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Article

Digital Twin Empowerment and Social Co-Governance: A New Paradigm for Sustainable Development of Urban Low-Altitude Transportation Infrastructure

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ABSTRACT

With the accelerated construction of urban low-altitude transportation infrastructure, the traditional sustainable development model focusing on environmental impact and carbon reduction has been difficult to meet the multi-dimensional needs of safety supervision, resource allocation and social coordination. This study proposes a new paradigm of sustainable development integrating digital twin (DT) technology and social co-governance, aiming to solve the practical dilemmas such as low efficiency of infrastructure operation management, insufficient public participation and lagging safety early warning. Based on the technical characteristics of digital twin (full-element mapping, real-time interaction, iterative optimization) and the core concept of social co-governance (multi-subject collaboration, shared responsibility), this study constructs a „digital twin + social co-governance" integrated framework for urban low-altitude transportation infrastructure, and verifies its feasibility and effectiveness through case studies of 8 typical cities in China, Germany and Singapore. The research results show that: (1) The digital twin system can reduce the operation and maintenance energy consumption of low-altitude transportation infrastructure by 18%-26% and improve the efficiency of fault diagnosis by 60%; (2) The social co-governance mechanism involving government, enterprises, communities and the public can increase the public acceptance of low-altitude transportation infrastructure by 35%-45% and reduce the conflict events caused by environmental impacts by 50%; (3) The integrated application of digital twin and social co-governance can realize the whole-life cycle intelligent management and multi-stakeholder win-win of low-altitude transportation infrastructure, and promote the sustainable development level to be improved by 40%-50% compared with the traditional model. Finally, this study puts forward targeted policy suggestions from the aspects of technical standardization, institutional guarantee and capacity building, which provides a new theoretical framework and practical reference for the high-quality and sustainable development of urban low-altitude transportation infrastructure worldwide.

Keywords: Urban low-altitude transportation infrastructure; Digital twin; Social co-governance; Sustainable development; Intelligent operation and maintenance; Public acceptance

1. Introduction

1.1 Research Background

Under the background of global urbanization and carbon neutrality goals, urban low-altitude transportation infrastructure, as an important part of the smart city transportation system, has become a key support for promoting the upgrading of the transportation industry and developing the low-altitude economy. However, with the continuous expansion of the scale of infrastructure construction and the increasingly complex operation environment, a series of new challenges have emerged in the process of sustainable development: on the one hand, the traditional operation and maintenance mode relies on manual inspection and regular maintenance, which has the problems of low efficiency, high energy consumption and lagging fault response, resulting in the waste of resources and the increase of carbon emissions; on the other hand, the lack of effective communication and interaction mechanisms between infrastructure construction and operation and the public leads to low public acceptance of low-altitude transportation, and even conflicts between infrastructure projects and community residents due to noise, electromagnetic radiation and other issues. In addition, the cross-departmental and cross-regional supervision of low-altitude transportation infrastructure is disjointed, and the lack of collaborative governance capacity makes it difficult to guarantee the safety and stability of infrastructure operation.

In recent years, digital twin technology has developed rapidly and been widely applied in the field of transportation infrastructure, which provides a new technical means for solving the above problems. Digital twin can realize the real-time mapping and dynamic simulation of physical infrastructure through the integration of multi-source data and multi-dimensional models, and provide support for intelligent decision-making. At the same time, the concept of social co-governance has gradually been valued in the field of urban governance, emphasizing the participation of multiple subjects such as government, enterprises, communities and the public in the governance process, which helps to improve the rationality and acceptability of decision-making. However, the existing research mostly focuses on the single application of digital twin technology in infrastructure or the independent discussion of social co-governance, and there is a lack of in-depth research on the integrated development of the two and its role in promoting the sustainable development of low-altitude transportation infrastructure. Therefore, exploring the integrated paradigm of digital twin empowerment and social co-governance is of great significance for promoting the sustainable development of urban low-altitude transportation infrastructure.

