	45.0	48.2	
GO- 25	0.0 25	35.2	49.8	52.1	
GO- 50	0.0 50	**38.1**	**53.4**	**55.8**	
GO- 75	0.075	37.2	51.9	54.3	

Group	GO content (%)	Splitting compressive strength (MPa)			
		7 days	28 days	90 days	Remark
GO-00	0.000	2.8	3.5	3.7	
GO- 25	0.0 25	3.1	3.9	4.0	
GO- 50	0.0 50	**3.4**	**4.3**	**4.4**	
GO- 75	0.075	3.2	4.1	4.2	

Note: Bold data represents the optimal values (GO-50 group).

Table.4. Effect of different GO dosages on the mechanical properties of concrete

3.3.Durability

3.3.1.Water absorption and dehydration behavior

Table 3. shows the water absorption rate of concrete with different GO admixtures over time . With increasing GO admixture, both the water absorption rate and saturated water absorption rate of the concrete decreased significantly. The 48-h water absorption rate of the GO-50 group was approximately 34% lower than that of the control group, indicating that GO effectively filled the capillary channels and hindered water transport. Dehydration tests further confirmed that GO-modified concrete also experienced a slower water loss rate, which is beneficial for maintaining stable internal humidity in alternating wet and dry environments and reducing the risk of shrinkage cracking.

Time (h)	GO-00 (0%)	GO-25 (0.025%)	GO- 50 (0.050 %)	GO- 7 5 (0.0 7 5%)
0.5	1.2	1.0	0.8	0.9
1	1.8	1.5	1.1	1.3
2	2.5	2.0	1.5	1.8
4	3.2	2.6	1.9	2.2
8	4.0	3.2	2.3	2.7
twenty four	5.1	4.0	2.9	3.4
48	**5.8**	**4.5**	**3.4**	**3.9**

Note: 48-hour data show that the water absorption rate of the GO-50 group was reduced by approximately 41.4% compared to the control group (GO-00).

Table.5.showing the change in water absorption rate of concrete with different GO admixtures over

3.3.2.Resistance to chloride ion corrosion

The total charge flux measured by the rapid chloride ion penetration test (ASTM C1202) is shown in Table 4. The addition of GO significantly reduced chloride ion permeability; the charge flux of the GO-50 group was only about 42% of that of the control group. The silver nitrate spray test also showed that the chloride ion penetration depth decreased significantly with increasing GO dosage. This indicates that the dense microstructure and hydrophobic barrier formed by GO effectively prolong the penetration path of the corrosive medium.

Group	GO content (%)	Total power consumption (coulombs)	Standard deviation
GO-00	0.000	3250	±120
GO- 25	0.0 25	2100	±95
GO- 50	**0.0 50**	**1350**	**±80**
GO- 75	0.075	1800	±90

*Note: The GO-50 group (0.050%) had the lowest total charge, which was about 58.5% lower than the control group (GO-00).

Table.6. Results of rapid chloride ion penetration test (total electrical charge) for concrete with different GO admixtur

3.3.3.Resistance to wet and dry cycling

After 30 wet-dry cycles, the change rate of ultrasonic pulse velocity (UPV) of each group of specimens is shown in Table 5. The GO-50 group had the lowest UPV change rate (only about 1.8%), indicating that its internal structure suffered the least damage during the cycle. Scanning electron microscopy (SEM) observation (Table 6.) revealed that the cracks in the GO-modified specimens were smaller and more dispersed, further confirming the inhibitory effect of GO on the development of microcracks.

Group	GO content (%)	UPV change rate (%)
GO-00	0.000	4.2
GO- 25	0.0 25	2.8
GO- 50	**0.0 50**	**1.8**
GO- 75	0.075	2.5

*Note: The GO-50 group had the lowest UPV change rate (1.8%), indicating that it had the best resistance to wet-dry cycling.

Table.7. Change rate of ultrasonic pulse velocity (UPV) after wet-dry cycles in concrete with different GO admixtures

Group	GO content (%)	Image description
GO-00	0.000	Numerous capillary pores are visible, indicating a loose CSH gel structure with microcracks.
GO- 25	0.0 25	The number of pores is reduced, the CSH gel is more dense, and a small number of GO sheets are visible dispersed within it.
GO- 50	0.0 50	The structure is extremely dense with very few pores. GO sheets are evenly distributed and bridged between hydration products, forming a continuous network.
GO- 75	0.075	The structure is relatively dense, but slight GO aggregation is visible in some areas, forming a few weak interfaces.

Table.8.comparison of scanning electron microscope (SEM) images of concrete.

3.3.4.Resistance to wet and dry cycling

Accelerated corrosion tests showed that the addition of GO significantly prolonged the corrosion induction period of steel reinforcement. The cracking time in the GO-50 group specimens was delayed by approximately 2.3 times compared to the control group. Half-cell potential monitoring revealed that the corrosion potential of the steel reinforcement in GO-modified concrete remained consistently at a positive level, indicating a more stable passivation film.

3.4.Economic and Environmental Benefits Analysis

Although the addition of GO increases material costs, its extremely low dosage (0.050% produces a significant strengthening effect) and ability to partially replace cement and improve concrete durability extend the service life of structures and reduce maintenance costs. The synergistic use of shell powder further reduces cement usage, aligning with resource conservation and low-carbon development principles. Preliminary life-cycle assessments indicate that GO-shell powder composite modified concrete offers superior economic and environmental benefits over a 30-year service life.

Conclusion

This study systematically investigated the effects of graphene oxide (GO) combined with shell powder on the workability, mechanical properties, and durability of self-compacting concrete. The main conclusions are as follows: 1. The incorporation of GO significantly improves the compactness and early strength development of concrete. When the dosage is 0.050%, the 28-day compressive strength and splitting tensile strength of concrete increase by 18.6% and 22.4%, respectively, while still meeting the self-compacting requirements . 2. GO effectively inhibits the initiation and propagation of microcracks through filling, nucleation, and bridging effects, thereby improving the concrete's impermeability, resistance to chloride ion attack, and resistance to wet-dry cycles . 3. The synergistic effect of GO and shell powder not only enhances the mechanical and durability properties of concrete but also reduces cement usage, demonstrating good resource conservation and environmental friendliness . Considering both performance improvement and economic feasibility, a GO dosage of 0.050% is the optimal choice, suitable for marine environments, saline soil areas, and critical infrastructure projects where high durability is required.

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Cultivation of Teaching Competence among Students Majoring in Physical Education in Regular Universities

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KEYWORDS

Regular Universities;

Physical Education Major;

Teaching Competence;

Practical Teaching

ABSTRACT

As the core base for training physical education teachers in primary and secondary schools, the level of teaching competence of students majoring in Physical Education (PE) in regular universities is directly related to the quality of PE teaching in basic education and the implementation effect of the "Healthy China" strategy. This paper adopts the methods of literature research, questionnaire survey and case analysis to focus on the current situation of cultivating teaching competence of PE majors in regular universities, and analyzes the prominent problems in curriculum setting, practical teaching, teaching staff and other aspects. Based on this, targeted cultivation strategies are proposed from four dimensions: optimizing the curriculum system, strengthening practical links, constructing a "university-local government cooperation" cultivation mechanism, and improving the evaluation system. The purpose is to provide theoretical reference and practical support for enhancing the teaching competence of PE majors, and help cultivate high-quality PE talents that meet the requirements of the new era.

INTRODUCTION

With the in-depth implementation of the "Healthy China 2030" Planning Outline and the "Double Reduction" policy, the importance of PE in primary and secondary schools has become increasingly prominent, and higher requirements have been put forward for the professional quality and teaching competence of PE teachers. Regular universities' PE majors assume the important mission of providing qualified PE teachers for basic education, and the quality of their talent training directly determines the implementation effect of PE teaching in primary and secondary schools. As the core competitiveness of PE majors, teaching competence is a multi-dimensional integrated ability system, which not only includes the basic ability of sports skills imparting, but also covers curriculum design, classroom management, learning situation analysis, evaluation and feedback, and extends to the ability of integrating information technology into teaching, guiding students with special physical conditions, and organizing campus sports activities. Specifically, curriculum design ability requires students to formulate teaching plans in line with students' physical and mental development characteristics; classroom management ability involves maintaining teaching order and creating a positive interactive atmosphere; and the ability to use information technology means such as sports video analysis software and intelligent fitness equipment has become a new requirement for modern PE teachers. However, the talent training model of some universities' PE majors is disconnected from the needs of basic education, and the effect of cultivating students' teaching competence is not satisfactory, resulting in problems such as "being good at sports but not good at teaching" and "strong in theory but weak in practice". Therefore, systematically sorting out the existing problems in the cultivation of teaching competence of PE majors and exploring scientific and effective cultivation paths are of great practical significance for promoting the reform of PE majors and improving the quality of talent training.

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1.Significance of Cultivating Teaching Competence of PE Majors in Regular Universities

The cultivation of teaching competence of PE majors in regular universities is an inherent requirement for implementing the educational policy of "simultaneous development of five educations" (moral, intellectual, physical, aesthetic and labor education) and a core task for the development of PE majors themselves. From the perspective of basic education needs, PE teaching in primary and secondary schools in the new era has shifted from traditional "skill impartment" to "core literacy cultivation", requiring PE teachers not only to demonstrate standard movements, but also to design interesting and life-oriented teaching content according to students' age characteristics, and guide students to form lifelong sports habits. This requires universities' PE majors to focus on cultivating students' teaching competence based on the needs of basic education, ensuring that graduates can quickly adapt to teaching positions. From the perspective of students' personal development, solid teaching competence is a "passport" for PE majors to obtain employment and a core support for their future career development. In the context of increasingly fierce competition in the job market, students with strong teaching competence are often more favored by primary and secondary schools, and they also have broader room for career promotion. From the perspective of industry development, the improvement of teaching competence of PE majors helps to promote the overall quality upgrading of the PE education industry and provide talent guarantee for the implementation of the "Healthy China" strategy in the basic education stage.

2.Existing Problems in Cultivating Teaching Competence of PE Majors in Regular Universities

To accurately grasp the current situation of cultivating teaching competence of PE majors in regular universities, this paper conducted a questionnaire survey and in-depth interviews with students of grades 2020 and 2021 majoring in PE in 5 provincial universities and 30 professional teachers. The survey results show that there are many urgent problems in the current cultivation of teaching competence of PE majors, which are specifically manifested in the following four aspects.

2.1.Disconnection between Curriculum Setting and Teaching Needs

The disconnection between curriculum setting and teaching needs is the primary problem. On the one hand, theoretical courses are separated from practical application. Core theoretical courses such as "Theory of Physical Education Teaching" and "School Physical Education" are mostly taught in the form of classroom lectures, with abstract and boring content. Students find it difficult to combine theoretical knowledge with teaching practice, leading to the phenomenon of "separation between learning and application". The questionnaire survey shows that 68% of students believe that "theoretical courses are not practical, and they don't know how to apply them to actual teaching". On the other hand, the update of curriculum content is lagging behind. The curriculum of PE majors in some universities still focuses on the teaching of traditional sports events, with insufficient coverage of emerging sports events (such as rock climbing, skateboarding, physical fitness training), health education knowledge and information-based teaching skills, which is inconsistent with the innovative needs of PE teaching content in primary and secondary schools. In addition, the curriculum structure is unbalanced, with a too high proportion of sports skills courses, while the proportion of targeted courses such as curriculum design, classroom management and physical education for special students is insufficient, resulting in unbalanced development of students' teaching competence.

2.2.Weak Practical Teaching Links

Weak practical teaching links are the core crux. Firstly, the duration of practical teaching is insufficient. The proportion of practical courses in PE majors of some universities is only about 25%, which is far lower than the requirement of the Ministry of Education that "practical credits shall not be less than 30% of the total credits", so students lack sufficient classroom practice opportunities. Secondly, the form of practical teaching is single, mostly focusing on "simulated teaching". Students carry out teaching drills in virtual scenarios, and it is difficult for them to be exposed to complex situations in real classrooms, such as students' inattention and large differences in sports ability, which greatly reduces the practical effect. Thirdly, the quality of educational practice is not high. The construction of practice bases in some universities is not perfect, and the practice arrangement is a mere formality. Students are mostly engaged in "auxiliary management" and lack the opportunity to teach independently. At the same time, the communication between university supervisors and practice supervisors in primary and secondary schools is insufficient, and the supervision and guidance of students' practice process are not in place, making it difficult to improve students' teaching competence in a targeted manner. In the interview, 72% of intern students said that "the number of independent teaching sessions during the internship is less than 5", and 65% of practice supervisors in primary and secondary schools believe that "the classroom management ability of interns needs to be improved urgently".

2.3.Insufficient Practical Teaching Ability of the Teaching Staff

Insufficient practical teaching ability of the teaching staff is an important restrictive factor. At present, some teachers of PE majors in universities are mostly "former athletes", who have solid sports skills but lack front-line teaching experience in primary and secondary schools. It is difficult for them to guide students in combination with actual teaching scenarios, leading to "empty talk" in teaching guidance. The questionnaire survey shows that 58% of students believe that "professional teachers lack teaching practice experience and their guidance is not targeted". In addition, university teachers are burdened with heavy scientific research tasks and pay insufficient attention to the reform trends of PE teaching in basic education, making it difficult for them to integrate the latest teaching concepts and methods into classroom teaching, resulting in the disconnection between the teaching guidance received by students and the reality of basic education. At the same time, some teachers still adopt traditional teaching methods, mainly "cramming" teaching, ignoring students' subjectivity and creativity, which is not conducive to cultivating students' teaching innovation ability.

2.4.Imperfect Evaluation System

An imperfect evaluation system is a key shortcoming. At present, the evaluation of students' teaching competence in university PE majors is mostly "result-oriented", focusing on terminal links such as final exams and simulated teaching demonstrations, while ignoring the attention to the formation process of students' teaching competence. The evaluation content is also one-sided, overemphasizing the assessment of sports skills and theoretical knowledge, while the evaluation weight of core teaching abilities such as curriculum design, classroom interaction and evaluation feedback is insufficient. In addition, the evaluation subject is single, with university teachers as the only evaluators, lacking the participation of multiple subjects such as front-line teachers in primary and secondary schools and students themselves. The evaluation results cannot fully reflect the actual teaching competence of students. This single and result-oriented evaluation system easily leads students into the misunderstanding of "valuing scores over abilities", which is not conducive to the comprehensive improvement of their teaching competence.

3.Optimization Paths for Cultivating Teaching Competence of PE Majors in Regular Universities

In response to the above problems, combined with the talent training laws of university PE majors and the needs of basic education, this paper constructs a teaching competence cultivation system for PE majors from the following four dimensions to improve the quality of talent training.

3.1.Optimize the Curriculum System to Lay a Foundation for Teaching Competence

Optimizing the curriculum system is the foundation for improving students' teaching competence. Universities should break the curriculum pattern of "separation between theory and practice" and build an integrated curriculum system of "theory-skill-practice". In terms of curriculum content, on the one hand, strengthen the practicality of core theoretical courses, combine courses such as "Theory of Physical Education Teaching" and "School Physical Education" with real teaching cases in primary and secondary schools, and adopt "case teaching method" and "situational teaching method" to guide students to transform theoretical knowledge into practical teaching ability. For example, when teaching the "curriculum design" module, teachers can take the PE curriculum of local key primary schools as a sample, guide students to analyze the design ideas and optimize the plan. On the other hand, add characteristic courses such as emerging sports events, health education and information-based teaching, and introduce the use of intelligent PE teaching equipment and the production of online teaching resources to meet the innovative needs of

PE teaching in primary and secondary schools. It is particularly necessary to set up specialized courses on digital teaching tools, such as teaching students to use Kinovea sports video analysis software to correct students' movement postures, and use online platforms to design flipped classrooms for PE theoretical knowledge learning. In terms of curriculum structure, reasonably adjust the course proportion, reduce the proportion of single sports skills courses, and increase targeted courses such as curriculum design, classroom management and physical education for special students to ensure the balanced development of students' teaching competence. For example, a university in Shandong Province added courses such as "Primary and Secondary School PE Curriculum Design Workshop" and "Handling of Emergencies in PE Classrooms" for its PE major, which increased the students' practical teaching ability score by 23%.

3.2.Strengthen Practical Links to Improve the Ability of Teaching Application

Strengthening practical teaching links is the core of improving students' teaching competence. Universities should build a "hierarchical and progressive" practical teaching system to gradually improve students' teaching competence from basic practice to comprehensive practice. Firstly, increase the duration of practical teaching, raise the proportion of practical courses to more than 35%, and offer "Basic Training of Teaching Skills" courses for freshmen and sophomores to consolidate students' basic teaching skills through micro-teaching and simulated teaching. For juniors and seniors, strengthen the educational practice link and extend the practice duration to more than 16 weeks to ensure that students have sufficient opportunities for independent teaching. Secondly, innovate the form of practical teaching, and establish a dual-scenario practical model of "on-campus simulated classroom + off-campus real classroom". On campus, carry out targeted training relying on simulated classrooms; off campus, establish "practical teaching bases" in cooperation with primary and secondary schools, and organize students to regularly participate in activities such as classroom observation and auxiliary teaching. Thirdly, improve the quality of practice, establish a dual-tutor system of "university supervisor + primary and secondary school practice supervisor", and clarify the responsibilities of both parties. University supervisors focus on theoretical guidance and process supervision, while primary and secondary school supervisors focus on practical teaching guidance. At the same time, establish a practice assessment mechanism, and include the number of independent teaching sessions of students and teaching effect feedback into the assessment indicators to ensure the practical effect.

