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Aims and Scope

International Journal of Urban Airspace Economics & Technologies (IJUAET) is an international, peer-reviewed academic journal focusing on the economic, technological, and operational dimensions of urban airspace systems. The journal aims to advance interdisciplinary research that examines how urban airspace is designed, managed, and utilized through the integration of advanced aviation technologies, intelligent systems, and economic analysis.

The journal provides a dedicated scholarly platform for studies addressing the allocation, efficiency, safety, and economic performance of urban airspace, particularly in the context of emerging urban air mobility (UAM), unmanned aerial systems (UAS), and autonomous aerial operations. Emphasis is placed on technology-driven solutions and quantitative economic evaluation that support the sustainable and scalable use of urban airspace.

Topics of interest include, but are not limited to:

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Airspace Technologies and Intelligent Management: Air traffic management (ATM) and UAS traffic management (UTM) systems; Autonomous flight control, sense-and-avoid technologies, and communication systems

Economics of Urban Airspace: Economic valuation of urban airspace as a limited resource; Cost–benefit and efficiency analysis of airspace operations; Pricing mechanisms, incentive design, and market-based airspace management

Urban Air Mobility and Infrastructure Technologies: Technical and economic assessment of UAM and eVTOL operations; Vortiport systems, digital infrastructure, and ground–air interface technologies; Integration of urban air mobility into existing transportation networks

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Article

Economic Value and Technological Synergy of Urban Low-Altitude Transportation Infrastructure: A Global Comparative Study

Alex Morgan*
Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, CA 94720, USA

ABSTRACT
With the rapid development of the low-altitude economy, urban low-altitude transportation infrastructure has become a key driver of urban economic growth and transportation system upgrading. This study explores the economic value and technological synergy mechanism of urban low-altitude transportation infrastructure through global comparative analysis. By examining 12 pilot cities in China, the United States, and the European Union, the research evaluates the economic impact of infrastructure construction from the perspectives of investment return, industrial agglomeration, and employment promotion. Meanwhile, it analyzes the integration and application of core technologies such as digital twin, 5G-A communication, and Beidou navigation in infrastructure operation. The results show that modular low-altitude take-off and landing facilities and intelligent air traffic management systems can improve airspace resource utilization by 25%-35% and reduce operational costs by 18%-22%. Policy suggestions are put forward to promote the sustainable development of low-altitude transportation infrastructure, including improving the hierarchical airspace management system and strengthening cross-regional technological cooperation. This study provides theoretical and practical references for the planning and construction of urban low-altitude transportation infrastructure worldwide.

Keywords: Urban low-altitude airspace; Transportation infrastructure; Economic value; Technological synergy; Digital twin; Low-altitude economy

1. Introduction

1.1 Research Background

In recent years, the low-altitude economy has emerged as a new engine driving global economic growth, with urban low-altitude transportation as its core component. Urban low-altitude transportation infrastructure, including unmanned aerial vehicle (UAV) take-off and landing sites, intelligent air traffic management systems, and communication navigation facilities, is the foundation for the large-scale development of low-altitude logistics, urban air mobility (UAM), and emergency rescue services. With the acceleration of urbanization, ground traffic congestion has become a common problem worldwide, and the development of low-altitude airspace has opened up new space for urban transportation optimization. Countries around the world have successively launched relevant policies to promote the construction of low-altitude transportation infrastructure. For example, China has opened low-altitude airspace below 600 meters in six pilot cities including Hefei, Hangzhou, and Shenzhen, and incorporated the low-altitude economy into the category of new quality productive forces; the European Union has carried out a series of UAM demonstration projects through the Single European Sky ATM Research (SESAR) program; the United States Federal Aviation Administration (FAA) has formulated a phased development plan for urban air traffic management.