1.2 Research Objectives and Questions

The main objective of this study is to construct a new paradigm of sustainable development of urban low-altitude transportation infrastructure based on digital twin empowerment and social co-governance, and clarify its operation mechanism, implementation path and application effect. To achieve this objective, the following research questions are proposed: (1) What is the connotation and theoretical framework of the integrated development of digital twin empowerment and social co-governance in the field of low-altitude transportation infrastructure? (2) How to design the technical system and institutional mechanism of the „digital twin + social co-governance" integrated paradigm? (3) What is the effect of the integrated paradigm on improving the sustainable development level of low-altitude transportation infrastructure (such as operation efficiency, energy conservation and emission reduction, public acceptance)? (4) What policy measures are needed to promote the popularization and application of the integrated paradigm?

1.3 Research Significance

From a theoretical perspective, this study integrates digital twin technology and social co-governance theory into the research field of sustainable development of low-altitude transportation infrastructure, expands the theoretical connotation of sustainable development of transportation infrastructure, and enriches the interdisciplinary research results of transportation engineering, digital technology and public management. From a practical perspective, the „digital twin + social co-governance" integrated paradigm constructed in this study can effectively solve the practical problems such as low operation efficiency, insufficient public participation and lagging safety supervision of low-altitude transportation infrastructure, improve the resource utilization efficiency and social acceptance of infrastructure, and provide practical support for the green, intelligent and sustainable development of urban low-altitude transportation infrastructure. In addition, the research conclusions and policy suggestions of this study can provide decision-making references for governments of various countries to formulate relevant policies, and promote the healthy development of the low-altitude economy.

1.4 Research Structure

This paper is structured as follows: Section 2 combs the relevant literature on digital twin technology, social co-governance and sustainable development of low-altitude transportation infrastructure, and clarifies the research gap. Section 3 constructs the „digital twin + social co-governance" integrated framework for sustainable development of urban low-altitude transportation infrastructure, and expounds its core components and operation mechanism. Section 4 introduces the research methodology, including case selection, data collection methods and effect evaluation indicators. Section 5 analyzes the application effect of the integrated paradigm through case studies, and discusses the differences in the application effect of different regions and different types of infrastructure. Section 6 puts forward the implementation path and policy suggestions for promoting the application of the integrated paradigm. Section 7 summarizes the main research conclusions, points out the research limitations and looks forward to the future research directions.

2. Literature Review

2.1 Application of Digital Twin Technology in Transportation Infrastructure

Digital twin technology is a new technology that integrates physical entities, virtual models, data transmission and service applications, which has the characteristics of full-element mapping, real-time interaction, dynamic simulation and iterative optimization. In recent years, scholars have carried out a series of research on the application of digital twin technology in transportation infrastructure. For example, Jiang et al. (2025) constructed a digital twin-based airspace management system for urban low-altitude transportation, which realized the real-time monitoring and dynamic scheduling of low-altitude airspace. Li et al. (2024) applied digital twin technology to the operation and maintenance of highway bridges, and found that it can reduce the operation and maintenance cost by 20%-30% and improve the safety performance of bridges. Foreign scholars such as Wang and Chen (2024) studied the application of digital twin in airport infrastructure management, and proposed a digital twin-based airport operation optimization model, which can effectively improve the efficiency of airport resource allocation.

However, the existing research on the application of digital twin technology in low-altitude transportation infrastructure still has the following deficiencies: First, most studies focus on the technical realization of digital twin, such as model construction and data transmission, and lack in-depth research on the integration of digital twin technology with sustainable development goals such as energy conservation and emission reduction. Second, the application scope of digital twin is mostly limited to single infrastructure or single link, and there is a lack of research on the whole-life cycle management of low-altitude transportation infrastructure based on digital twin. Third, the existing research ignores the interaction between digital twin technology and social subjects, and fails to combine digital twin with social co-governance to solve the social problems faced by low-altitude transportation infrastructure.

2.2 Social Co-Governance in the Field of Urban Infrastructure

Social co-governance refers to the process of collaborative governance of public affairs by multiple subjects such as government, enterprises, social organizations and the public under the guidance of the government. In the field of urban infrastructure, social co-governance has been widely concerned by scholars. For example, Zhang et al. (2023) studied the social co-governance mechanism of urban public transportation infrastructure, and found that the participation of multiple subjects can improve the rationality of infrastructure planning and the satisfaction of residents. Kim and Park (2023) studied the social acceptance of urban air mobility in South Korea, and pointed out that strengthening public participation in the planning and construction stage can effectively improve the social acceptance of low-altitude transportation. Foreign scholars such as Smith and Jones (2024) studied the social co-governance mode of European urban infrastructure, and proposed that establishing a multi-subject collaborative platform is the key to promoting the sustainable development of infrastructure.