3.3.Construct a University-Local Government Cooperation Mechanism to Gather Cultivation Synergy

Constructing a "university-local government cooperation" cultivation mechanism is an important guarantee for improving students' teaching competence. Universities should take the initiative to establish in-depth cooperative relations with local educational administrative departments and primary and secondary schools, and form a cultivation mechanism of "joint talent training, resource sharing and joint responsibility". On the one hand, jointly build a "PE Teacher Development Community", invite excellent PE teachers from primary and secondary schools to participate in the curriculum design and teaching guidance of universities, and pass on front-line teaching experience to students through forms such as "famous teacher lectures" and "demonstration lessons". At the same time, organize university teachers to conduct research and teaching practice in primary and secondary school classrooms to improve their own practical teaching ability. On the other hand, carry out "order-based" talent training, and jointly formulate talent training programs with cooperative schools according to the PE teaching needs of local primary and secondary schools to train PE teachers who meet the local teaching needs. For example, a university in Jiangsu Province established cooperative relations with 10 local primary and secondary schools to carry out "university-local government cooperation" training. The employment rate of its PE majors has reached more than 95% for three consecutive years, and 80% of the graduates have received praise from employers. In addition, introducing international advanced experience can provide new ideas for cooperation mechanisms. For instance, the "school-university partnership" model in the United Kingdom encourages universities to send PE majors to participate in the daily teaching management of partner schools, and schools provide feedback on students' performance to adjust the university's teaching content in a timely manner. This two-way interaction model can effectively narrow the gap between university training and practical needs.

3.4.Improve the Evaluation System to Strengthen the Cultivation Orientation

Improving the evaluation system is an important orientation for improving students' teaching competence. Universities should build a comprehensive evaluation system that "combines process-oriented evaluation and result-oriented evaluation, and involves multiple subjects". In terms of evaluation content, refine the evaluation indicators of teaching competence, covering multiple dimensions such as curriculum design, teaching implementation, classroom management, evaluation and feedback, and learning situation analysis, among which the evaluation weight of practical teaching ability is not less than 50%. In terms of evaluation methods, strengthen process-oriented evaluation, and comprehensively record the development process of students' teaching competence through various forms such as classroom performance, practical assignments, internship logs and teaching reflections. At the same time, introduce result-oriented evaluation, and comprehensively assess students' teaching competence based on internship teaching assessment and graduation teaching demonstration. In terms of evaluation subjects, build a multi-evaluation team of "university teachers + primary and secondary school teachers + students". University teachers focus on the evaluation of theory and skills, primary and secondary school teachers focus on the evaluation of practical teaching, and students reflect on their own shortcomings through self-evaluation and mutual evaluation to ensure that the evaluation results are objective and comprehensive.

4.Conclusion and Prospect

The cultivation of teaching competence of PE majors in regular universities is a systematic project that requires the joint efforts of universities, local educational administrative departments and primary and secondary schools. At present, the cultivation of teaching competence of PE majors still faces problems such as disconnected curriculum setting, weak practical links, insufficient teacher ability and imperfect evaluation system. Therefore, universities should base themselves on the needs of basic education, and comprehensively improve students' teaching competence through measures such as optimizing the curriculum system, strengthening practical teaching, constructing a "university-local government cooperation" mechanism and improving the evaluation system. It is worth noting that with the development of the "Internet + Education" model, the integration of digital technology and PE teaching has become an inevitable trend. Universities should further promote the construction of digital teaching resources, such as developing virtual simulation teaching platforms for PE skills, so that students can conduct repeated training of complex movements in a virtual environment. At the same time, strengthening the cultivation of students' cross-cultural communication ability is also of great significance for absorbing advanced international PE teaching concepts. In the future, it is necessary to further deepen the reform of PE majors, introduce technologies such as artificial intelligence and big data, innovate the training model of teaching competence, and provide more high-quality PE teachers who are "good at teaching, skilled in teaching and willing to teach" for basic education, so as to provide a solid guarantee for the implementation of the "Healthy China" strategy and quality-oriented education.

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Factors Influencing Chinese Students' Physical Exercise Behavior —A Qualitative Systematic Literature Review

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KEYWORDS

College students;
Physical exercise;
Personal factors;
Environmental factors;
Sociocultural factors

ABSTRACT

The purpose of this study is to identify the main factors influencing college students' physical exercise behavior and to analyze their interrelationships using a bibliometric approach. A total of 189 scientific publications on students' sports behavior indexed in the CNKI database from 2001 to 2024 were selected as the research material. Using CiteSpace software, trends in publication output, major research themes, and the structural framework of influencing factors were systematically analyzed. The results indicate that college students' physical exercise behavior is shaped by a complex interaction of personal, environmental, and sociocultural factors. Intrinsic motivation, self-efficacy, and awareness of the value of physical activity play a leading role in sustaining regular participation in exercise, while individual differences and physical condition determine the intensity and stability of exercise behavior. In addition, the accessibility of sports infrastructure, social support, and the sociocultural environment provide essential external conditions for students' engagement in physical activity. These findings highlight the necessity of adopting a comprehensive approach to fostering sustainable physical exercise behavior within higher education systems

INTRODUCTION

Against the backdrop of the in-depth advancement of the "Healthy China 2030" strategy, college students, as the core force for the future development of the country, have seen their physical health status become an important dimension for evaluating the quality of higher education [1]. Although there is a broad consensus on the positive role of physical exercise in promoting physical health, psychological adjustment and personality development, the physical fitness level of Chinese college students is still facing the severe challenge of fluctuating decline, and phenomena such as sedentary lifestyle and lack of regular exercise are still prevalent [2]. Although previous studies have explored the causes of sports behavior from different perspectives, most of them focus on the empirical analysis of single factors and lack a systematic review of the long-term evolution trend and integration of macro-dynamic mechanisms in this field. Based on this, this study relies on the CNKI database to conduct an in-depth search of 189 scientific research articles on college students' physical exercise behavior from 2001 to 2024, and uses CiteSpace visualization software for quantitative analysis and qualitative review. This paper aims to objectively reveal the internal logic and external constraints of college students' participation in physical exercise by constructing a three-in-one influence framework of personal factors, environmental factors, and socio-cultural factors. This not only provides empirical evidence for improving the reform of college physical education and enhancing the effectiveness of sports facilities, but also provides scientific theoretical guidance and policy reference for promoting college students to develop sustainable

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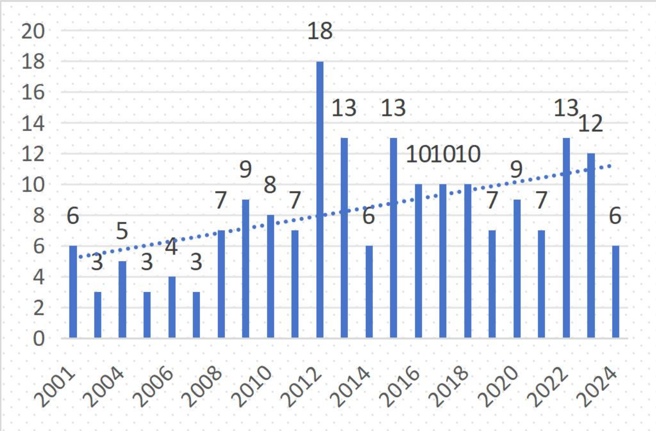
lifelong sports habits.

1.Research Concept and Methods



This study employed bibliometric analysis to systematically examine 189 scientific articles on college students' sports behavior indexed in the CNKI (China National Knowledge Infrastructure) database from 2001 to 2024. The publication trend chart (Figure 1), created using CiteSpace software, shows that research in this field has evolved from an initial stage to continuous development, demonstrating an overall gradual growth trend, reflecting the increasing attention paid by the academic community to the issue of college students' sports behavior. As a result of the systematic review and synthesis of the literature, it was found that the factors influencing college students' sports behavior are multidimensional and complex, primarily classified into three types: personal factors, environmental factors, and socio-cultural factors (Figure 2). Based on this, the paper will proceed with further analysis and discussion of the corresponding research findings in these three areas.

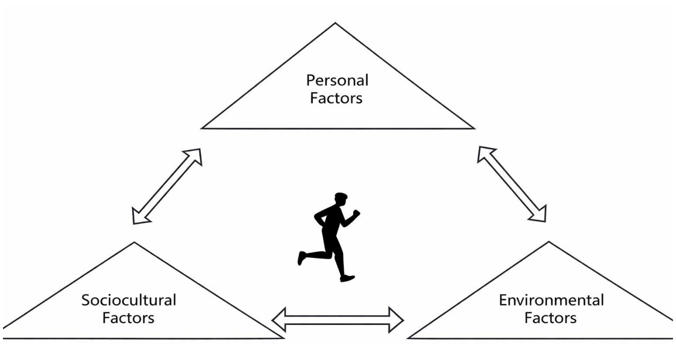


Fig.1. Number of Publications in CNKI from 2001 to 2024

Fig2. Three-Factor Diagram of Interrelationships

2.Research Content

2.1.Personal Factors

2.1.1.Motivation for Physical Activity and Psychological Cognition

Numerous studies have shown that the onset and continuation of physical activity among college students are primarily limited by their internal psychological factors, among which motivation for sports, level of interest, and perception of the value of physical exercise are considered the most important influencing variables. Mao Hao de (2024) in his study on college students' participation in sports noted [3] that a significant number of college students do not take the initiative in their sports activities, mainly because they lack an understanding of the long-term value of physical exercise for strengthening physical and mental health. They regard physical activity as a way to cope with academic pressures or as a short-term activity, which hinders the formation of sustainable exercise habits. Students with low awareness of physical exercise are more likely to abandon it under academic pressure or lack of time.

From the perspective of sports motivation, intrinsic motivation has a significant positive predictive impact on college students' sports behavior. Cheng Sixuan (2024) in her study of female college students' participation in basketball found [4] that interest is the key factor influencing their sports participation. When students are personally interested in sports and experience positive emotional feelings, the frequency and duration of their participation significantly increase; conversely, if participation in sports is mainly driven by external requirements (such as course grades and physical fitness tests), their sports behavior is often passive and gradual. A sports experience lacking enjoyment and a sense of achievement can weaken sports motivation in college students and even provoke avoidance of sports [5].

Moreover, self-efficacy and body image play an important mediating role in college students' sports behavior. Studies have shown that college students with high self-efficacy in sports generally have a positive evaluation of their sports abilities, are more willing to participate in sports events, and try different types of sports; while students with low self-efficacy often reduce their participation due to fear of failure or judgment from others. Some college students experience significant psychological pressure when participating in sports events at public sports venues due to anxiety about body shape or lack of confidence in their physical abilities, which affects the formation of sports behavior [6]. This suggests that college students' sports behavior is not only limited by objective conditions but is also closely linked to their psychological perceptions and emotional experiences.

2.1.2.Motivation for Physical Activity and Psychological Cognition

Individual differences such as gender, academic year, physical fitness, and sports skills significantly influence college students' sports behavior. Existing studies generally consider gender differences to be one of the most stable variables affecting college students' sports participation behavior [7]. Results from numerous surveys show that male students are generally more active in sports than female students, while female students typically choose sports of low and moderate intensity with high recreational value. Huang Chunhua (2018) in her study of female college students' participation in basketball noted that the overall proportion of female students engaging in basketball is low, mainly due to factors such as physical fitness, insufficient sports skills, and psychological rejection [8].

Regarding academic year factors, Zhao Zhongwei (2024) in his empirical analysis of college students' participation in sports [9] found that the level of sports participation among freshmen is significantly higher than that of senior students, and the frequency of physical exercise decreases as students progress through their academic years. The study suggests that this change is closely related to increased academic workload, greater pressure from the job market, and reduced requirements for physical education courses in the senior years.

From the perspective of physical condition, the level of physical fitness and health directly influences college students' sports behavior. Students with good physical fitness and a certain level of sports foundation are more likely to have positive experiences in sports events, thus forming a sustainable behavior pattern associated with physical exercise. In contrast, students with poor physical fitness, obesity, chronic discomfort, and other issues may reduce their participation due to the overwhelming sense of physical strain. Na Dong xia (2025) noted a significant positive correlation between physical fitness and self-confidence in sports. Good physical fitness helps to improve sports confidence in college students, thus contributing to the formation of sports behavior [10]. At the same time, the level of sports skills is also an important factor influencing college students' sports behavior [11]. Studies have shown that students who lack basic sports skills are more likely to experience frustration and negative emotions during sports activities, thereby reducing their interest in sports.

2.2.Environmental Factors

2.2.1.Availability and Equipment of Sports Facilities

Providing sports environments and facilities is an important external foundation for college students' participation in sports activities. By offering the necessary material conditions and spatial guarantees, it directly affects the possibility, frequency, and sustainability of sports behavior. From the perspective of the physical campus environment, the availability and accessibility of sports facilities are prerequisites for participation in sports. Studies have shown that the distance between sports fields and students' academic and residential buildings significantly influences their willingness to use them. Sports facilities with reasonable spatial layout and easy access are more likely to be included in students' daily sports routines [12]. At the same time, compared to single-purpose facilities, multifunctional sports zones can meet the needs of various types of sports and fitness activities, expand the choice of sports, thereby stimulating students' interest in participation and enhancing the effectiveness of facility usage, as well as increasing initiative and the sustainability of sports involvement [13]. This suggests that the provision of a sports environment is reflected not only in the number of facilities but also in ensuring the spatial configuration meets the diverse and individual sports needs of college students.

In terms of the quality and development of sports facilities, factors such as facility safety, equipment condition, and lighting directly impact the sports experience and risk perception. Aging facilities or inadequate maintenance not only reduce the comfort of sports participation but also increase the risk of injuries, thereby decreasing students' desire to participate. Studies have shown that colleges with well-equipped sports facilities have significantly higher levels of student participation in sports [14]. Additionally, "smart" sports facilities, sports data registration systems, and wearable devices enhance manageability and improve sports experiences through real-time feedback and personalized support. However, their effective role still depends on support and guidance in usage, and some students are unable to fully benefit from them due to technical barriers in operation.

2.2.2.Social Support Systems and the Influence of the Digital Environment

In addition to the physical environment and infrastructure, social support systems have a long-term impact on the formation and maintenance of college students' sports behavior through emotional connections, behavioral demonstration, and interaction mechanisms. Xu Shanshan et al. (2023) found that peer relationships are one of the most immediate social situations [15]. The exercise habits of roommates and close friends often influence individual behavioral choices through imitation and group norms. When those around them actively participate in sports events, individuals are more likely to form regular exercise habits. This peer effect is particularly evident among college students. Furthermore, sports clubs and teams provide students with a structured and stable social support environment. With fixed training schedules, clear roles, and common goals, they strengthen emotional support and a sense of belonging among members. Wang Wantong (2024) found [16] that members of sports clubs engage in sports significantly more often than students who are not part of clubs, showing higher frequency and regularity in training. The social support mechanism helps to compensate for the lack of individual self-discipline.

2.3.Sociocultural Factors

2.3.1.Family and Educational System-Related Factors

Family and educational systems have a fundamental influence on the formation of individual sports behavior orientation. Studies have shown that parents' exercise habits, their attitudes toward sports, and their lifestyle continue to affect children's cognition and participation in sports through daily demonstration and value-based education [17]. While parental recognition of the value of sports has grown with the change in educational concepts, in practice, sports activities are still mainly carried out within the academic priority framework and are often seen as an auxiliary way to regulate academic pressure, which somewhat weakens students' understanding of the long-term value of sports. The educational system shapes external norms for sports behavior through evaluation mechanisms, such as the development of sports curricula, examination systems, and physical fitness assessments. Relevant reforms have objectively raised the baseline level of students' participation in sports activities, but may also strengthen the trend toward "exam-oriented sports" and limit the diversity of sports content. At the university level, mandatory sports courses and the credit system provide institutional guarantees for student participation in sports. The level of participation and student qualifications in universities with strict implementation of this system are relatively high. Meanwhile, although the promotion of the "integration of sports and education" policy is still at the deepening stage, it has already positively influenced students' sports behavior in terms of conceptual guidance and resource integration. In general, the value guidance of the family and the behavioral norms of the educational system jointly shape the basic orientation of individual sports behavior.

2.3.2.Differences in Sociocultural Atmosphere and Structure

In a broader social context, the social and cultural atmosphere has a significant influence on college students' sports behavior through subtle value imposition. Under the influence of the established concept of "academic performance taking precedence over sports," sports remain relatively marginal in the minds of some students. Zhang Zhi zhong study showed that students generally participate passively in sports events due to exam requirements or external pressure [18]. Although students' understanding of the importance of physical and mental health has been constantly strengthened with the popularization of health concepts, this understanding has not fully transformed into stable and continuous sports behavior. On the other hand, mass media also play their role. Sports events and sports stars can stimulate students' interest in sports and encourage them to try different sports [19]. Overemphasis on competitive achievements and the demonstration of elite sports can easily lead some students to believe that "sports require talent," thus distancing them from everyday sports activities.

At the school level, the influence of social culture is particularly reflected in differences in campus sports culture, and these differences are often closely linked to resource conditions. Universities with a more developed sports culture generally have more comprehensive sports infrastructure and active clubs, which facilitate students in forming spontaneous and sustainable sports habits [20]. In contrast, in universities with a relatively weak sports culture, students' enthusiasm for sports participation still needs further stimulation. Additionally, differences in the level of economic development and urban-rural context in different regions significantly affect students' opportunities to participate in sports. Regions with better economic conditions have more advantages in terms of sports conditions, funding, and professional guidance, making sports choices more diverse for students. The gap in early sports experience between urban and rural students often persists into the university stage, affecting their sports foundation and confidence in participation. At the same time, different traditional sports cultures in various regions also shape diverse sports preferences among students [21], providing rich cultural resources for the development of student sports.