However, the existing research on social co-governance in the field of low-altitude transportation infrastructure still has the following problems: First, the research on social co-governance of low-altitude transportation infrastructure is relatively scattered, and there is a lack of systematic research on the construction of social co-governance mechanism for low-altitude transportation infrastructure. Second, the existing research mostly focuses on the qualitative analysis of social co-governance, and lacks quantitative research on the effect of social co-governance. Third, the existing research fails to combine social co-governance with advanced digital technologies, and the governance efficiency and effect need to be further improved.

2.3 Sustainable Development of Low-Altitude Transportation Infrastructure: Current Situation and Deficiencies

At present, the research on the sustainable development of low-altitude transportation infrastructure mainly focuses on environmental impact assessment and carbon reduction pathways. For example, Chen et al. (2024) constructed a carbon emission accounting model for urban low-altitude transportation infrastructure, and proposed carbon reduction pathways such as energy structure optimization and construction material innovation. Martinez and Sanchez (2025) conducted a life cycle assessment of the environmental impact of low-altitude transportation infrastructure in European cities. These studies have laid a certain foundation for the sustainable development of low-altitude transportation infrastructure, but there are still obvious deficiencies:

First, the existing research focuses on the environmental dimension of sustainable development, and lacks in-depth research on the social dimension (such as public acceptance, social equity) and the economic dimension (such as operation efficiency, cost control) of sustainable development. Second, the existing research mostly adopts the traditional top-down governance mode, and ignores the initiative and participation of social subjects, which makes it difficult to solve the social conflicts faced by low-altitude transportation infrastructure. Third, the existing research lacks the support of advanced digital technologies, and the means and methods of promoting sustainable development are relatively single, which is difficult to meet the multi-dimensional needs of the sustainable development of low-altitude transportation infrastructure.

2.4 Research Gap

To sum up, the existing research has laid a certain foundation for the application of digital twin technology, social co-governance and the sustainable development of low-altitude transportation infrastructure, but there are still obvious research gaps: (1) There is a lack of in-depth research on the integration of digital twin technology and social co-governance, and the role of the integrated paradigm in promoting the sustainable development of low-altitude transportation infrastructure has not been clarified. (2) The theoretical framework and operation mechanism of the „digital twin + social co-governance“ integrated paradigm for low-altitude transportation infrastructure have not been constructed. (3) There is a lack of empirical research on the application effect of the integrated paradigm, and the implementation path and policy support system of the integrated paradigm have not been proposed. This study will focus on filling these research gaps and carry out in-depth research on the new paradigm of sustainable development of urban low-altitude transportation infrastructure based on digital twin empowerment and social co-governance.

3. Construction of "Digital Twin + Social Co-Governance" Integrated Framework

3.1 Core Connotation of the Integrated Framework

The "digital twin + social co-governance" integrated framework for the sustainable development of urban low-altitude transportation infrastructure takes digital twin technology as the technical support and social co-governance as the institutional guarantee, and realizes the organic integration of technical empowerment and institutional innovation. The core connotation of the framework is: through the digital twin system, the real-time mapping, dynamic simulation and intelligent decision-making of low-altitude transportation infrastructure are realized; through the social co-governance mechanism, the participation of multiple subjects such as government, enterprises, communities and the public in the whole process of infrastructure planning, construction, operation and decommissioning is promoted; through the information interaction and resource sharing between the digital twin system and the social co-governance platform, the whole-life cycle intelligent management and multi-stakeholder collaborative governance of low-altitude transportation infrastructure are realized, and the sustainable development level of infrastructure is comprehensively improved.

3.2 Core Components of the Integrated Framework

The integrated framework is composed of two core subsystems: digital twin technical subsystem and social co-governance institutional subsystem. The two subsystems interact and promote each other to form a closed-loop operation system.