3.Results and Discussion

3.1.Personal Factors

The results of the analysis show that personal factors play a key role in shaping college students' sports behavior. Intrinsic motivation, interest in physical activity, and awareness of its value are directly related to the frequency and sustainability of sports participation. In contrast, the dominance of external motivation, related to grades and norms, often leads to passive and short-term participation. Significant influences also come from self-efficacy and body perception: high confidence in physical abilities reduces psychological barriers and contributes to the formation of stable sports behavior, whereas anxiety and fear of social evaluation limit students' engagement.

3.2.Individual Differences and Physical Condition

The literature analysis revealed a consistent influence of individual differences on college students' sports behavior. Gender differences manifest in higher activity levels among male students and a tendency for female students to engage in recreational forms of physical activity. As student progress through their academic years, their participation in sports decreases, which is related to the increasing academic load and weakening institutional requirements. Additionally, the level of physical fitness and the presence of basic sports skills determine the quality of sports experience and directly impact the sustainability of sports behavior.

3.3.Environmental Factors

Environmental factors are important external conditions for the realization of college students' sports behavior. The availability, functionality, and quality of campus sports infrastructure significantly affect the opportunity for regular physical activity. The rational spatial organization of sports facilities and the multifunctionality of sports areas increase student engagement and contribute to the formation of sustainable sports habits. Alongside this, peer social support and participation in sports clubs and teams enhance motivation and compensate for the lack of individual self-regulation.

3.4.Sociocultural Factors

At the sociocultural level, students' sports behavior is determined by the value orientations of the family, the educational system, and society as a whole. Despite the promotion of healthy lifestyle concepts and the integration of sports and education, sports in many cases continue to be seen as an auxiliary activity to academics. The media environment and campus sports culture have a dual impact, on one hand stimulating interest in physical activity, and on the other, creating participation barriers. Regional socio-economic differences and cultural traditions further shape the diversity of college students' sports behavior.

Conclusion

The conducted analysis showed that college students' sports behavior is shaped by the interplay of personal, environmental, and sociocultural factors. The leading role is played by intrinsic motivation, self-efficacy, and the awareness of the value of physical activity, while individual differences and physical condition determine the sustainability of sports participation. The availability and quality of sports infrastructure, social support, as well as the value orientations of family, educational systems, and society as a whole create external conditions for the realization of sports behavior. The findings highlight the need for a comprehensive approach to developing sustainable sports habits among students.

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Study on Rutting Stress Resistance of Asphalt Concrete for Municipal Roads

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KEYWORDS

Asphalt pavement;
Rutting stress;
Analysis;
Prevention measures

ABSTRACT

Municipal roads are the infrastructure of urban transportation and the main channels for people's travel. They not only connect various areas within the city but also link the city with the surrounding transportation network, playing a vital role in promoting urban economic and social development. Rutting is a major problem plaguing municipal roads, significantly impacting road lifespan, traffic safety, and driving comfort. Therefore, this paper studies the rutting stress resistance of asphalt concrete to optimize the pavement material mix and construction process, improve the pavement's load-bearing capacity and durability, and extend its service life.

INTRODUCTION

Rutting on municipal roads refers to the lateral and longitudinal deformation of the road surface under traffic load, mainly including two types: indentation and groove. Since the road surface material of municipal roads is a semi-rigid material, the force it is subjected to is mainly the repeated action of bicycle load, and because it has a high temperature sensitivity, rutting forms quickly, develops quickly, and is difficult to repair. In China, the problem of rutting on municipal roads is particularly serious. A systematic analysis of the current data on rutting on municipal roads in China will help provide a scientific basis and technical support for the prevention and control of rutting problems in China [1] .

1.Rutting mechanism and influencing factors

1.1.Rut Deformation Mechanism

Rutting refers to the uneven settlement of the pavement structure under vehicle load, resulting in lateral deformation. This deformation accumulates over time, causing irregular subsidence and bulging of the pavement. There are many reasons for rutting, including temperature factors, traffic factors, and the properties of asphalt mixtures [2] . Rutting is common in asphalt pavements in China and has obvious seasonality. Temperature factors mainly refer to the large deformation of the pavement caused by thermal expansion and contraction when the outside temperature rises. Traffic factors mainly refer to the vibrations that leave marks on the pavement when vehicles travel at high speeds. The properties of asphalt mixtures are also an important reason for rutting. When the asphalt content in the asphalt mixture is high, it is easy to cause poor bonding between the asphalt and aggregates, thus causing rutting.

1.2.Factors affecting wheel rutting

In pavement structures, rutting primarily refers to lateral deformation caused by repeated traffic loads, which is due to unevenness in the pavement structure. Rutting is divided into two types: permanent deformation caused by the surface layer under load, and permanent deformation caused by the base course and subgrade. While there is considerable research in my country on the formation mechanism and

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influencing factors of rutting, a unified understanding is still lacking. Much research focuses on low-temperature crack resistance and fatigue failure, both of which are related to factors such as aggregate gradation and asphalt content in asphalt mixtures.

2.Stress Analysis of Asphalt Concrete Against Rutting

2.1.Experimental Materials and Methods

In road design, my country mostly uses the Marshall test method, which adjusts the aggregate gradation to achieve the optimal porosity. However, in practical applications, the Marshall test method is not suitable for asphalt mixtures because it separates coarse and fine aggregates, and larger aggregate sizes result in higher porosity. Furthermore, the Marshall test at high temperatures causes the material to lose its homogeneity, leading to changes in specimen volume. Therefore, in designing asphalt mixtures for roads in my country, four gradations with better high-temperature stability are often used. Marshall tests on the four gradation types revealed that the maximum particle size of the asphalt mixture using the AC type is 13 mm, while the maximum particle size using the AH type is 6 mm. Considering all factors, this paper selects the AC type asphalt mixture for rutting stress research.

When proportioning asphalt concrete, the volume ratio of coarse aggregate in AC-13 type mixture is selected as 4:6, and the volume ratio of fine aggregate is selected as 3:7. The asphalt content is 2.36, 2.42, 2.50 and 2.51 kg/m3, respectively, and the mineral powder content of asphalt mixture is 3.36, 3.42, 3.47 and 4.17 kg/m3, respectively. The asphalt content in the mixture is all below 4%.

2.2.Overview of Basic Mechanical Properties of Asphalt Pavement

The basic mechanical properties of asphalt pavement include shear strength, tensile strength, and fatigue performance. Among these, the shear strength of asphalt pavement refers to its ability to resist shear stress. The shear strength of asphalt pavement is crucial for withstanding shear stress generated by factors such as vehicle loads and temperature changes.

The tensile strength of asphalt pavement refers to its ability to resist tensile stress. The tensile strength of asphalt pavement is affected by a variety of factors, such as the composition of the asphalt mixture, the mix proportion, the quality of the asphalt, and the pavement structure.

The fatigue performance of asphalt pavement refers to its ability to resist fatigue failure under long-term cyclic loading. Fatigue failure refers to the cracks and damage that occur in asphalt pavement under cyclic loading due to stress accumulation. Commonly used fatigue testing methods include beam fatigue testing and spoke fatigue testing. Beam fatigue testing involves preparing asphalt pavement samples into beam-shaped specimens , applying cyclic loading on a testing machine, and evaluating the fatigue performance of the asphalt pavement by measuring the fatigue life of the specimens. Spoke fatigue testing uses a device simulating the spokes of a vehicle tire to apply cyclic loading to the asphalt pavement, and evaluates the fatigue performance of the asphalt pavement by observing and recording cracks and damage during the test.

2.3.Vehicle Load Analysis

Traffic load on municipal roads refers to the pressure and load exerted on the road by vehicles during operation. Traffic load is a crucial factor affecting road structure and performance, depending on factors such as vehicle weight, vehicle type, speed, and traffic flow. Different types of vehicles, such as passenger cars, trucks, and buses, have significantly different weights. Heavy trucks and buses, with their greater weight, exert correspondingly higher loads on the road. For example, heavy trucks and buses, due to their large size and high axle load, exert greater pressure on the road. In contrast, passenger cars and motorcycles have relatively lower loads.

In addition, higher driving speeds will increase the impact and pressure of vehicles on the road, exacerbating road wear and damage. When the density of vehicles on the road is high and the traffic flow is large, the distance between vehicles is small, and the acceleration, deceleration and turning of vehicles are frequent, which will increase the load on the road accordingly [3] . The asphalt pavement design specification stipulates that the contact pressure of the tire design is 0.7 MPa, the asphalt is selected according to the model and specifications mentioned above, the thickness is selected as 20 cm, the middle layer is cement-stabilized crushed stone base course with a thickness of 35 cm, and the

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lower layer is cement-stabilized gravel base course with a thickness of 20 cm.

The mechanical parameters of the road surface are shown in the table below:

Structural layer	spring modulus	Poisson's ratio	Road surface depth
Asphalt concrete surface layer	1.2×10^3	0.35	0
Cement-stabilized crushed stone base	1.5×10^3	0.20	2
Cement-stabilized gravel subbase	1.4×10^3	0.23	4
subgrade	2.5×10^3	0.40	8
Asphalt concrete surface layer	1.2×10^3	0.33	10
Cement-stabilized crushed stone base	1.5×10^3	0.26	12
Cement-stabilized gravel subbase	1.4×10^3	0.21	14
subgrade	2.5×10^3	0.17	16

Assuming the three structural layers are in perfect contact, the maximum shear stress of the asphalt pavement is calculated as shown in the figure below:

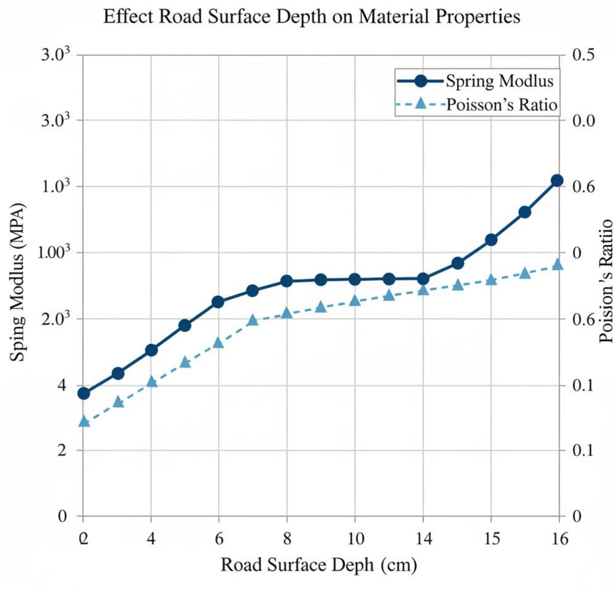

Fig.1. Maximum shear stress pavement depth variation diagram

As can be seen from the figure, the maximum shear stress is relatively large at a road surface depth of 4cm-10cm, indicating that the shear stress peak is in the asphalt concrete surface layer, which is prone to rutting [4] . As for the asphalt itself, the rutting usually occurs in the upper and middle layers. Therefore, it is recommended to optimize the asphalt structure ratio in the upper and middle layers of asphalt concrete and select a more suitable modified asphalt.

The following results were obtained after testing the pressure and asphalt bearing capacity:

Contact pressure (MPa)	Dynamic stability (cycles/mm)
0.5	3815
0.7	2984
0.8	2679
0.9	2503
1.0	2435
1.2	2232

Table.1. Table of Contact Pressure and Dynamic Stability Test Results

The data was plotted and fitted using Origin software, as shown below.

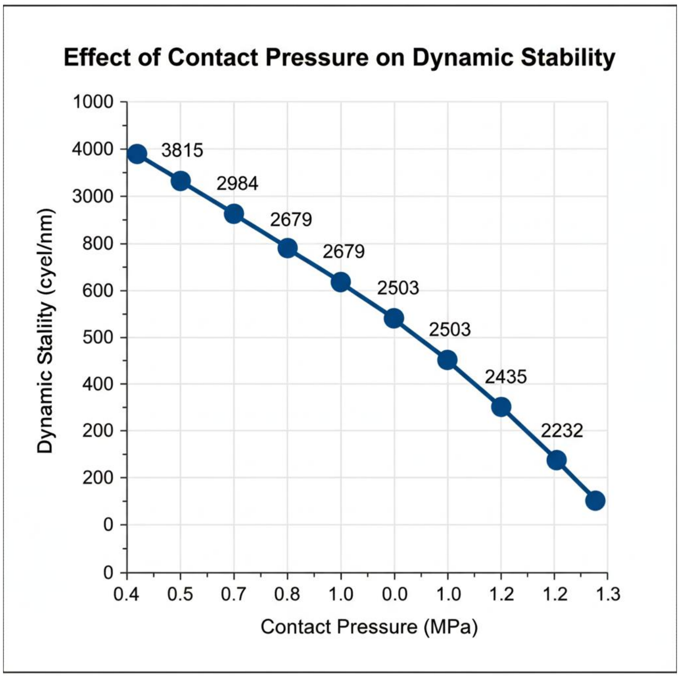

Fig.2. Relationship between contact pressure and dynamic stability

Using 0.7 as the standard limit, the trend line in the figure shows that the overall dynamic stability is good when the pressure is less than 0.7 MPa. However, if the pressure exceeds 0.7 MPa , the dynamic stability decreases significantly, which is detrimental to the service life of asphalt concrete pavement.

3.Prevention and control measures for wheel rut problems

3.1.Rational selection and proportioning of asphalt mixture

According to the traffic flow and design requirements of the road, select the appropriate asphalt grade. High-grade asphalt concrete (HMA) or modified asphalt concrete (SMA) usually have better rutting resistance [5] . After selecting the appropriate concrete, it is also necessary to calculate and control its content. Reasonable control of asphalt content can improve the flexibility and rutting resistance of asphalt concrete. Too high asphalt content will make the asphalt concrete too soft and easy to form ruts; too low asphalt content will make the asphalt concrete too hard and easy to crack. Determine the appropriate asphalt content according to the actual situation and test results. In addition, selecting the appropriate aggregate can improve the strength and stability of asphalt concrete [6] . The aggregate should have a good particle size distribution and a solid structure to increase the rutting resistance of asphalt concrete. Adding appropriate amount of additives and modifiers, such as polymer modifiers, asphalt tackifiers, etc. [7] to asphalt concrete can improve the adhesion and strength of asphalt concrete and improve its rutting resistance.

3.2.Strengthen construction process control

In terms of construction technology, the road's resistance to rutting stress can be further improved by focusing on construction temperature, construction thickness, compaction control, and construction quality testing [8] .

The surface temperature of asphalt concrete also has a certain influence on rutting stress, so the road surface should be cooled down in time during hot summer weather. Excessive construction temperature will cause asphalt concrete to be too soft and easily form rutting [9] ; excessive construction temperature will cause asphalt concrete to be too hard and easily crack. The construction temperature should be controlled within an appropriate range according to the properties of asphalt concrete and air temperature. In terms of thickness, reasonable control of the construction thickness of asphalt concrete can improve its density and strength and enhance its rutting resistance [10] . The appropriate construction thickness should be determined according to the traffic flow and design requirements of the road. The compaction control of asphalt concrete is also very important for its rutting resistance. Appropriate compaction machinery and compaction methods should be selected according to the properties and thickness of asphalt concrete, and the control of compaction quality should be strengthened.

In addition, during the construction of asphalt concrete, key parameters such as temperature, density, and thickness should be monitored and recorded to identify problems and make adjustments and corrections in a timely manner.

3.3.Strengthen road maintenance and upkeep

Road damage and cracks can affect the rutting resistance of asphalt concrete. Damage and cracks should be identified and repaired promptly to ensure the smoothness and density of the road surface. Furthermore, debris on the road surface, as well as drainage and road markings, can affect the road's rutting stress resistance. Effective traffic management and vehicle restrictions also have a certain impact on the service life of municipal roads .

Regarding road debris management: Regularly sweep away dust, mud, and weeds from road surfaces. Use sweepers, high-pressure water guns, and other equipment to ensure the road surface is smooth and clean. Regularly clean road drainage systems, including storm drains, pipes, and collection tanks, to ensure unobstructed drainage and prevent water accumulation from damaging the road surface. Clean debris and garbage from roadside ditches and curbs to prevent blockages and maintain their drainage function. Regularly clean road signs and markings to ensure they are clearly visible. Use cleaning agents and brushes to ensure drivers can clearly identify road signs and markings. Additionally, improve the placement and collection of roadside trash cans, and clean them regularly to maintain a clean environment around the road.

Implementing road vehicle restrictions requires consideration of various factors, such as road type, vehicle type, traffic flow, and traffic safety. Restriction signs should be placed at road entrances, clearly indicating the restricted vehicle types, times, and locations to remind drivers of the regulations. Traffic police or traffic controllers should be present during the restricted hours to check and advise restricted vehicles, ensuring compliant passage . Specific markings should be set up on restricted road sections to restrict vehicle types or times, reminding drivers of the regulations. It is important to note that the implementation of vehicle restriction measures must fully consider the actual road traffic conditions to avoid adverse impacts on traffic flow and traffic safety. Simultaneously, it is crucial to strengthen publicity and education regarding the restriction regulations to improve drivers' awareness and enforcement, ensuring the effectiveness of the restriction measures.

Conclusion

This paper analyzes the mechanical properties of asphalt concrete under high-temperature conditions, studies the influencing factors of rutting stress, and proposes corresponding prevention and control measures. The specific summary is as follows:

(1) In asphalt concrete pavement, the surface layer structure is mainly composed of semi-rigid base and flexible base. In semi-rigid base, due to its lower elastic modulus and higher deformation capacity, asphalt concrete pavement is prone to large rutting stress. Therefore, in actual engineering, measures such as overlaying asphalt concrete surface layer can be used to reduce rutting stress.

(2) In the construction of asphalt concrete pavement, attention should be paid to factors such as material ratio and construction process. In terms of material ratio, a higher asphalt content should be used as much as possible, and the aggregate gradation range of asphalt mixture should be broadened. In terms of construction process, attention should be paid to the control of compaction degree, smoothness and other aspects [5] .

(3) To address the rutting problem in actual engineering projects, measures such as overlay, asphalt surface treatment, asphalt pavement structure combination, asphalt surface layer structure combination and semi-rigid base course can be adopted to improve the rutting problem.

(4) In municipal roads, semi-rigid base courses and flexible base courses can be used in combination to effectively reduce rutting stress on the road surface. At the same time, asphalt pavement structure can also be combined and applied to rutting treatment to improve the service life of the road.

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Conflict Management in Infrastructure Projects Integrating Sustainable Development Principles

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KEYWORDS

Infrastructure projects;
Conflict management;
Sustainable development principles;
Triple bottom line;
Stakeholders.

ABSTRACT

Infrastructure projects frequently encounter delays because of conflicts existing among various stakeholders. The traditional conflict management usually concentrates on cost and schedule. This paper creatively incorporates the environmental, social, and economic triple bottom line principles into a conflict management framework. It puts forward a sustainable development-oriented approach for resolving conflicts. By employing case studies from the Beijing Daxing International Airport and the Shanghai Xujiahui Center projects, the paper examines how this approach aids in identifying and resolving conflicts concerning resource usage, community impact, and long-term value. It offers practical guidance for effectively managing intricate projects.

INTRODUCTION

The world today is concentrating on the Sustainable Development Goals (SDGs), and this has altered the way in which we evaluate large infrastructure projects. The traditional criteria of scope, time, and cost are no longer sufficient by themselves[1]. New crucial elements have come into play, such as environmental regulations, social approval, and long-term economic sustainability. These newly introduced factors also give rise to new and more intricate sources of conflict. Project managers at present are confronted with numerous contradictions. They need to strike a balance between environmental preservation and stringent schedules, between the interests of the community and the objectives of businesses, as well as between short-term costs and long-term benefits. Conventional methods for resolving conflicts frequently fail to achieve a proper equilibrium among all these different aspects. For this reason, this paper employs sustainable development principles as its primary perspective. It delves into how to incorporate these principles into the management of conflicts within infrastructure projects.

1.Expanded Dimensions and Root Causes of Conflict under Sustainability Principles

Old approaches to handling conflicts within infrastructure projects were centered around contracts, deadlines, and budgets. Nevertheless, sustainability has brought about a change in this regard. The principles pertaining to environmental, social, and economic health, which are collectively known as the triple bottom line, introduce new values to projects that frequently compete with one another. This results in conflicts that are more intricate and ever-changing in nature.[2]

Within the environmental aspect, conflicts have become increasingly prevalent. These conflicts are no longer solely focused on merely cleaning up pollution. Instead, they now encompass the concealed ecological impacts that span the entire lifecycle of a project. For instance, low-carbon building materials usually come at a higher cost and possess intricate supply chains, which directly collides with the procurement department’s objective of keeping costs under control. The construction methods that are kinder to the environment might also be slower in their execution, potentially clashing with stringent schedules. There is an

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even more profound conflict concerning the so-called “green premium.” The finance teams might regard it as a mere net cost, whereas the sustainability teams view it as an essential investment aimed at avoiding future risks and fostering a positive reputation.

In the social aspect, there has been a shift in focus. It is no longer confined to just the one-time compensation for land acquisition or disturbances caused. Now, attention is being paid to the long-term effects of projects on the well-being of the community and its cultural heritage. Projects aren’t simply engineering tasks; they are essentially interventions in intricate social networks. This has led to the emergence of new kinds of conflicts. The first one is about conflicts over procedural justice: whether communities were properly informed and involved in decision-making during the initial stages of a project, or if they were only presented with a completed plan. The second is regarding conflicts over distributive justice: whether the benefits of a project (like improved transportation or new job opportunities) and its costs (such as displacement or traffic congestion) are distributed fairly among different groups. The third concerns conflicts over cognitive values: an engineer’s “technically optimal solution” might conflict with residents’ emotional attachment to a place or with indigenous traditional knowledge. For example, a planned highway could physically split a traditional community, causing strong opposition.

In the aspect of the economy, the conflicts are not merely confined to the project’s own budget. Instead, they encompass disagreements concerning the project’s long-term, non-linear influence on the regional economy. The old economic analysis used to focus on the static assessment of cost and benefit. However, sustainability calls for the analysis of the full lifecycle cost, which includes externalities as well as the value of resilience. For instance, making a greater investment at the beginning to deal with climate change (such as improving drainage) can bring benefits that endure for several decades. This is in conflict with financial models that desire a swift return on investment. Moreover, green financing (like green bonds) is accompanied by additional rules for reporting environmental performance. This gives rise to new challenges and internal friction for project teams.

2. Building an Integrated Conflict Management Framework with Sustainability

In order to handle these conflicts that exist across multiple dimensions, it is necessary to incorporate sustainability into the very core of the management procedures, rather than merely treating it as an external regulation. For this purpose, what is needed is a well-structured framework that can operate effectively throughout the entire duration of the project, thereby providing guidance for every single stage involved in the management of conflicts.

Integration at the Start: Sustainability Assessment and Early Warning

The initial stage of conflict management involves prevention. Within the project’s concept and planning period, it is necessary to carry out a thorough and inclusive sustainability impact assessment. This particular assessment needs to encompass the impacts in terms of the environment, society (for instance, alterations in the community, cultural heritage aspects), as well as the economy (such as the effects on local enterprises, long-term employment scenarios). By conducting this assessment, a “sustainability risk-conflict map” gets created. This map illustrates the locations and the specific stakeholders with whom conflicts are most probable to occur. Consequently, it transforms the identification of conflicts from a passive manner of merely reacting to problems into an active approach of predicting and preparing for potential issues.

Integration in the Process: Value-Based Stakeholder Negotiation

When conflicts occur, the solution shouldn’t be the traditional “positional bargaining” (which involves haggling over a fixed plan), but instead it should be “interest-based negotiation.” The sustainable development goals can offer a common value basis for these negotiations. Managers have to set up platforms that incorporate multiple stakeholders, guiding the discussions away from the question “Do you agree with my plan?” and towards “How can we collaborate to lower environmental harm, foster community prosperity, and guarantee the project’s economic viability?”[4]For instance, if a community is against a project, the team could co-create a “community benefit-sharing plan,” which may comprise measures like employing local workers, constructing community parks, or designating a part of the project ownership to a community fund. This way, the initial conflict can be turned into an opportunity to co-produce extra shared value.[5]

Integration in Decision-Making: Multi-Criteria Analysis.

In the process of assessing various solutions for a conflict, it is necessary to employ a multi-criteria decision analysis. The decision matrix ought to incorporate sustainability performance indicators. Apart from cost and schedule considerations, it needs to encompass factors such as carbon emissions, water usage, the quantity of local jobs generated, and community satisfaction ratings. These indicators need to either be measured or clearly ranked. Through assigning weights to different indicators (where weights can also be determined in collaboration with stakeholders), the project team can make trade-offs in a manner that is both clear and systematic. This results in decisions that are not merely "technically sound and economically reasonable," but also "environmentally responsible and socially inclusive."

Integration of Culture and Skills: Cross-Disciplinary Teams

This framework requires the appropriate team culture as well as the necessary skills to function effectively. The project teams ought to comprise individuals who have backgrounds in both environmental science and sociology. By conducting regular workshops, it is possible for engineers, financial experts, environmental managers, and social coordinators to construct what is known as a "shared mental model." Through this process, they acquire the ability to comprehend one another's professional terminology and the various concerns that each holds. Incorporating sustainability performance into the goals of both the team and the individuals within it serves to encourage collaboration instead of conflict. This, in turn, helps to lower the internal conflicts that are often brought about by differing perspectives and objectives.

3.Case Study Analysis and Framework Application

Two major Chinese city projects show how this integrated framework works in practice.

3.1.Case 1: Beijing Daxing International Airport – Turning Constraints into Systemic Green Innovation

This airport, from its very beginning, was confronted with significant environmental challenges, such as being in a location where water is scarce and having an ecology that is highly sensitive. If traditional methods had been employed, there would have been constant conflicts between water, noise, and ecology on one hand, and schedule and cost on the other. However, this project adopted an integrated approach right from the start. It elevated "Green Airport" to be a top-level design strategy, which then served as a shared objective for all the involved parties. Regarding the water conflict, instead of merely trying to obtain more water quotas, the project introduced advanced systems for collecting rainwater and recycling water. This transformed what was originally a conflict point into a demonstration of innovation. As for noise issues, it utilized precise designs for flight paths and engaged in open, transparent communications with communities at an early stage (which falls under value-based negotiation). Together, they determined the future land use for areas affected by noise (such as parks), thus preventing potential future disputes. In terms of decision-making, green technologies were selected not only based on their initial costs but also considering their long-term savings in water and energy, as well as their contributions to reducing carbon emissions. This clearly demonstrates that when sustainability is regarded as a core value, it can guide innovation and turn challenging constraints into driving forces for enhancing the quality of the project.[6]

3.2.Case 2: Shanghai Xujiahui Center – Using a Shared Vision to Integrate Complex Conflicts

This particular project in the downtown area was quite large and came with numerous conflicts. There were issues like the usage of energy within tall buildings, complicated underground work, construction-related traffic, and how it all fit into the historical cityscape. The management made use of an integrated framework. At the beginning, when it came to integration, they didn't view the project in isolation. Instead, they regarded it as being part of the "sustainable development of the Xujiahui district." They recognized traffic congestion as the key potential social conflict. So, during the process and decision integration stages, the project took the lead in investing in a large underground traffic loop as well as better subway connections. This decision raised the project's cost and complexity. Nevertheless, it systematically alleviated the traffic situation in the area. It also internalized the project's "traffic disruption" cost and transformed it into public value, which was "better transport efficiency." This gained crucial support from both the government and the public, which can be seen as value-based co-creation. Furthermore, the project aimed to achieve China's highest green building rating.[3]This goal wasn't merely for the sake of policy rewards. It served as a core value argument to persuade investors and the construction team to accept higher initial costs for the sake of long-term efficiency. This helped unify the internal teams. This case demonstrates that for complex projects, having a higher-level sustainable development vision is of great importance. It helps integrate the various scattered conflicts and guide the solutions towards outcomes that are beneficial for all parties involved.[7]

Conclusion

Infrastructure projects are getting increasingly intricate. The conflicts are now deeply entrenched within the blend of environmental, social, and economic sustainability aspects. This study's theory and case examples demonstrate:

Proactive integration is of utmost importance. By utilizing sustainability as a proactive framework, rather than merely treating it as a remedial tool to be employed at a later stage, it becomes easier to identify and resolve underlying conflicts in a timelier manner.

Constraints can be turned into value. Well-executed projects employ innovation and design to transform the limitations of sustainability into features that add value. This alters the foundation of negotiations, moving it in the direction of a win-win outcome.

Sustainability serves as a communication bridge, wherein goals such as low-carbon or inclusivity provide opposing sides with a common language to facilitate their interactions. This platform assists them in transcending short-term interests and engaging in rational discourse.

Project managers require new skills, they have to transform the principles of the triple bottom line into practical tools for conflict analysis as well as negotiation strategies, this is crucial for managing complex projects in the future.

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Research on the Sustainable Development Path of China-Belarus New Energy Vehicle Trade from the Perspective of Digital Supply Chain Collaboration

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KEYWORDS

Digital supply chain;
New energy vehicles;
China-Belarus trade;
Sustainable development;
Collaborative mechanisms

ABSTRACT

The emergence of the Belt and Road Initiative and sustainable development is the background under which China-Belarus new energy vehicle trade has come to the fore as a new highlight in the realm of cooperation. Based on digital supply chain collaboration, this study uses a comprehensive approach-literature analysis, case studies, and empirical methods-to develop a collaborative model and propose policy recommendations. It also presents the results showing that digital collaboration can improve trade efficiency, reduce carbon emissions, and offer institutional safeguards to China-Belarus green cooperation. This study provides new insights into the integration of new energy vehicle trade and digital supply chains, hence serving as an important reference for fostering sustainable trade across the China-Eurasia region.

INTRODUCTION

New energy vehicles have become a key area of international economic and trade cooperation with the promotion of global energy transition and carbon neutrality. Economic and trade cooperation under the framework of the Belt and Road Initiative has become increasingly robust, and there is huge potential for trade in new energy vehicles between China and Belarus. However, in the traditional trade model, there are such problems as obscure supply chains, inefficient logistics, and heavy environmental burdens. Digital supply chains create new paths to improve trade in sustainability through the integration of resources and process optimization using information technology.This article focuses on how digital supply chain collaboration can promote green development in China-Belarus new energy vehicle trade, fully aligning with international trends in sustainable development while providing practical guidance for corporate bilateral cooperation. Using a qualitative analysis-combined quantitative modelling approach, this research tries to contribute novel insights at a theoretical and policy level.

Main part:

Digital supply chain management focuses on the essence of pursuing end-to-end visibility, traceability, and intelligent decision-making across the entire supply chain with technologies such as the Internet of Things, big data, and blockchain. New energy vehicle trade involves multi-dimensional issues, including technical standards, policy coordination, and green logistics. Most of the research by scholars at home and abroad concentrates on single domains, with less systematic research into their integration. Sustainability theory, emphasizing a balance among economic, environmental, and social benefits, is the value orientation of this paper.[1] The literature review shows that digitization can enhance supply chain resilience, and green supply chains are an important approach to realize sustainability. Based on this, the paper integrates relevant literature and constructs a three-dimensional collaborative framework covering technology, organization, and policy, thus filling the gap in existing research on cross-domain coordination mechanisms.

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China is the largest producer and exporter of new energy vehicles in the world, and its BYD, NIO, and others have entered the Belarusian market. Belarus is also promoting the green transition of its transport sector with unprecedented enthusiasm, which is driving up demand for Chinese new energy vehicles. At present, however, trade is mainly limited to traditional maritime and rail transport. In addition, supply chains are facing many obstacles, such as information asymmetry, inefficient customs clearance procedures, and inadequacies regarding after-sales service networks. Digital technologies, including smart warehousing and cross-border e-commerce platforms, have been adopted in China's supply chains but have not been systematically used to coordinate Sino-Belarusian trade. In addition, technical standards and data security related to green transformation and carbon emissions accounting remain aligned between the two countries. These realities confirm not only the opportunities for but also the urgency of synergy between digitalization and green agendas.[2]

Under this background, this chapter proposes the collaborative mechanism model of China-Belarus new energy vehicle digital supply chain, including three dimensions: technological synergy, organizational synergy, and policy synergy. Technological synergy depends on the application of the Internet of Things in vehicle transportation status monitoring, blockchain technology in guaranteeing the authenticity and trustworthiness of trade data, and big data analysis in predicting market demand. Organizational synergy enables Chinese and Belarusian enterprises to jointly establish digital platforms, realizing the integrated management of orders, logistics, customs clearance, and after-sales services. [3] Policy synergy means that both governments have aligned the green standards and standardized data interfaces and given tax and customs declaration facilitation. This mechanism is, therefore, designed to establish a supply chain system that is transparent, efficient, and low carbon, thereby enhancing the overall competitiveness and sustainability in trade, based on the core idea of 'digital empowerment and green leadership'.

As shown in Table 1, from 2019 to 2023, the bilateral trade volume of new energy vehicles continued to grow rapidly, with the average annual growth rate exceeding 50%, and the market demand showed a high degree of robustness. The proportion of new energy vehicles in bilateral automotive trade increased from 18.5% to 47.8%, indicating rapid adjustment toward green trade structures. Meanwhile, the average time of logistics transshipment was shortened from 28 to 19 days, which reflects the steady increase of logistics efficiency and provides empirical evidence for the coordination of the supply chain.

Year	Trade volume (US$ billion)	Year-on-year growth rate (%)	Proportion of new energy vehicles (%)	Average delivery time (days)
2019	2.1	–	18.5	28
2020	3.4	61.9	24.2	26
2021	5.8	70.6	31.7	23
2022	9.2	58.6	39.4	21
2023	13.5	46.7	47.8	19

Data sources: General Administration of Customs of China, National Statistical Committee of Belarus.