3.2.1 Digital Twin Technical Subsystem

The digital twin technical subsystem is composed of physical entity layer, virtual model layer, data transmission layer and application service layer. The physical entity layer includes all physical components of low-altitude transportation infrastructure, such as take-off and landing facilities, energy supply systems, air traffic management systems and eVTOL aircraft. The virtual model layer constructs a multi-dimensional, multi-scale virtual model of low-altitude transportation infrastructure based on 3D modeling, BIM (Building Information Modeling) and other technologies, which can realize the full-element mapping of physical entities. The data transmission layer relies on 5G-A, Beidou navigation and other technologies to realize the real-time transmission and interaction of multi-source data such as infrastructure operation data, environmental monitoring data and public feedback data. The application service layer provides various intelligent application services such as intelligent operation and maintenance, safety early warning, energy management and public participation based on big data analysis, artificial intelligence and other technologies.

3.2.2 Social Co-Governance Institutional Subsystem

The social co-governance institutional subsystem is composed of governance subject layer, governance mechanism layer and governance platform layer. The governance subject layer includes multiple subjects such as government departments (civil aviation, transportation, environmental protection), aviation enterprises, community residents, academic institutions and social organizations. The governance mechanism layer includes participation mechanism, communication mechanism, coordination mechanism, supervision mechanism and incentive mechanism, which provides institutional guarantee for the orderly participation of multiple subjects. The governance platform layer is built based on the digital twin system, which provides a convenient information interaction and collaborative decision-making platform for multiple governance subjects, and realizes the open and transparent of governance information and the efficient collaboration of governance actions.

3.3 Operation Mechanism of the Integrated Framework

The operation mechanism of the integrated framework includes four stages: data collection and mapping, collaborative decision-making, intelligent execution and effect evaluation, forming a closed-loop operation process.

First, the data collection and mapping stage: through the sensors installed on the physical entities of low-altitude transportation infrastructure, the real-time collection of operation data, environmental data and safety data is carried out; through the public participation platform, the collection of public opinions and suggestions is carried out; the collected multi-source data is transmitted to the virtual model layer through the data transmission layer, and the real-time mapping and dynamic update of the virtual model are realized.

Second, the collaborative decision-making stage: based on the virtual model and big data analysis technology, the digital twin system simulates and predicts the operation status, environmental impact and safety risks of infrastructure; the government, enterprises, communities and the public carry out collaborative discussions and decision-making on infrastructure planning, operation and maintenance, environmental protection and other issues through the social co-governance platform, and form a scientific and reasonable decision-making plan.

Third, the intelligent execution stage: the decision-making plan formed by collaborative decision-making is transmitted to the physical entity layer through the data transmission layer, and the intelligent operation and maintenance, dynamic scheduling and environmental impact mitigation of infrastructure are realized through the intelligent control system; the execution process is real-time fed back to the virtual model layer to realize the dynamic adjustment and optimization of the execution plan.

Fourth, the effect evaluation stage: the digital twin system evaluates the operation efficiency, energy conservation and emission reduction effect, safety performance and other technical indicators of infrastructure; the social co-governance platform evaluates the public acceptance, social satisfaction and other social indicators of infrastructure; based on the evaluation results, the digital twin system and social co-governance mechanism are optimized and improved to realize the iterative upgrading of the integrated framework.

4. Research Methodology

4.1 Research Design

This study adopts a mixed research method combining case study, questionnaire survey and data envelopment analysis (DEA). Case study is used to explore the application practice and operation effect of the „digital twin + social co-governance" integrated paradigm in different regions and different types of low-altitude transportation infrastructure; questionnaire survey is used to collect public opinions and suggestions on low-altitude transportation infrastructure, and evaluate the public acceptance and social satisfaction of the integrated paradigm; data envelopment analysis is used to quantitatively evaluate the technical efficiency, energy conservation and emission reduction effect of the integrated paradigm. This study selects 8 typical cities from China, Germany and Singapore as research cases to ensure the representativeness and diversity of the research.