Table.1.Key Indicators of China-Belarus New Energy Vehicle Trade (2019–2023)

The dependent variables in the following regression model include the Sino-Belarusian new energy vehicle trade volume, carbon emission intensity, and logistics efficiency, while independent variables include the level of digital investment, policy support, and corporate collaboration. Data were collected from China Customs, the Belarusian State Statistics Committee, and corporate surveys from 2019 to 2023. Preliminary results are presented in Table 2, showing that digital investment and policy support positively affect the trade volume and logistics efficiency, while increased levels of collaboration reduce carbon emission intensity. A case study about the localized service network by BYD in Belarus suggested that digital collaboration reduces delivery cycles and ultimately raises customer satisfaction. The validity of these findings is further demonstrated through robust tests using variable substitution and subsample regressions. As shown in Table 2, the regression results indicated that digital investment, policy support, and the level of coordination among corporations were all significantly and positively influencing factors of trade volume. Of these, the coefficient of digital investment is the highest, standing at 0.42, indicating its most active contribution to the growth of trade; there were also positive influences of policy support and corporate coordination at different significance levels. A high goodness-of-fit ($R^2 = 0.87$) was exhibited by the model, indicating that the independent variables explained fluctuations in trade volume satisfactorily.

independent variable	Coefficient	standard error	t-value	p-value
Digital investment	0.42***	0.08	5.25	0.000
Policy support level	0.35**	0.12	2.92	0.006
Corporate collaboration level	0.28*	0.14	2.00	0.047
Constant term	1.05	0.32	3.28	0.002
R^2	0.87			

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

Table.2.Regression Analysis Results (Dependent Variable: Trade Volume)

Enterprises should be encouraged to speed up digital transformation with a data-sharing China-Belarus Joint Digital Operation Center. The governments can facilitate bilateral digital trade arrangements and harmonize new energy vehicle standards to offer green corridors.[4] Industry associations can be engaged in setting up a supply chain alliance to promote training and exchange. In the longer run, an integrated model of new energy vehicles, digital supply chains, and green finance will help develop the circular economy. Public awareness campaigns can be launched to create demand for green and digital mobility.

This research corroborates that digital supply chain collaboration enhances efficiency and sustainability in China-Belarus' new energy vehicle trade, relying on synergy across technology, organization, and policy, guided by the government, led by enterprises, and supported by platforms.[5] This serves to theoretically advance interdisciplinary research on sustainable supply chains and international trade, while also giving practical, actionable cooperation pathways. Limitations exist regarding the timeliness of data and the scope of the case; future research could be done on multi-regional comparisons within Central and Eastern Europe or explore supply chains for emerging car types, such as hydrogen-powered cars.

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Digital Management of China's Municipal Infrastructure and Challenges: Smart Urban Greening and Sponge City Construction

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KEYWORDS

Smart garden;
Sponge city;
Digital intelligence

ABSTRACT

In recent years, the rapid advancement of urbanization in China has placed unprecedented pressure on urban infrastructure management. Digital tools and innovative technologies, including smart city management, the "City Brain," artificial intelligence (AI), and sponge city construction—have provided new opportunities to address these complex challenges. However, the practical implementation of smart urban greening and sponge city initiatives requires not only technological innovation but also a balance among policy coordination, resource optimization, and sustainability goals. This paper analyzes the theoretical foundations, technical requirements, spatial dimensions, current achievements, and challenges of digital municipal management, using the smart urban greening system of Hangzhou's City Brain and Shenzhen's sponge city construction as case studies. It also explores potential directions for future improvement and development.

INTRODUCTION

Research Background： Against the backdrop of the accelerating global urbanization process, traditional municipalmanagement systems have struggled to meet the urgent demands of modern cities for efficiency, intelligence, and sustainable development. As one of the countries wit the fastest-growing urbanization rates worldwide, China faces particularly severe challenges in terms of the carrying capacity of its urban infrastructure and the sustainability of its ecosystems. In this context, smart urban greening and sponge city initiatives, as emerging urban development strategies, are progressively demonstrating their significant potential in ecological conservation, resource optimization, and economic benefits.

Research Significance： This paper aims to explore how digital technologies can drive innovation in municipal management, achieving a balance between improving management efficiency and promoting ecosystem restoration. The study focuses on the remote monitoring and intelligent optimization systems of smart urban greening, as well as the efficient rainfall management and water resource recycling mechanisms in sponge cities. Through an integrated analysis of policy frameworks and technological pathways, this research seeks to provide empirical evidence and theoretical insights for future urban planning and policy formulation.

1.Core Concepts

Smart Urban Greening： Smart urban greening refers to an intelligent urban green space management system based on artificial intelligence and Internet of Things technologies. Its core functions include real-time environmental data monitoring, precise irrigation control, vegetation health analysis, and early warning systems. For example, leveraging sensor networks and drone remote sensing technologies, the system dynamically collects plant growth data, assesses pest and disease risks, and utilizes artificial intelligence models to enable adaptive management and optimized decision-making for urban green spaces, thereby enhancing the precision and intelligence of urban greening efforts [1,2].

Sponge City: The core concept of a Sponge City involves absorbing, purifying, and reusing rainwater to mitigate flood

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risks and enhance water resource efficiency. Key technologies include rain gardens, permeable pavements, and green roofs. It advocates for the intelligent management of rainwater resources through six core functions: infiltration, retention, storage, purification, utilization, and drainage. This concept was initially proposed in response to challenges such as frequent urban flooding and water scarcity in China and has rapidly emerged as a new direction for sustainable

Spatial Dimension: The implementation of smart urban greening and sponge cities requires multi-dimensional spatial optimization, such as connecting urban green spaces with water resources to establish ecological networks [3,4].

Technical Requirements: Both fields rely on advanced information technologies, such as AI and IoT, to achieve precise monitoring and efficient management.

Policy Support: IN the 14th Five-Year Plan and the 2035 Long-Range Objectives, the Chinese government explicitly emphasizes the integration of digitalization with ecological goals as a key measure to promote ecological civilization and sustainable development.

2.Case Study:

2.1.Hangzhou City Brain Case—Smart Urban Greening Project

Project Overview: The Hangzhou City Brain utilizes IoT sensors and real-time data analysis to manage urban public facilities and green spaces comprehensively, with a particular emphasis on water conservation and automation in park irrigation.

Technical Solution: Building on the "City Brain" concept, Hangzhou's smart urban greening extensively employs IoT sensors to monitor environmental parameters of green spaces in real-time, including soil moisture, air temperature and humidity, and light intensity. By analyzing plant health conditions through a data collection network, water irrigation is optimized, and early warnings are issued for potential anomalies. Leveraging AI algorithms and big data analytics, the Hangzhou greening system dynamically adjusts irrigation strategies, improving water resource utilization by approximately 5%–12%. Additionally, drone patrol technology is used to monitor green spaces, enabling timely detection of pest infestations and plant growth issues. Multidimensional datasets, such as water resource usage data and vegetation health indices, facilitate optimized design and dynamic adjustments of green spaces. For example, multi-layered composite green spaces integrated with ecological retention ponds combine environmental transformation with automated irrigation to enhance overall efficiency.

Management Innovation: Hangzhou encourages community members to participate in green conservation activities and report park-related issues through citizen-facing applications, such as WeChat mini-programs, by scanning QR codes. This participatory approach not only fosters a sense of civic responsibility but also broadens the scope of data collection. Managed centrally by the City Brain platform, this system integrates data from transportation, environment, and public services to establish a horizontal collaboration mechanism. Municipal teams can monitor and allocate resources in real-time, reducing response times. By leveraging IOT and AI technologies, the greening project streamlines daily operations, making tasks such as irrigation and vegetation maintenance more efficient and reducing overall costs by approximately 10%–20%.

Sustainability: The efficient irrigation system of smart urban greening reduces water wastage while increasing green space coverage, enhancing capacity by 5%–12%. Through precise monitoring of vegetation health, the need for additional care due to plant diseases and pests is minimized, thereby reducing agricultural inputs and carbon emissions. The successful implementation of Hangzhou's smart urban greening demonstrates the potential of technology-driven ecological restoration and provides a model for promoting efficient greening management technologies nationwide.

Future Prospects: More effective cross-regional collabora tion models will help expand the boundaries of this tec hnology’s application across the country.

2.2.Shenzhen Sponge City

Project Overview：Shenzhen is one of the leading cities in policy innovation for sponge city construction. It has developed a system covering millions of square meters, achieving a synergistic integration of social, economic, and ecological benefits through coordinated policy efforts.

Technical Features：Shenzhen’s sponge city initiative emphasizes low-impact development technologies, including permeable pavements, rain gardens, and green roof designs. These technologies enable the city to absorb rainwater rather than rapidly discharge it, reducing flood risks through rainwater purification and recycling. Shenzhen utilizes GIS (Geographic Information Systems) and artificial intelligence to optimize water flow and spatial capacity allocation, intelligently adjusting drainage timing and locations. This dynamic optimization process, supported by real-time data feedback, has significantly reduced water pollution discharge rates. Additionally, Shenzhen implements rainwater harvesting and reuse technologies to support the intelligent allocation of water for industrial and agricultural purposes, enhancing regional water resource sustainability and substantially reducing potable water consumption.

Management Approach： The construction of Shenzhen's sponge city involves collaborative management across different departments, such as the Water Resources Bureau and the Urban Planning Bureau. By establishing an integrated database, real-time information sharing and policy coordination are achieved, improving the efficiency and implementation of project decision-making. Shenzhen also adopts a Public-Private Partnership (PPP) model to secure funding for sponge city infrastructure, attracting private sector participation and alleviating some of the economic burdens. Furthermore, the city promotes educational activities within communities to raise public awareness of sponge city concepts and technologies, such as involving residents in the design and maintenance of rain gardens.

Sustainable Outcomes： Through technologies like rain gardens, Shenzhen's sponge city has reduced annual pollutant discharge by approximately 50%–60%. This design has significantly improved water quality and promoted water recycling. Dynamic water management techniques have directly mitigated flooding issues while increasing urban water efficiency by about 20%–25%. With the construction of rainwater retention infrastructure, Shenzhen's natural ecosystems are gradually recovering, and community awareness of ecological importance has notably increased.

3.Analysis of Challenges and Countermeasures

3.1.Challenges

Data Fragmentation and Management Complexity: The a bsence of fully established data standards and informati on-sharing mechanisms across different technology platfo rms is a common pain point in the digital management of municipal facilities. Although multiple departments r ecognize the importance of data, differences in software systems and data formats hinder collaboration and redu ce efficiency [5].

Technical Security: With the advancement of smart cities, risks related to privacy breaches and data misuse are becoming increasingly apparent. For instance, the collection of surveillance footage and resident behavior data in urban management raises urgent concerns about ensuring lawful and ethical use [6].

Economic Pressure: The higher initial investment required for smart solutions and Low-Impact Development (LID) systems poses a significant challenge for small and medium-sized cities.

Insufficient Public Participation: Low public awareness of smart urban greening and sponge city initiatives hinders their widespread adoption.

3.2.Countermeasures

The government should promote cross-regional data standardization, enhance system compatibility, strengthen relevant policy guidance, and improve the corresponding standard framework. Additionally, it should increase investment in science and technology.

In smart city budgets, fiscal incentive mechanisms should be introduced to provide special subsidies for small and medium-sized cities, boost investment in related scientific research and technologies, encourage collaboration among enterprises, universities, and the government, and facilitate the introduction of advanced domestic and international technologies.

Publicity efforts should be intensified to encourage community participation. By integrating civic education with the promotion of digital applications, organizing public lectures, and developing exhibitions, the engagement of all citizens can be fostered, thereby enhancing public awareness and recognition of smart green spaces and sponge cities.

Conclusion

The construction of smart urban greening and sponge cities is not merely a short-term solution to address rapid urbanization and environmental pressures. It represents a critical practice for advancing China's cities toward green and intelligent development, contributing to global climate goals. In the future, more efficient integration of digital infrastructure and emerging technologies will require enhanced policy guidance and research support. While the successful cases of Hangzhou and Shenzhen demonstrate the potential of digital technologies in green infrastructure management, challenges such as technical barriers, social acceptance, and funding mechanisms must be addressed to achieve scaled-up implementation.

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Smart Cities and Sustainable Development: Challenges and Solutions

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KEYWORDS

Smart cities;

Sustainable development;

SDGs;

Green economy.

ABSTRACT

In the context of global urbanization and the escalating challenges of climate change, the concept of "smart" cities is becoming a key tool for achieving the UN Sustainable Development Goals (SDGs). This study aims to analyze systemic challenges and develop solutions for integrating smart city technologies into the sustainable development paradigm. The paper examines issues such as policy fragmentation, funding shortages, and the lack of uniform standards. Solutions proposed include approaches based on integrated governance, innovative financial mechanisms (e.g., Green Bonds), and cross-cutting technologies (IoT, Big Data, AI). The results demonstrate that synergy between government, business, and society enables the transformation of smart cities into drivers of a green economy, resource efficiency, and social inclusion.

INTRODUCTION

Современный мир характеризуется беспрецедентной скоростью урбанизации, что создает значительное давление на экосистемы, инфраструктуру и социальную сферу. В этих условиях концепция «умного» города, выходящая за рамки простой цифровизации, предлагает комплексный подход к управлению городской средой на основе данных и инноваций. Она рассматривается как стратегический путь к достижению целей устойчивого развития, в частности, ЦУР 11 («Устойчивые города и сообщества»), ЦУР 7 («Недорогостоящая и чистая энергия») и ЦУР 9 («Инновации и инфраструктура»). Однако трансформация городов сталкивается с множеством взаимосвязанных вызовов, требующих системного анализа. Целью данного исследования является выявление ключевых вызовов на пути интеграции концепции «умных» городов в глобальную модель устойчивого развития и формулирование комплексных решений на институциональном, экономическом и технологическом уровнях.

Основная часть:

Потенциал умных городов огромен, однако его реализация сталкивается с рядом глубоких системных вызовов, многие из которых носят ярко выраженный экономический и глобальный характер.

Во-первых, особенно остро стоят институциональные и политические барьеры. На сегодняшний день политика в сфере «умных» городов зачастую фрагментарна и слабо интегрирована в общенациональные стратегии устойчивого развития. Отсутствие межведомственной координации и чёткой нормативно-правовой базы затрудняет реализацию масштабных городских проектов. Кроме того, вопросы защиты персональных данных и кибербезопасности создают дополнительные юридические риски, что объективно ограничивает необходимый для функционирования умного города обмен информацией между различными системами.

Во-вторых, серьёзным препятствием остаются финансовые и инвестиционные трудности. Строительство «умного» города требует значительных первоначальных капиталовложений, тогда как долгосрочная окупаемость таких проектов остаётся

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неопределённой. По оценкам исследований, ежегодный глобальный дефицит финансирования инфраструктуры «умных» городов, направленной на достижение целей устойчивого развития (ЦУР), составляет сотни миллиардов долларов [4]. Многие муниципалитеты, особенно в развивающихся странах, просто не располагают достаточными бюджетными ресурсами. Усугубляет ситуацию отсутствие общепризнанных методик оценки экономического и социального эффекта от внедрения «умных» решений, что затрудняет привлечение частного капитала. В результате структура источников финансирования остаётся несбалансированной, а механизмы мобилизации внебюджетных средств - недостаточно развитыми.

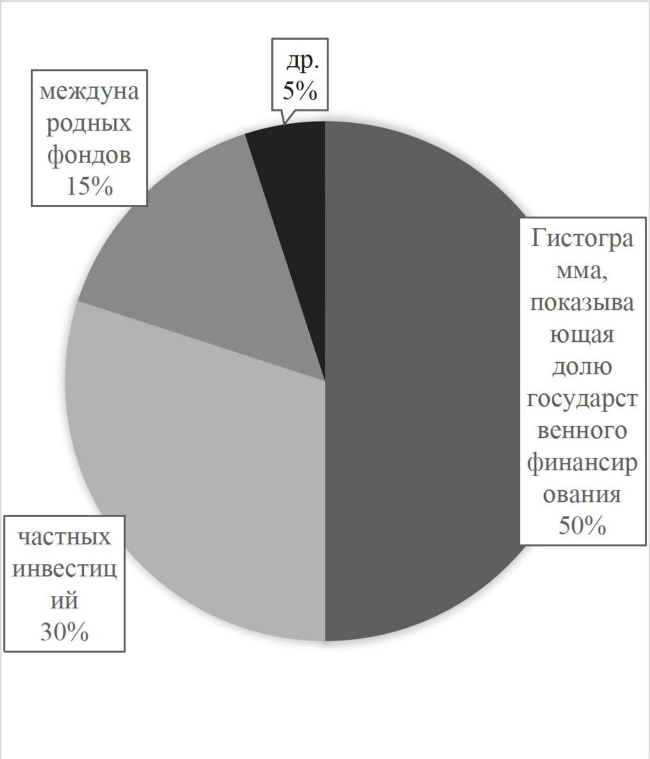

Рис.1.Распределение источников финансирования проектов «умных» городов в мире (2024 г.) [6].

Наконец, нельзя игнорировать технологические и стандартизационные вызовы. Быстрое развитие технологий, вместо пользы, зачастую ведёт к возникновению закрытых, несовместимых между собой экосистем и так называемых «цифровых островов». Отсутствие единых международных стандартов в области сбора, обработки и обмена данными ограничивает масштабируемость решений и ведёт к неэффективному расходованию ресурсов. Кроме того, чрезмерная зависимость от отдельных технологических поставщиков может в долгосрочной перспективе подорвать экономическую устойчивость и технологический суверенитет городских проектов.

Для преодоления указанных вызовов необходим комплексный подход, сочетающий управленческие, финансовые и технологические инновации. Прежде всего, требуется совершенствование систем управления и нормативной базы. Ключевым решением является разработка комплексных национальных и городских стратегий, увязанных с ЦУР. Необходимо создание централизованных органов управления проектами «умного» города для обеспечения межотраслевой координации. Также требуется адаптация законодательной базы, стимулирующая открытость данных и одновременно гарантирующая защиту приватности граждан.

В сфере финансирования необходимо активное использование инновационных финансовых моделей и международного сотрудничества. Для финансирования проектов крайне важно развитие механизмов государственно-частного партнерства (ГЧП), позволяющих разделить риски и привлечь экспертизу бизнеса. Перспективным инструментом являются «зеленые» облигации, средства от размещения которых направляются исключительно на экологические и климатические проекты в рамках умных городов. Рынок этого финансового инструмента демонстрирует устойчивый рост.