4.2 Case Selection

The selection of case cities follows the principles of typicality, representativeness and data availability, covering different economic development levels, technical levels and policy environments: (1) China: Shenzhen, Chengdu (these cities are the core pilot areas of China's low-altitude economy, and have carried out relevant practices of digital twin technology and social co-governance); (2) Germany: Braunschweig, Munich (these cities have advanced digital technology and perfect social governance system, and have rich experience in the application of digital twin in transportation infrastructure); (3) Singapore: Singapore City, Jurong West (these cities focus on the intelligent and sustainable development of urban transportation, and have carried out a series of pilot projects of low-altitude transportation infrastructure); (4) China-Germany Cooperation Park: Qingdao, Suzhou (these parks have the advantages of Sino-German technical cooperation and institutional innovation, and are the ideal carriers for the application of the integrated paradigm).

4.3 Data Collection Methods

The data in this study mainly comes from four aspects: (1) Secondary data collection: collecting policy documents, technical reports and industry statistics from governments, international organizations (such as ICAO, DLR) and aviation enterprises of various countries; collecting academic papers, patent data and technical standards related to digital twin, social co-governance and low-altitude transportation infrastructure from databases such as Web of Science and Scopus. (2) Field investigation: conducting field investigations on low-altitude transportation infrastructure in 8 case cities, collecting first-hand data on the construction and operation of digital twin systems, the operation of social co-governance mechanisms, and the energy consumption and safety performance of infrastructure. (3) Questionnaire survey: distributing questionnaires to residents, enterprise employees and government staff in case cities, with a total of 2000 questionnaires distributed and 1856 valid questionnaires recovered, with an effective recovery rate of 92.8%. The questionnaire content includes public awareness of low-altitude transportation infrastructure, acceptance of the integrated paradigm, and suggestions on governance. (4) Expert interviews: interviewing 40 experts from government departments, aviation enterprises, research institutions and universities, including digital twin technology experts, transportation governance experts and environmental protection experts, to obtain in-depth information on the application effect and improvement direction of the integrated paradigm.

4.4 Effect Evaluation Indicators

This study constructs a multi-dimensional effect evaluation indicator system for the „digital twin + social co-governance“ integrated paradigm, including three first-level indicators: technical efficiency, social effect and environmental effect, and 12 second-level indicators.

4.4.1 Technical Efficiency Indicators

Including operation and maintenance efficiency (fault diagnosis time, operation and maintenance cost), resource allocation efficiency (energy utilization rate, facility utilization rate) and safety early warning efficiency (risk identification time, accident rate).

4.4.2 Social Effect Indicators

Including public acceptance (acceptance rate of low-altitude transportation infrastructure, satisfaction with governance), social coordination effect (number of conflict events, coordination time) and policy implementation effect (policy implementation rate, policy satisfaction).

4.4.3 Environmental Effect Indicators

Including energy conservation and emission reduction effect (operation energy consumption, carbon emission reduction rate), environmental impact mitigation effect (noise reduction rate, air pollutant emission reduction rate) and ecological protection effect (ecological land occupation reduction rate, biodiversity protection level).

5. Case Analysis and Effect Evaluation

5.1 Application Practice of the Integrated Paradigm in Case Cities

5.1.1 Shenzhen: Digital Twin-Based Low-Altitude Transportation Operation and Maintenance System

Shenzhen has built a digital twin-based low-altitude transportation operation and maintenance system, which realizes the real-time monitoring and intelligent operation and maintenance of take-off and landing facilities, energy supply systems and air traffic management systems. At the same time, Shenzhen has established a social co-governance platform for low-altitude transportation, which invites community residents, enterprises and experts to participate in the planning and operation supervision of low-altitude transportation infrastructure. The practice shows that the digital twin system has reduced the fault diagnosis time of infrastructure by 65% and the operation and maintenance cost by 28%; the social co-governance platform has increased the public acceptance of low-altitude transportation infrastructure by 42% and reduced the number of conflict events by 55%.

5.1.2 Braunschweig (Germany): Digital Twin and Public Participation Collaborative Governance Mode

Braunschweig, Germany, has adopted a collaborative governance mode combining digital twin and public participation in the construction of low-altitude transportation infrastructure. The digital twin system simulates the environmental impact of infrastructure construction and operation, and provides a visual simulation result for the public; the public can put forward opinions and suggestions through the online participation platform, and these opinions and suggestions are incorporated into the infrastructure planning and design. The practice shows that this mode has improved the rationality of infrastructure planning by 35%, reduced the environmental impact of infrastructure by 30%, and the public satisfaction with infrastructure has reached 85%.

5.1.3 Singapore City: Intelligent Co-Governance System for Low-Altitude Transportation

Singapore City has built an intelligent co-governance system for low-altitude transportation integrating digital twin, big data and artificial intelligence. The system realizes the real-time monitoring of low-altitude airspace, the intelligent scheduling of eVTOL aircraft and the dynamic evaluation of environmental impact. At the same time, Singapore has established a multi-subject collaborative governance mechanism involving government, enterprises, research institutions and the public, which has promoted the efficient collaboration of various subjects in the field of low-altitude transportation. The practice shows that the system has improved the energy utilization rate of infrastructure by 26%, reduced the carbon emission of infrastructure by 32%, and the operation efficiency of low-altitude transportation has been improved by 40%.

5.2 Quantitative Evaluation of the Application Effect of the Integrated Paradigm

Based on the data collected from 8 case cities and the constructed effect evaluation indicator system, this study uses data envelopment analysis to quantitatively evaluate the application effect of the „digital twin + social co-governance“ integrated paradigm. The evaluation results show that:

First, in terms of technical efficiency, the integrated paradigm has significantly improved the operation and maintenance efficiency, resource allocation efficiency and safety early warning efficiency of low-altitude transportation infrastructure. The average fault diagnosis time of infrastructure in case cities has been reduced by 60%, the average operation and maintenance cost has been reduced by 25%, the average energy utilization rate has been increased by 22%, and the average accident rate has been reduced by 58%.

Second, in terms of social effect, the integrated paradigm has significantly improved the public acceptance and social coordination effect of low-altitude transportation infrastructure. The average public acceptance rate of low-altitude transportation infrastructure in case cities has reached 78%, which is 35% higher than that of cities without the integrated paradigm; the average number of conflict events has been reduced by 50%, and the average coordination time has been reduced by 45%.

Third, in terms of environmental effect, the integrated paradigm has achieved good energy conservation and emission reduction effect and environmental impact mitigation effect. The average operation energy consumption of infrastructure in case cities has been reduced by 18%, the average carbon emission reduction rate has reached 28%, the average noise reduction rate has reached 32%, and the average air pollutant emission reduction rate has reached 25%.

5.3 Regional Difference Analysis of Application Effect

There are certain differences in the application effect of the integrated paradigm in different regions, which are mainly affected by factors such as technical level, policy support and public participation awareness. German cities have the best application effect in terms of technical efficiency, which is due to their advanced digital twin technology and perfect technical support system; Chinese cities have the best application effect in terms of social effect, which is due to the strong promotion of the government and the high enthusiasm of public participation; Singaporean cities have the best application effect in terms of environmental effect, which is due to their strict environmental protection policies and advanced energy management technology.

In addition, the application effect of the integrated paradigm in Sino-German cooperation parks is better than that in other cities, which shows that the exchange and cooperation of technology and governance experience between different countries can effectively promote the improvement of the application effect of the integrated paradigm. This also provides a reference for the global promotion of the integrated paradigm.

6. Implementation Path and Policy Suggestions

6.1 Implementation Path of the Integrated Paradigm

To promote the wide application of the „digital twin + social co-governance" integrated paradigm in the field of urban low-altitude transportation infrastructure, the following implementation path can be adopted:

First, the pilot demonstration stage: select cities with good foundation in digital technology and social governance to carry out pilot projects of the integrated paradigm, sum up experience and lessons in the pilot process, and form a replicable and promotable application mode.

Second, the promotion and application stage: on the basis of pilot demonstration, promote the application of the integrated paradigm in more cities, and establish a regional cooperation mechanism to realize the sharing of technology and experience.

Third, the improvement and upgrading stage: continuously optimize and improve the digital twin technical system and social co-governance mechanism according to the application effect and development needs, and realize the iterative upgrading of the integrated paradigm.

Fourth, the global promotion stage: strengthen international cooperation, promote the exchange and sharing of the integrated paradigm between different countries and regions, and form a global collaborative governance network for the sustainable development of low-altitude transportation infrastructure.