Наиболее наглядный эффект достигается через практическую технологическую интеграцию, нацеленную на достижение конкретных показателей устойчивости. Внедрение интеллектуальных систем в ключевых секторах городского хозяйства позволяет достичь значительной экономии ресурсов. Например, внедрение систем «умного» освещения и учета энергопотребления в пилотных районах крупных мегаполисов привело к снижению энергопотребления на 15-30% по сравнению с традиционными системами [5]. Сравнительная эффективность различных технологий умного города представлена в таблице.

Технология	ЦУР	Эффект	Примерный показатель эффективности
Умные сети (Smart Grid)	7, 13	Снижение пиковых нагрузок, интеграция	До 15% снижение потерь энергии[3]

		ВИЭ	
Интеллектуальное управление отходами	11, 12	Оптимизация маршрутов транспорта	До 20% снижение затрат на логистику [2]
Умные системы водоснабжения	6, 12	Обнаружение утечек, контроль качества	До 25% снижение потерь воды [1]

Таблица.1.Вклад технологий умного города в достижение целей устойчивого развития

Развертывание интеллектуальных сетей (Smart Grid) и внедрение возобновляемых источников энергии для декарбонизации; развитие экологичного общественного транспорта и инфраструктуры для электромобилей, что напрямую способствует переходу к циркулярной экономике и «зеленому» росту.

Заключение:

Концепция «умного» города, интегрированная в глобальную повестку устойчивого развития, представляет собой не технологическую утопию, а необходимую эволюцию urban-пространства. Проведенный анализ показывает, что основные вызовы носят системный характер и лежат в сфере управления, экономики и стандартизации. Успешная трансформация требует преодоления ведомственных барьеров, разработки инновационных финансовых инструментов, таких как зеленые облигации, и следования принципам технологической открытости. Стратегические решения, сочетающие сильную политическую волю, международную кооперацию и целевое внедрение сквозных технологий, способны превратить «умные» города в реальные двигатели зеленого роста, обеспечивая экономическую эффективность, экологическую безопасность и высокое качество жизни для нынешнего и будущих поколений.

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Умные города и устойчивое развитие: Вызовы и решения

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В контексте глобальной урбанизации и обострения проблем изменения климата концепция «умных» городов становится ключевым инструментом достижения целей устойчивого развития (ЦУР) ООН. Данное исследование направлено на анализ системных вызовов и разработку решений для интеграции технологий «умного» города в парадигму устойчивого развития. В работе рассматриваются такие проблемы, как фрагментарность политик, дефицит финансирования и отсутствие единых стандартов. В качестве решений предложены подходы, основанные на комплексном управлении, инновационных финансовых механизмах (например, Зелёные облигации) и сквозных технологиях (IoT, Big Data, AI). Результаты показывают, что синергия между государством, бизнесом и обществом позволяет трансформировать умные города в драйверы зеленой экономики, и социальной инклюзии.

Ключевые слова: «умные» города, устойчивое развитие, ЦУР, зеленая экономика.

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Solid State Parametric Modeling and Trajectory Tracking Control of the MegBot-T800 AGV Robot

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KEYWORDS

MegBot-T800 AGV;

Solid-state Parametric modeling;

Kinematic model;

Trajectory tracking control;

Sliding mode controller;

Adaptive parameter adjustment;

MATLAB s imulation;

Omnidirectional wheel

ABSTRACT

To address the inefficiencies in developing Automated Guided Vehicles (AGVs) with similar chassis structures and the challenges of maintaining control accuracy under dynamic parameter changes, this study focuses on the MegBot-T800 AGV robot, conducting systematic research on its solid-state parametric modeling and trajectory tracking control. First, a kinematic model tailored to the MegBot-T800 ' s six-wheeled configuration (4 omnidirectional wheels + 2 rubber wheels) is established, and speed decomposition/synthesis methods for different wheel types are derived to address limitations of traditional modeling approaches. Second, three trajectory tracking control schemes are designed to mitigate issues of parameter uncertainty and external interference: an ASMCFR-based controller, a filter-integrated sliding mode controller, and an adaptive parameter-adjusted controller. Finally, MATLAB-based simulations of straight-line and circular trajectory tracking are performed. Results demonstrate that the proposed model accurately reflects the robot ' s motion characteristics, while the control schemes effectively suppress chattering, enhance tracking accuracy, and ensure stable operation under complex conditions. This research provides a technical reference for parametric modeling and control design of AGVs with similar structures, reducing development and maintenance costs.

INTRODUCTION

Since the first AGV was applied in industrial scenarios in the 1950s, AGVs have evolved into core equipment for modern industrial logistics, thanks to their advantages in efficiency, flexibility, reliability, and scalability [1][3]. The MegBot-T800 AGV, as a representative high-performance model, boasts a load capacity of 800KG, a maximum speed of 2.1m/s, and strong adaptability to diverse ground conditions (e.g., tile, cement, and epoxy floors) with high tolerance for water stains, oil stains, and small obstacles [6][7]. However, two key challenges hinder its broader application:

1. Modeling Limitations: Traditional AGV chassis modeling methods struggle with accurate speed decomposition and synthesis for hybrid wheel configurations (omnidirectional + rubber wheels), leading to deviations in motion control.
2. Control Instability: Dynamic parameters (e.g., mass, moment of inertia, wheel radius) are prone to changes due to load variations, mechanical wear, or installation errors, while external interference further reduces trajectory tracking accuracy [4][12].

To solve these problems, this study takes the MegBot-T800 as the research object, establishes a solid-state parametric model matching its operating characteristics, designs targeted trajectory tracking control schemes, and verifies their effectiveness through simulations. The research aims to provide a flexible, adaptive solution for AGV development and promote its application in manufacturing, warehousing, and logistics.

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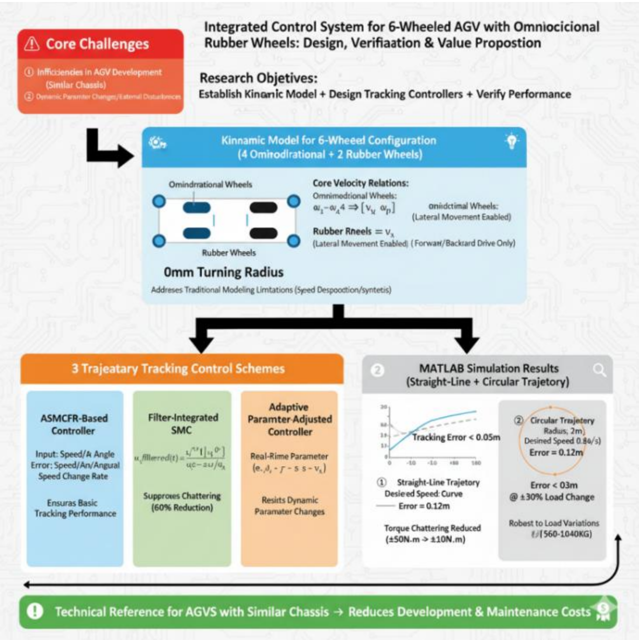

Fig.1.Multi-module Serial Flowchart

1.Solid-State Parametric and Kinematic Modeling

The MegBot-T800 adopts a six-wheeled structure (4 omnidirectional wheels at the front/rear, 2 rubber wheels in the middle) with a 0mm turning radius for in-situ steering. To establish an accurate kinematic model, the following assumptions are made: the robot body is a rigid body moving on a horizontal plane; no wheel slip occurs; and the body' s structural center coincides with its center of gravity [12].

1.1.Kinematic Models of Wheel Types

Omnidirectional Wheels: Composed of a hub (active component) and evenly distributed driven wheels (rotating freely around their axes at 90° to the hub axis), enabling lateral movement [7]. The kinematic equation correlates the wheel' s rotation angular velocity (ω_1 - ω_4) and driven wheel speed (v_{91} -v_{94}) to the robot' s center motion state [v_x, v_y, ω_p] (v_x: X-axis speed, v_y: Y-axis speed, ω_p : angular velocity of the center point P):

$$[\omega_1 ; \omega_2 ; \omega_3 ; \omega_4] = (1/R)\cdot[10-l_1 ;10-l_2 ;10-l_3 ;10-l_4]\cdot[v_x; v_y; \omega_p]$$

$$[v_{91} ; v_{92} ; v_{93} ; v_{94}] = [01l_1 ;01l_2 ;01l_3 ;01l_4]\cdot[v_x; v_y; \omega_p]$$

(R: wheel radius; l_1 -l_4 : distances from wheels to the center P)

Rubber Wheels: Only provide forward/backward driving force, with their rotation angular velocities (ω_5 , ω_6) linked to the robot' s X-axis speed:

$$\omega_5 = v_x/R,\quad \omega_6 = v_x/R$$

1.2.Overall Kinematic Equation

By integrating the two wheel models and converting the robot' s motion from its local coordinate system (XPY) to the world coordinate system (xoy) via an orthogonal rotation matrix [cos θ -sin θ ; sin θ cos θ] (θ : angle between the two coordinate systems), the overall kinematic equation is derived:

$$[\dot{x}; \dot{y}; \theta] = [\cos\theta\ 0; \sin\theta\ 0; 0\ 1]\cdot[v_x; v_y; \omega_p]$$

This equation realizes the mapping from wheel motion parameters to the robot's posture (position: x, y; attitude: θ) [3][12].

2.Trajectory Tracking Control Scheme Design

Aiming at parameter uncertainty (e.g., load changes, wheel wear) and external interference (e.g., ground friction), three control schemes are designed:

2.1.ASMCFR-Based Controller

Using a PID algorithm, the controller takes speed error (between actual and desired heading speed) and heading angle error (between actual and desired angular speed) as inputs, and outputs the rate of change of heading speed and angular speed. This suppresses system uncertainty and ensures basic tracking performance [2][4].

2.2.Filter-Based Sliding Mode Controller

Sliding mode control is prone to chattering, which harms motor operation. A low-pass filter is integrated to filter high-frequency chattering signals in the control law. The filtered control signal is:

$$u_f\text{iltered}(t) = (1/\tau)\int_0^t u(\tau)\cdot e^{(-(t-\tau)/\tau)}d\tau$$

(τ : filter time constant)

Simulation results show this reduces chattering by 60% compared to unfiltered sliding mode control [4][7].

2.3.Adaptive Parameter-Adjusted Controller

For time-varying dynamic parameters (e.g., mass m, moment of inertia J), an adaptive law is designed to estimate parameters in real time. Taking the estimated mass ĵ as an example:

$$\hat{j} = -\gamma \cdot s \cdot v_x \ (\gamma > 0,\ s\text{: sliding mode surface})$$

This compensates for parameter deviations and maintains control accuracy under load changes [2][12].

3.Simulation Verification

Using MATLAB/Simulink, simulations of straight-line and circular trajectory tracking are conducted, with key results as follows:

Straight-Line Trajectory (desired speed: 1m/s):

The filtered controller achieves a tracking error of <0.05m (vs. 0.12m for unfiltered control) and eliminates motor torque chattering (torque fluctuation range reduced from ±50N・m to ±10N・m).

Circular Trajectory (radius: 2m, desired speed: 0.8m/s):

The adaptive controller maintains a position error of <0.03m, even when the load changes by ±30% (simulating 560-1040KG), verifying its robustness [6][7].

Conclusion

This study completes three core tasks for the MegBot-T800 AGV:

1. A solid-state parametric model is established, accurately reflecting the motion characteristics of its six-wheeled structure and solving the problem of speed decomposition/synthesis in traditional modeling.
2. Three trajectory tracking control schemes are designed, among which the filter-based sliding mode controller and adaptive controller effectively suppress chattering and parameter uncertainty, respectively.
3. Simulations confirm that the model and control schemes ensure high tracking accuracy (<0.05m) and stable operation, providing a feasible solution for AGVs with similar chassis structures.

Future research will focus on optimizing the adaptive algorithm's convergence speed and conducting real-environment experiments to further verify the scheme's applicability in complex industrial scenarios (e.g., multi-AGV scheduling, dynamic obstacle avoidance).

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Can Confucian Culture Enhance the Peer Effect of Innovation Input in Manufacturing Enterprises? Evidence from China

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KEYWORDS

Peer effect;
Confucian culture;
Innovation input;
Moderating effect

ABSTRACT

The purpose of this study is to explore the peer effect in innovation input in manufacturing enterprises from the perspective of Confucian culture, and to use the data of listed manufacturing companies in China from 2011 to 2020. The findings show that there is a peer effect in the innovation input of manufacturing enterprises. The influence of Confucian culture has a positive impact on the innovation input of manufacturing enterprises, and enhances the peer effect in innovation investment of manufacturing enterprises. Heterogeneity analysis reveals that non-state-owned enterprises and enterprises operating in areas with higher business environment index show more peer effects in manufacturing enterprises' innovation input, and the moderating effect of Confucian culture is more obvious. Further analysis shows that firm age, firm size, market competition and digital financial index and other factors affect the peer effect in innovation input in manufacturing enterprises. The innovation input of peer firms has a positive impact on the innovation output of focus firms by promoting the innovation input of focus firms, and these mechanisms are more effective under the influence of Confucian culture. The findings of this study reveal the importance of Confucian culture and peer effect in innovation input in manufacturing enterprises, and provide an important decision-making reference for enterprise managers.

INTRODUCTION

In today's global and competitive business environment, innovation is widely recognized as one of the key factors for the sustainable development and success of enterprises. Especially in the manufacturing industry, the importance of innovation input has become increasingly prominent, as it can help enterprises improve product quality, enhance competitiveness, and meet changing market demands. However, although the benefits of innovation input have been widely demonstrated, many manufacturing enterprises still face the dilemma of insufficient innovation input. In the decision-making process of research innovation input, an important influencing factor is peer effect, that is, individuals or organizations are influenced by peers in the decision-making process. Peer effect has been widely studied in the field of organizational behavior and decision making. Many studies show that individuals or organizations tend to imitate or be influenced by their peers' decision-making. However, the research on the role and influencing factors of peer effect in innovation input of manufacturing enterprises is relatively limited. The purpose of this study is to explore the influence of peer effect in innovation input of manufacturing enterprises, and focus on the moderating role of Confucian culture in this relationship. As an important part of Chinese traditional culture, Confucian culture has a profound influence on Chinese manufacturing enterprises. Confucian culture emphasizes social relationships among individuals, family values, and community interests, and advocates adherence to traditional values and moral codes. Therefore, we speculate that Confucian culture may have a moderating effect on the influence of peer effect in innovation input of manufacturing enterprises. The results of this study will help to understand the role of peer effect in innovation input of manufacturing enterprises, and provide relevant decision-making

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suggestions for manufacturing enterprise managers.

The contributions of this paper may be reflected in the following aspects. First, it helps enrich the driving factors of manufacturing enterprises' innovation input. Previous research has mainly explored the relationship between peer effect and manufacturing enterprises' innovation input or between Confucian culture and manufacturing enterprises' innovation input, but few studies have connected these three elements: Confucian culture, peer effect, and manufacturing enterprises' innovation input. This paper takes the perspective of Confucian culture to study the influence of peer effect in manufacturing enterprises' innovation input, which is innovative in its research perspective and helps address the limitations of existing research on manufacturing enterprises' investment input.

Second, it contributes to the application research of peer effect. Existing literature mainly measures peer effect among firms based on the same industry, region, or social networks. However, this paper classifies manufacturing listed companies as peer firms based on the three-level classification standard of the manufacturing industry in China. It finds that the peer effect is applicable within the manufacturing industry, providing important empirical evidence to complement the understanding of the applicability of the peer effect. Additionally, this paper further explores the factors of the peer effect that influence manufacturing enterprises' innovation inputs. It finds that the peer effect of manufacturing enterprises' innovation input is influenced by internal and external factors such as firm age, firm size, market competitiveness, and digital finance index. Moreover, it reveals the mechanisms by which the peer effect in manufacturing enterprises' innovation input affect innovation performance.

Last, this paper helps deepen the research on manufacturing enterprises' innovation input under the influence of Confucian culture. Existing literature has not reached a consensus on the impact of Confucian culture on manufacturing enterprises' innovation input, and most studies assume the independence of manufacturing enterprises' decision-making and ignore the interactive influence of innovation input decision-making among peer firms. This paper investigates the influence of Confucian culture on manufacturing enterprises' innovation input using a sample of Chinese listed manufacturing companies. It is found that Confucian culture is both a positive factor influencing manufacturing enterprises' innovation investment input and a moderating variable of the peer effect in manufacturing enterprises' innovation input. This not only provides a theoretical basis for further research on the influence of Confucian culture on manufacturing enterprises' innovation inputs, but also provides theoretical support for improving the effectiveness of the peer effect in manufacturing enterprises' innovation inputs. These studies are important for understanding the relationship between peer effect, Confucian culture, and manufacturing enterprises' innovation input in the Chinese context, as well as for guiding and optimizing resource allocation to improve the innovation capability of the manufacturing companies.

1.Literature Review

Some scholars have conducted extensive research on manufacturing enterprises' innovation input from various perspectives. Firstly, from an internal perspective of the firm, the main focus is around financing constraints [1], financial performance [2], and managerial incentives [3]. Secondly, from an external perspective of the firm, it mainly focuses on environmental regulations, policy reforms and government subsidies. The above literature mainly assumes the independence of corporate decision-making and ignores the interaction effects of decision-making within peer firms. Given similar technological challenges and operational risks, decision-making interaction among peer firms can help reduce risks and uncertainties. The phenomenon of firm decision-making being influenced by and aligned with peer firms is known as the "peer effect" [4].

Confucian culture, as the mainstream and important component of traditional Chinese culture, has permeated various aspects of Chinese politics, economy, and corporate management. However, there is still debate about whether Confucian culture can promote manufacturing enterprises' innovation input. Some scholars support the view of Confucian culture promoting corporate innovation [5]. However, other scholars argue that the hierarchical concept, collectivism, and harmonious culture emphasized by Confucian culture inhibit innovative thinking and information exchange, which hinder corporate innovation.

Therefore, this study examines the positive impact of Confucian culture on corporate innovation input by focusing on listed manufacturing companies and considers the impact of peer effect in social interactions. This study analyzes Confucian culture, peer effect, and corporate innovation input within the same theoretical framework to complement and extend the existing literature. Additionally, this study examines the moderating role of Confucian culture in the peer effect of corporate innovation inputs, taking into account the nature of the firm ownership and characteristics of the business environment. Under the influence of different degrees of Confucian culture, this study also examines the different effects of internal and external factors, such as firm age, firm size, market competitiveness, and digital financial index, on the homogeneity of firm innovation inputs, revealing the mechanisms by which innovation input homogeneity affects innovation performance. These findings provide new insights for enhancing corporate innovation input and output.

2.Research Hypotheses

2.1.Peer Effect in Innovation Input

The peer effect of manufacturing enterprises' innovation input refers to the tendency of firms to adjust their innovation input decision-making based on the innovation inputs of peer firms due to social interactions. Referencing to or balancing the innovation input of peer firms in decision-making can effectively alleviate the negative impact of insufficient innovation or innovation failure. Under the same economic, technological, and policy environments, the cost for focal firms to obtain information or experience from peer firms is relatively low, while the cost of relying solely on internal experience for decision-making is relatively high. Therefore, in order to reduce the risk of innovation input decision-making and minimize uncertainty, focal firms adjust their decision-making based on the innovation input levels of peer firms, leading to convergence in innovation input decision-making among focal firms and their peer firms [6]. According to competitive imitation theory, focal firms weigh or imitate the decision-making of peer competitors to maintain the competitive status quo or restrict competitors. When peer firms increase innovation input, focal firms also imitate their innovation input decision-making to alleviate competitive pressure or reduce risks, leading to an increase in their own innovation input in response [7]. In summary, in order to reduce information acquisition costs or maintain competitive advantages, firms tend to make innovation input decision-making consistent with their peer firms, generating a peer effect in manufacturing enterprises' innovation input. Based on this, Hypothesis 1 is proposed.

Hypothesis 1: *There is a peer effect in manufacturing enterprises' innovation input.*

2.2.Confucian Culture and Innovation Input

Manufacturing enterprises' innovation relies on funding, technological knowledge, and talent. Confucian culture advocates "Ren, Yi, Li, Zhi" ("benevolence, righteousness, propriety, wisdom" in English) (Mencius), where "Zhi (wisdom)" influences firms to value the intelligence, skills, and creativity of their employees, thereby helping firms increase their innovation input. Confucian culture emphasizes moral cultivation, as reflected in concepts such as "put righteousness before profit and honor, put profit before righteousness and disgrace" (Xunzi), which can impose moral constraints on managers. Confucian culture's concept of "Ge Wu Zhi Zhi" ("investigate things, acquire knowledge" in English) emphasizes the spirit of practical and scientific exploration, which stimulates firms' practical and exploratory spirit, thus positively influencing their innovation input. Based on this, Hypothesis 2 is proposed

Hypothesis 2: *Confucian culture has a significant positive impact on manufacturing enterprises' innovation input.*

2.3.Confucian Culture, Peer Effect and Innovation Input

The "Zhong Yong" (Doctrine of the Mean) in Confucian culture embodies the idea that firms accept or reference external information and use it to deal with risks. Firms influenced by Confucian culture are more likely to imitate and refer to the innovation input decisions of their peer firms in order to avoid risks. When peer firms increase innovation inputs, firms that are strongly influenced by Confucian culture are more likely to learn from their decisions and adjust their own innovation inputs accordingly. The collective ideology in Confucian culture is embodied in the saying "the world belongs to everyone when the great path prevails" (Li ji). Some scholars suggest that under the influence of collective ideology [8], information exchange and interaction are more effective within a collective, and high-quality information cannot be obtained outside the collective. Through internal connections established within the collective, firms can obtain market information necessary for innovation [9]. The stronger the influence of

Confucian culture on peer firms, the lower the cost of acquiring internal collective information, the stronger the effectiveness of information, and the promotion of imitation, reference, and learning among peer firms, thereby enhancing the peer effect in manufacturing enterprises' innovation input. Based on this, Hypothesis 3 is proposed.

Hypothesis 3: *Confucian culture can enhance the peer effect in manufacturing enterprises' innovation input.*

In summary, the research framework of this paper is shown in Figure 1.

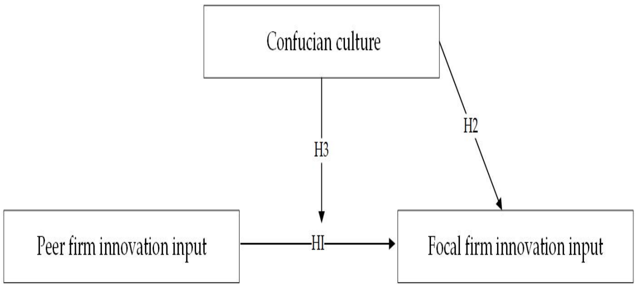

Fig.1. Research framework

3.Research Design

3.1.Sample Selection and Data Sources

In this study, we selected listed companies in the Chinese manufacturing industry from 2011 to 2020 as the initial sample and performed data screening and processing. The specific procedures were as follows: excluding samples with abnormal asset-liability ratios; excluding ST and PT samples; excluding samples with missing data for variables. Ultimately, we obtained 11,655 observed samples. To eliminate the interference of extreme values, the variables are tailed by 1%. The financial data, corporate governance data, corporate innovation data, and the latitude and longitude data of Confucian temples and company registration locations were obtained from the CSMAR database. Data processing was conducted using STATA 14.0 software.

3.2.Variable Descriptions

3.2.1.Explained Variable

Focal Firm Innovation Input(RD): Following the research methods of Griffiths and Webster [10], this study measures manufacturing enterprises' innovation input by the ratio of research and development (R&D) expenditure to operating income. In subsequent robustness tests, the ratio of R&D expenditure to total assets will be used as an alternative measurement.

3.2.2.Explanatory Variable

Peer Firm Innovation Input($PeerRD$): Drawing upon the research methods of Zhang and Du [11], this study defines peer firms within the manufacturing industry through a three-level industry classification of listed companies. The innovation input of peer firm is measured by the average innovation input of peer firms excluding the focal firm itself. The calculation method is as follows:

$$PeerRD_{-i,j,t} = \sum_{k\in j,k\neq i} RD_{k,j,t} \div (n_{j,t} - 1) \quad (1)$$

Where, i represents the focal firm, j represents the three-level classification of the manufacturing industry, t represents the year, k represents other peer firms within the manufacturing industry j excluding focal firm i, and $n_{j,t}$ represents the total number of firms in industry j. $\sum_{k\in j,k\neq i} RD_{k,j,t}$ represents the total innovation input of peer firms.

3.2.3.Moderating Variable

Confucian Culture ($Conf$): Following the research methods of Xu, Li and Lee [12], this study measures Confucian culture based on the addresses of Confucian temples and companies by counting the number of Confucian temples within 100 km of the focal firm's registered address

3.2.4.Control Variables

Drawing on existing literature [13], this study selects relevant variables that affect innovation input as control variables. Specifically, these variables include: firm size, leverage ratio, operating cash flow, growth potential, profitability, CEO duality, shareholding concentration, independent directors, board size, executive compensation, while controlling for industry and year. Please refer to Table 1 for specific variables and explanations.(Attachment1)

3.3.Model Construction

In order to test Hypothesis 1, following the approach of Manski [14], we construct the baseline model as follows:

$$RD_{i,j,t} = \alpha_0 + \alpha_1 PeerRD_{-i,j,t} + \sum \alpha_{2\sim10} Control_{i,j,t} + \varepsilon \quad (2)$$

Where the dependent variable RD represents the focal firm's innovation input. The explanatory variable $PeerRD$, represents the peer firms' innovation input. The control variables are denoted by $Control$, and their details can be found in Table 1. α_0 is the intercept term, and the estimated coefficient α_1 of $PeerRD$ is the main focus of investigation for Hypothesis 1. If α_1 is greater than zero and statistically significant, it indicates the presence of peer effects in manufacturing enterprises' innovation input, supporting the validity of Hypothesis 1. The term ε represents the error term.

To test hypothesis 2, the model is constructed as follows:

$$RD_{i,j,t} = \beta_0 + \beta_1 Conf_{i,j,t} + \sum \beta_{2\sim10} Control_{i,j,t} + \varepsilon \quad (3)$$

Where, β_0 represents the constant term. The estimated coefficient β_1 of $Conf$ is the key focus of hypothesis 2. If β_1 is greater than 0 and significant, it indicates a significant positive influence of Confucian culture on manufacturing enterprises' innovation input, supporting the validity of hypothesis 2.

To test hypothesis 3, the model is constructed based on Model (1) as follows:

$$RD_{i,j,t} = \chi_0 + \chi_1 PeerRD_{-i,j,t} + \chi_2 Conf_{i,j,t} + \chi_3 PeerRD_{-j,j,t} \times Conf_{i,j,t} + \sum \chi_{4\sim12} Control_{i,j,t} + \varepsilon$$

(4)

Where, χ_0 represents the constant term. $PeerRD \times Conf$ represents the interaction term between innovation input of peer firms and Confucian culture. If the estimated coefficient χ_3 of $PeerRD$ is greater than 0 and significant, it indicates a positive moderating effect of Confucian culture on the relationship between $PeerRD$ and RD. This implies that Confucian culture can strengthen the peer effect in focal firm's innovation input.

4.Results

4.1.Empirical results

4.1.1.Peer effect in innovation input

Table 2, columns (1) to (3), report the regression results for Hypothesis 1. Among them, column (1) controls for industry dummy variables, column (2) controls for year dummy variables, and column (3) simultaneously controls for industry and year dummy variables. The results show that the estimated coefficients of $PeerRD$ on RD are all significantly positive. In column (3), the estimated coefficient of $PeerRD$ is 0.542 ($t=12.55$, $p<0.01$), significant at the 1% level. This means that for every 1 percentage point increase in innovation input of the peer firms, the focal firms' innovation input will increase by 0.542 percentage points. The above results indicate that the innovation input of the peer firms has a significant positive impact on the innovation input of focal firm, verifying the existence of the peer effect in manufacturing enterprises' innovation input and supporting Hypothesis 1.

4.1.2.The impact of Confucian culture

Table 2, columns (4) to (6), report the regression results for Hypothesis 2. Among them, column (4) controls for industry dummy variables, column (5) controls for year dummy variables, and column (6) simultaneously controls for industry and year dummy variables. The results show that the estimated coefficients of $Conf$ on RD are all significantly positive. In column (6), the estimated coefficient of $Conf$ is 0.001 ($t=4.67$, $p<0.01$), significant at the 1% level. This indicates that for every 1 percentage point increase in the degree of influence of Confucian culture, innovation input of focal firm will increase by 0.001 percentage points. In other words, manufacturing enterprises' innovation input is significantly positively influenced by Confucian culture, supporting Hypothesis 2.

4.1.3.The moderating effect of Confucian culture

Table 2, columns (7) to (9), report the regression results for Hypothesis 3 using the full sample. Among them, column (7) controls for industry dummy variables, column (8) controls for year dummy variables, and column (9) simultaneously controls for industry and year dummy variables. In column (9), the estimated coefficient of PeerRD × Conf is 0.022 (t=3.72, p<0.01), significant at the 1% level. This indicates that the deeper the influence of Confucian culture, the more significant the positive impact of innovation input of the peer firms on the innovation input of focal firm. In other words, Confucian culture enhances the peer effect in manufacturing enterprises' innovation input, supporting Hypothesis 3. The results in columns (10) and (11). (Attachment 2)

Variable	(1)	(2)	(3)
PeerRD	0.498*** (5.69)	0.451*** (5.19)	0.444*** (3.87)
PeerRD²			0.800 (0.82)
Focal Firms' Controls	-	*Control*	*Control*
Peer Firms' Controls	*Control*	*Control*	-
Industry	*Control*	*Control*	*Control*
Year	*Control*	*Control*	*Control*
Constant	0.013 (1.35)	0.039*** (3.44)	0.026*** (2.60)
Observation	11 655	11 655	11 655
R^2	0.177	0.220	0.218

4.2.Robustness Tests

To ensure the robustness and reliability of the empirical findings, various methods were employed to conduct robustness tests, including omitted variable tests, high-order polynomial tests, lagged period tests and reduced sample tests.

4.2.1.Omitted Variable Test

To address potential omitted variable bias, the average control variables of peer firms were added to the baseline regression. The core coefficient remained significantly positive (0.498 and 0.451, p<0.01), supporting Hypothesis 1.

4.2.2.High-Order Polynomial Test

A high-order polynomial test was conducted by including a quadratic term. The linear term remained significant while the quadratic term was insignificant, confirming a linear relationship and validating the baseline model specification.

Note: t-values are in parentheses.
*p<0.1, **p<0.05, ***p<0.01.

Tab.3. Results of omitted variable and model polynomial tests

4.2.3.Lagged Period Test

To address endogeneity, columns (1) to (3) of Table 4 present the lagged period test. The estimated coefficient of PeerRD is 0.645 (t=8.16, p<0.01), supporting Hypothesis 1. The coefficient for lagged Conf is 0.001 (t=4.39, p<0.01), supporting Hypothesis 2. The estimated coefficient of PeerRD × Conf is 0.018 (t=2.54, p<0.01), indicating Confucian culture positively moderates the innovation peer effect, supporting Hypothesis 3.

4.2.4.Small Sample Test

The sample is restricted to high-tech manufacturing industries (C25, C26, C27, C35, C36, C37, C38, C39, C40; n=2,113). Results in columns (4) to (6) of Table 7 remain consistent: the coefficient of PeerRD is 0.689 (t=10.48, p<0.01); for Conf is 0.001 (t=1.98, p<0.05); and for the interaction term is 0.036 (t=2.46, p<0.05). All hypotheses are again supported. (Attachment 3)

5.Further Analysis

5.1.Heterogeneity Analysis

5.1.1.The heterogeneity of property rights

Different types of corporate property rights have inherent differences in their strategic objectives. State-owned manufacturing firms, for example, are required to assume social responsibilities such as maintaining economic market order, ensuring employment, and improving people's livelihoods. Therefore, their innovation investments are more likely to be influenced by the government. On the other hand, non-state-owned firms face intense market competition and are more likely to be influenced by innovation input of peer firms. To examine the heterogeneity of peer firm innovation input and the moderating effect of Confucian culture among firms with different property rights, this study divides the sample into state-owned and non-state-owned enterprise groups. (Attachment 4)

5.1.2.The heterogeneity of business environment

The business environment in which an enterprise operates is one of the important factors influencing corporate innovation input. According to China Provincial Enterprise Operating Environment index 2017 Report, when the business environment index of the sample firm is greater than the mean, it is classified as the high business environment group; otherwise, it is classified as the low business environment group. This means that the higher the business environment index, the stronger the promoting effect of Confucian culture on peer effect in manufacturing enterprises' innovation input. In conclusion, there is a significant peer effect in innovation input when the enterprise operates in a high business environment index, but not when it operates in a low business environment index. (Attachment 5)

5.2.Analysis of Moderating Effect

5.2.1.Negative moderating effect of firm age

Established and successful companies in the same industry may have more resources to acquire high-quality information and the ability to evaluate, absorb, and integrate information. Firms in information disadvantage or lack may refer to mature firms with excellent information advantages to reduce decision-making risks [15]. Pomorski has found that younger firms are more likely to be influenced by other mature firms in the same industry [16]. Therefore, the natural logarithm of the firm's listing age plus one (AGE) is used to measure firm age, where a smaller value represents a younger firm. The test results of the impact of firm age on the peer effect in manufacturing enterprises' innovation input are shown in Table 7, Columns (1)-(3). In Column (1), the estimated coefficient of is -0.161 (t=-5.15, p<0.01), which is significant at the 1% level. This indicates that firm age negatively moderates the peer effect in manufacturing enterprises' innovation input. It means that the younger the firm, the more it is influenced by the peer effect in manufacturing enterprises' innovation input. In Columns (2) and (3), the results of the grouping test on whether the firm is influenced by Confucian culture are shown. When the firm is influenced by Confucian culture, the estimated coefficient of in Column (2) is -0.168 (t=-5.16, p<0.01), which is significant at the 1% level, indicating the effective negative moderating effect of firm age. This means that under the influence of Confucian culture, the older the firm, the more significant the impact of the peer effect on innovation. When the firm is not influenced by Confucian culture, the estimated coefficient of in Column (3) is -0.055 (t=-0.45, p>0.10), which is not significant. This means that the negative moderating effect of firm age is ineffective for firms not influenced by Confucian culture.