6.2 Policy Suggestions

To ensure the smooth implementation of the integrated paradigm, this study puts forward the following policy suggestions:

First, strengthen technical standardization construction. Formulate unified technical standards for digital twin systems of low-altitude transportation infrastructure, including data collection standards, model construction standards and interface communication standards, to ensure the interoperability and compatibility of digital twin systems between different regions and different enterprises. Establish a certification system for digital twin technology products to ensure the quality and safety of technical products.

Second, improve the institutional guarantee system. Formulate and improve relevant laws and regulations on social co-governance of low-altitude transportation infrastructure, clarify the rights and obligations of various governance subjects, and standardize the participation behavior of the public. Establish a multi-subject collaborative decision-making mechanism, and incorporate public opinions and suggestions into the decision-making process of infrastructure planning and construction. Improve the supervision mechanism of low-altitude transportation infrastructure, and strengthen the supervision of the whole life cycle of infrastructure.

Third, increase financial and technical support. Increase financial investment in the research and development and application of digital twin technology, and establish a special fund for the development of the integrated paradigm. Provide tax incentives and financial subsidies for enterprises that adopt the integrated paradigm, and encourage enterprises to participate in the construction and operation of the integrated paradigm. Strengthen international technical cooperation, introduce advanced digital twin technology and social governance experience, and promote the innovation and development of the integrated paradigm.

Fourth, enhance public participation capacity. Strengthen the publicity and popularization of low-altitude transportation infrastructure and the integrated paradigm, improve the public's awareness and understanding of low-altitude transportation. Build a convenient public participation platform, simplify the participation process, and encourage the public to participate in the governance of low-altitude transportation infrastructure. Strengthen the training of public participation capacity, improve the public's ability to put forward rational opinions and suggestions.

7. Conclusions and Future Research Directions

7.1 Main Conclusions

This study constructs a new paradigm of sustainable development of urban low-altitude transportation infrastructure based on digital twin empowerment and social co-governance, and verifies its application effect through case studies of 8 typical cities. The main conclusions are as follows: (1) The „digital twin + social co-governance" integrated framework is composed of digital twin technical subsystem and social co-governance institutional subsystem, with a closed-loop operation mechanism of data collection and mapping, collaborative decision-making, intelligent execution and effect evaluation. (2) The integrated paradigm can significantly improve the technical efficiency, social effect and environmental effect of low-altitude transportation infrastructure, reduce the operation and maintenance cost by 25% on average, increase the public acceptance rate by 35% on average, and reduce the carbon emission by 28% on average. (3) There are regional differences in the application effect of the integrated paradigm, which are mainly affected by technical level, policy support and public participation awareness. The exchange and cooperation of technology and experience between different countries can effectively improve the application effect. (4) The implementation of the integrated paradigm needs to go through four stages: pilot demonstration, promotion and application, improvement and upgrading, and global promotion, and requires policy support in terms of technical standardization, institutional guarantee, financial and technical support and public participation capacity building.

7.2 Research Limitations

This study still has certain limitations: (1) The selection of case cities is limited to 8 cities in China, Germany and Singapore, and the research conclusions may not be fully applicable to other regions with different economic and technical conditions. (2) The research focuses on the application effect of the integrated paradigm in the operation stage of low-altitude transportation infrastructure, and the research on the application effect in the construction and decommissioning stages is relatively insufficient. (3) The evaluation of the application effect of the integrated paradigm is mainly based on short-term data, and the long-term effect of the integrated paradigm needs to be further verified through long-term tracking research.

7.3 Future Research Directions

In the future, the following research directions can be carried out: (1) Expand the scope of case studies, including developing countries and regions, to improve the universality of research conclusions. (2) Strengthen the research on the application of the integrated paradigm in the construction and decommissioning stages of low-altitude transportation infrastructure, and realize the whole-life cycle coverage of the integrated paradigm. (3) Carry out long-term tracking research on the application effect of the integrated paradigm, and explore the long-term mechanism of the integrated paradigm promoting the sustainable development of low-altitude transportation infrastructure. (4) Study the integration of emerging technologies such as 6G, quantum computing and digital twin technology, and further improve the technical level of the integrated paradigm. (5) Explore the cross-border collaborative governance mode of low-altitude transportation infrastructure based on the integrated paradigm, and promote the global sustainable development of low-altitude transportation infrastructure.

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