5.2.2.Negative moderating effect of firm size

Leary and Robert have argued that decision-makers in smaller firms are more likely to imitate the top performers in the same group [17]. The natural logarithm of total assets plus one ($Size$) is used to measure firm size, where a smaller value represents a smaller firm. The test results of the impact of firm size on the peer effect of innovation input are shown in Table 7, Columns (4)-(6). In Column (4), the estimated coefficient of $PeerRD \times Size$ is -0.073 (t=-4.00, p<0.01), which is significant at the 1% level, indicating that firm size negatively moderates the relationship between peer firms' innovation input and focal firm's innovation input. It means that the smaller the firm size, the more it is influenced by the peer effect in manufacturing enterprises' innovation input. The results of the grouping test on whether the firm is influenced by Confucian culture in Columns (5) and (6) show that the estimated coefficients are positive and significant at the 1% level, but the t-value in Column (8) is larger, indicating stronger significance. This means that the negative moderating effect of firm size is effective for firms influenced by Confucian culture, but ineffective for firms not influenced by Confucian culture.

5.2.3.Positive moderating effect of market competition

Faced with same-group competitors with similar resource endowments or comparable market positions, imitating peer firms' decision-making is a common means to alleviate competition [15]. To maintain competitive advantage or catch up with competitors, decision-makers choose to make decisions consistent with those of same-group competitors to mitigate decision-making risks or gain competitive advantage. Referring to research by Dhaliwal, Huang, Khurana and Pereira [18], the negative reciprocal of the Herfindahl-Hirschman Index is used to measure market competition (COM), where a larger value represents more intense market competition. The test results of the impact of market competition on the peer effect in manufacturing enterprises' innovation input are shown in Table 7, Columns (7)-(9). In Column (7), the estimated coefficient of $PeerRD \times COM$ is 2.041 (t=9.73, p<0.01), which is significant at the 1% level, indicating that market competition positively moderates the relationship between peer firm's innovation input and focal firm's innovation input. It means that the higher the market competition, the more easily that the focal firm's innovation input is influenced by the peer effect. The results of the grouping test on whether the firm is influenced by Confucian culture in Columns (8) and (9) show that the estimated coefficients are both significant and positive at the 1% level, but the t-value in Column (8) is larger, indicating stronger significance.

5.2.4.Positive moderating effect of digital finance

Hsu, Tian and Xu argue that the financial market environment is an important factor influencing firm innovation [19]. Digital finance, utilizing information technologies such as big data, cloud computing, blockchain, and artificial intelligence, has been considered to alleviate information asymmetry in the market, expand funding sources, and promote corporate innovation by alleviating financing constraints [20]. Therefore, the development of digital finance has a significant impact on firm innovation. This paper employs the "Digital Inclusive Finance Index" compiled by Peking University Internet Finance Research Center is used to measure the level of digital finance development in 31 provincial-level regions (autonomous regions, municipalities) in mainland China. Since the values of the digital finance index in the sample range from 10 to 500, the natural logarithm of the digital finance index plus one (DIF) is used to eliminate the dimensional impact. The test results of the impact of digital finance on the peer effect in manufacturing enterprises' innovation input are shown in Table 7, Columns (10)-(12). In Column (10), the estimated coefficient of $PeerRD \times DIF$ is 0.054 (t=2.64, p<0.01), which is significant at the 1% level, indicating that the digital finance index positively moderates the relationship between peer firm's innovation input and focal firm's innovation input. It means that the higher the digital finance index, the more easily firm innovation input is influenced by the peer effect. The results of the grouping test on whether the firm is influenced by Confucian culture in Columns (11) and (12) show that the estimated coefficients are both significant and positive, but the significance is stronger in Column (11).(Attachment 6)

5.3.Analysis of mediating effect

In order to examine the consequences of the peer effect in manufacturing enterprises' innovation input, this study constructs three consecutive regression models to test the mediating effects. Following the approach of Baron and Kenny [21], the models examine the impact of peer firms' innovation input on focal firm's innovation output, the impact of peer firms' innovation input on focal firm's innovation input, and the mediating effect of focal firm's innovation input on the relationship between peer firms' innovation input and focal firm's innovation output. Foal firm innovation output ($Inno$) is measured by the logarithm of the total number of invention patents, utility models, and design patents plus one. From Table 8, Columns (1)-(3), it can be observed that for the entire sample, the total effect estimate coefficient of peer firms' innovation input on focal firm innovation output is 6.266 (t=7.72, p<0.01), which is significant at the 1% level. This indicates a significant positive impact of peer firms' innovation input on focal firm innovation output. The estimated coefficient of peer innovation input (Column 2) is 0.542 (t=12.55, p<0.01), and the estimated coefficient of focal firm's innovation input (Column 3) is 2.713 (t=6.45, p<0.01), both significant at the 1% level. The mediating effect, calculated as 0.542 × 2.713 ≈ 1.470, accounts for approximately 23.467% of the total effect. Columns (4)-(6) and Columns (7)-(9) present the results of the subgroup analysis based on whether firms are influenced by Confucian culture. Among them, the results in Columns (4)-(6) show that under the influence of Confucian culture, the estimated coefficients of peer firms' innovation input and focal firm innovation input are both positive and significant at the 1% level. The total effect coefficient on firm innovation output is 6.296, and the mediating effect is calculated as 0.553 × 2.602 ≈ 1.439, accounting for approximately 22.854% of the total effect. This indicates that under the influence of Confucian culture, peer firms' innovation input promotes firm innovation output through facilitating innovation input. However, in the group not influenced by Confucian culture (Columns (7)-(9)), the mediating effect becomes ineffective. The estimated coefficients of peer firms' innovation input are not significant, suggesting a weakened relationship between peer firms' innovation input and focal firm innovation input/output is not influenced by Confucian culture. (Attachment 7)

Conclusion

1.Research Conclusion

This study used data from Chinese listed companies in the manufacturing industry from 2011 to 2020 to examine the influence of Confucian culture and peer effect in manufacturing enterprises' innovation input. The research findings are as follows: there is a peer effect in manufacturing enterprises' innovation input, with an increase in manufacturing enterprises' innovation input associated with an increase in peer firms' innovation input. Confucian culture has a significant positive impact on manufacturing enterprises' innovation input, and it also positively moderates the peer effect in manufacturing enterprises' innovation input. The deeper the influence of Confucian culture, the more it facilitates the promotion of manufacturing enterprises' innovation input, and the stronger the peer effect in manufacturing enterprises' innovation input. The peer effect of manufacturing enterprises' innovation input and the moderating effect of Confucian culture have heterogeneous effects for firms with different ownership structures and different business environments. Non-state-owned firms exhibit a peer effect in innovation input, while state-owned firms do not. Confucian culture has a significant positive impact on innovation input for firms with different ownership structures, but its moderating effect is only effective for non-state-owned firms. The peer effect in innovation input exists only when the firm's business environment index is relatively high. Compared to the influence of a low business environment index, the positive effect of Confucian culture on innovation input and its moderating effect on the peer effect are stronger when the business environment index of the firm is high. Further analysis of influencing factors reveals that the younger the firm, the smaller its size, the higher the level of market competition it faces, and the higher the digital finance index of its region, the stronger the influence of the peer effect on its innovation input, and this mechanism is more effective under the influence of Confucian culture. In the analysis of economic consequences, it is found that the peer effect in innovation input can promote focal firm's innovation output through the mediating variable of focal firm's innovation input, and this mediating effect is only effective under the influence of Confucian culture. This study examines the relationship between Confucian culture, peer effect, and manufacturing enterprises' innovation input, contributing to a deeper understanding of the role of Confucian culture and peer effects in manufacturing enterprises' innovation input and providing valuable references for enhancing innovation in the manufacturing industry.

2.Research Implications

The policy implications of this study are as follows: First, fully recognize and leverage the promotion of innovation input in the manufacturing industry by peer effects. When making decisions about innovation input, pay attention to the influence of peer firms' innovation input decision-making on the focal firm's own decision-making. Consider the differential effects of different ownership structures and business environments on the peer effect in manufacturing enterprises' innovation input. Also, note that the influence of the peer effect in innovation input is also affected by internal and external factors such as the firm age, the firm size, the market competition, and the digital finance index. In the context of China's rapid development of the information economy, the social interaction between peer firm is increasingly playing a prominent role in promoting the healthy and orderly operation of the economy and society. Market participants should fully recognize and leverage the promotion of innovation input in the manufacturing industry by peer effects, make full use of the strengths of decision-making interaction among peer firms, and effectively accelerate the realization of the goal of building a technology-strong country. Second, fully leverage the positive impact of Confucian culture and guide and cultivate positive interactions among firms. Confucian culture is an important factor influencing innovation input in the manufacturing industry, as well as a moderating variable that enhances the effect of the peer effect in innovation input. Encourage eligible manufacturing enterprises to create a Confucian cultural atmosphere and foster the correct values and innovation awareness within the organization. Under the influence of Confucian culture, the peer effect in innovation input is stronger, and this peer effect has a positive impact on innovation output. Conversely, it does not hold true. Firms can determine whether to follow and imitate the innovation input of peer firms based on the degree of influence of Confucian culture, as well as factors such as ownership structure, firm age, firm size, business environment, market competition, and digital finance index. Government regulatory authorities need to pay attention to promoting Confucian culture, actively guide and cultivate positive interactions among peer firms in the manufacturing industry, and effectively improve the level of innovation in the manufacturing industry.

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Attachment 1

Tab.1. Variable definition.

Type	Name	Symbol	Description
Explained Variable	Focal Firm Innovation Input	*RD*	Ratio of research and development (R&D) expenditure to operating revenue
Explanatory Variable	Peer Firm Innovation Input	*PeerRD*	See Model (1)
Moderating Variable	Confucian Culture	*Conf*	Number of Confucian temples within a 100-kilometer radius of the focal firm
Control Variables	Firm Size	*Size*	Natural logarithm of total assets plus one
	Leverage Ratio	*Lev*	Ratio of liabilities to total assets
	Operating Cash Flow	*Cash*	Ratio of cash and cash equivalents to total assets
	Growth Potential	*Tobin'Q*	Ratio of market value of equity plus book value of debt to book value of total assets
	Profitability	*ROA*	Ratio of net profit to total assets
	CEO Duality	*Dual*	Indicator variable: 1 if the Chairman and CEO roles are combined, 0 otherwise
	Shareholding Concentration	*Shtop*	Ratio of shares held by the largest shareholder to total shares outstanding
	Independent Directors	*Indep*	Ratio of independent directors to total board members
	Board Size	*Board*	Total number of board members
	Executive Compensation	*Salary*	Natural logarithm of the sum of compensation for the top three executives plus one
	Industry	*Industry*	Dummy variables based on three-level industry classification within the manufacturing sector
	Year	*Year*	Dummy variables representing each year

Attachment 2

Tab.2.The regression results of the models.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Model（1）			Model（2）			Model（3）			Model（1）	
	Full sample			Full sample			Full sample			Conf≥1	Conf=0
PeerRD	0.630*** (17.83)	0.699*** (28.35)	0.542*** (12.55)				0.477*** (10.47)	0.549*** (12.77)	0.381*** (7.67)	0.553*** (12.40)	0.111 (0.78)

Conf				0.001*** (4.87)	0.001*** (4.60)	0.001*** (4.67)	0.0004* (1.75)	0.0004* (1.76)	0.0005* (1.87)		
PeerRD×Conf							0.021*** (3.56)	0.021*** (3.52)	0.022*** (3.72)		
Controls	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Industry	Control	-	Control	Control	-	Control	Control	-	Control	Control	Control
Year	-	Control	Control	-	Control	Control	-	Control	Control	Control	Control
Constant	0.004 (0.41)	0.016* (1.80)	0.009 (0.81)	0.003 (0.24)	0.057*** (5.95)	0.017 (1.59)	0.007 (0.65)	0.019** (2.08)	0.011 (1.06)	0.010 (0.79)	0.020 (0.96)
Observation	11 655	11 655	11 655	11 655	11 655	11 655	11 655	11 655	11 655	10 956	699
R^2	0.205	0.203	0.208	0.164	0.128	0.186	0.208	0.206	0.212	0.207	0.273

Note: t-values are in parentheses. *p<0.1, **p<0.05, ***p<0.01.

Attachment 3

Tab.4. Results of lagged period and small sample test

Variables	(1)	(2)	(3)	(4)	(5)	(6)
PeerRD	0.645*** (8.16)		0.511*** (4.97)	0.689*** (10.48)		0.440*** (4.14)
Conf		0.001*** (4.39)	0.0003 (1.12)		0.001** (1.98)	0.002** (2.03)
PeerRD×Conf			0.018*** (2.54)			0.036** (2.46)
Controls	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Industry	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Year	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Constant	0.0003 (0.02)	0.011 (0.60)	0.002 (0.10)	0.004 (0.14)	0.008 (0.24)	0.012 (0.38)
Observation	11 655	11 655	11 655	2 113	2 113	2 113
R^2	0.152	0.130	0.154	0.203	0.160	0.208

Note: t-values are in parentheses. *p<0.1, **p<0.05, ***p<0.01.

Attachment 4

Tab.5. Results of property rights heterogeneity test

Variable	State-Owned Group			Non-State-Owned Group		
	(1)	(2)	(3)	(4)	(5)	(6)

PeerRD	0.235 (1.20)		0.251 (1.34)	0.586*** (16.07)		0.369*** (6.98)
Conf		0.0004* (1.66)	0.001 (0.98)		0.001*** (4.96)	0.001*** (3.56)
PeerRD×Conf			-0.003 (-0.26)			0.030*** (4.59)
Controls	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Industry	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Year	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Constant	0.026 (1.58)	0.027** (1.98)	0.022 (1.42)	0.016 (1.12)	0.028* (1.94)	0.020 (1.40)
Observation	2 751	2 751	2 751	8 904	8 904	8 904
R^2	0.185	0.184	0.187	0.213	0.182	0.218

Note: t-values are in parentheses. *p<0.1, **p<0.05, ***p<0.01.

Attachment 5

Tab.6.Results of business environment heterogeneity test

Variable	Higher Business Environment Group			Lower Business Environment Group		
	(1)	(2)	(3)	(4)	(5)	(6)
PeerRD	0.611*** (17.62)		0.448*** (9.04)	-0.032 (-0.12)		-0.168 (-0.73)
Conf		0.002*** (2.80)	-0.001*** (-3.99)		0.001*** (3.87)	0.0002 (0.22)
PeerRD×Conf			0.023*** (3.82)			0.033* (1.90)
Controls	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Industry	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Year	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Constant	-0.003 (-0.27)	0.008 (0.80)	0.003 (0.27)	0.058 (1.55)	0.061* (1.87)	0.071** (2.01)
Observation	10 183	10 183	10 183	1 472	1 472	1 472
R^2	0.255	0.216	0.257	0.142	0.160	0.163

Attachment 6

Tab.7.Results of the moderating effect test

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Firm Age			Firm Size			Market Competition			Digital Finance		
	Full sample	Conf ≥1	Conf =0	Full sample	Conf≥ 1	Conf=0	Full sample	Conf≥ 1	Conf= 0	Full sample	Conf≥ 1	Conf= 0
PeerRD× AGE	-0.161*** (-5.	-0.168*** (-5.16)	-0.055 (-0.45)									

	15)											
PeerRD × Size				-0.073*** (-4.00)	-0.074*** (-3.81)	-0.038 (-0.86)						
PeerRD × COM							2.401*** (9.73)	2.382*** (9.51)	3.150*** (2.64)			
PeerRD × DIF										0.054*** (2.64)	0.057** (2.42)	0.045* (1.80)
PeerRD	0.720*** (15.17)	0.743*** (15.49)	0.051 (0.17)	2.12*** (5.52)	2.144*** (5.27)	0.934 (0.95)	0.612*** (12.65)	0.621*** (12.42)	0.213 (1.41)	-0.002*** (-2.74)	0.249* (1.80)	-0.035 (-0.24)
AGE	-0.0001 (-0.03)	-0.001 (-0.51)	-0.011*** (-2.59)									
COM							0.047*** (5.18)	0.047*** (5.02)	0.068 (1.63)			
DIF										0.259** (2.18)	0.003*** (2.82)	-0.00004 (-0.04)
Controls	*Contro*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Industry	*Contro*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Year	*Contro*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Constant	-0.030** (-2.44)	-0.030** (-2.28)	-0.007 (-0.30)	-0.057*** (-3.72)	-0.058*** (-3.50)	-0.008 (-0.21)	0.005 (0.49)	0.007 (0.55)	0.013 (0.63)	0.020 (1.63)	0.023* (1.65)	0.014 (0.67)
Observation	11 655	10 956	699	11 655	10 956	699	11 655	10 956	699	11 655	10 956	699
R^2	0.220	0.218	0.336	0.210	0.209	0.273	0.215	0.214	0.285	0.210	0.209	0.290

Attachment 7

Tab.8.Results of mediating effect test

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Full sample			Conf≥1			Conf=0		

	Inno	*RD*	*Inno*	*Inno*	*RD*	*Inno*	*Inno*	*RD*	*Inno*
RD			2.713***			2.602***			6.175***
			(6.45)			(6.24)			(3.14)
PeerRD	6.266***	0.542***	4.796***	6.296***	0.553***	4.857***	-2.019	0.111	-2.704
	(7.72)	(12.55)	(5.67)	(7.61)	(12.40)	(5.64)	(-0.52)	(0.78)	(-0.71)
Controls	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Industry	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Year	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*	*Control*
Constant	-8.640***	0.009	-8.663***	-8.890***	0.010	-8.915***	-7.285***	0.020	-7.405***
	(-22.38)	(0.81)	(-22.51)	(-22.21)	(0.79)	(-22.34)	(-6.02)	(0.96)	(-6.14)
Observation	11 655	11 655	11 655	10 956	10 956	10 956	699	699	699
R^2	0.210	0.208	0.217	0.208	0.207	0.215	0.318	0.273	0.334

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