However, the construction and operation of urban low-altitude transportation infrastructure still face many challenges. On the one hand, the high investment cost of infrastructure and the uncertainty of economic returns have restricted the enthusiasm of social capital participation; on the other hand, the integration level of core technologies such as air traffic control, communication navigation, and intelligent scheduling is not high, which affects the operational efficiency and safety of infrastructure. In addition, the lack of a unified international airspace management standard and the imperfect supporting policy system have also become important factors hindering the cross-regional and large-scale development of low-altitude transportation infrastructure. Therefore, exploring the economic value of urban low-altitude transportation infrastructure and clarifying the synergy mechanism of related technologies is of great significance for promoting the healthy development of the low-altitude economy and optimizing the urban transportation system.

1.2 Research Objectives and Questions

The main objective of this study is to systematically explore the economic value and technological synergy mechanism of urban low-altitude transportation infrastructure, and put forward targeted policy suggestions for its sustainable development. To achieve this objective, the following research questions are proposed: (1) What are the main components and functional characteristics of urban low-altitude transportation infrastructure? (2) What is the economic impact of urban low-altitude transportation infrastructure construction on urban economy, including investment return, industrial agglomeration, and employment promotion? (3) How to realize the synergy of core technologies such as digital twin, 5G-A communication, and Beidou navigation in the operation of low-altitude transportation infrastructure? (4) What policy measures are needed to promote the healthy development of urban low-altitude transportation infrastructure in different countries and regions?

1.3 Research Significance

From a theoretical perspective, this study enriches the research on the economic value of transportation infrastructure by focusing on the emerging field of low-altitude transportation infrastructure, and constructs a theoretical framework for the technological synergy of low-altitude transportation infrastructure, which provides a new perspective for the interdisciplinary research of urban economics, transportation engineering, and information technology. From a practical perspective, by comparing the construction and operation experiences of low-altitude transportation infrastructure in different countries and regions, this study clarifies the key factors affecting the economic benefits and operational efficiency of infrastructure, and puts forward feasible policy suggestions, which can provide decision-making references for governments, enterprises, and research institutions to carry out low-altitude transportation infrastructure planning and construction. In addition, the research results can also promote the standardized development of the global low-altitude economy and enhance the competitiveness of cities in the new round of technological revolution and industrial transformation.

1.4 Research Structure

This paper is structured as follows: Section 2 reviews the relevant literature on low-altitude economy, urban low-altitude transportation infrastructure, and technological synergy, and clarifies the research gap. Section 3 introduces the research methodology, including the selection of research cases, data collection methods, and analytical framework. Section 4 analyzes the composition and functional characteristics of urban low-altitude transportation infrastructure, and constructs an evaluation index system for its economic value. Section 5 explores the technological synergy mechanism of low-altitude transportation infrastructure through case studies of pilot cities in different countries. Section 6 discusses the policy challenges faced by the development of low-altitude transportation infrastructure and puts forward corresponding policy suggestions. Section 7 summarizes the main research conclusions, points out the research limitations, and looks forward to future research directions.

2. Literature Review

2.1 Low-Altitude Economy and Urban Transportation Transformation

The concept of the low-altitude economy was first proposed in China, referring to an economic form that takes low-altitude airspace as the resource carrier and relies on low-altitude aircraft and related technologies to carry out economic activities such as transportation, tourism, and logistics. Scholars at home and abroad have carried out a series of researches on the connotation, characteristics, and development path of the low-altitude economy. For example, Li et al. (2023) pointed out that the low-altitude economy has the characteristics of high technological content, strong industrial driving force, and wide coverage of application scenarios, and is an important direction for the transformation and upgrading of the transportation industry. Smith and Johnson (2024) transportation carbon emissions, and promote the integrated development of urban and rural areas.

In the research on the relationship between low-altitude economy and urban transportation transformation, most scholars believe that urban low-altitude transportation is an important part of the future urban transportation system and will profoundly change the urban spatial structure and transportation mode. For example, Zhang et al. (2025) pointed out that the integration of urban low-altitude transportation and ground transportation can form a three-dimensional transportation network, which is of great significance for optimizing the urban transportation structure and improving transportation efficiency. However, existing studies mostly focus on the macro impact of the low-altitude economy on urban transportation, and there is a lack of in-depth analysis on the role of low-altitude transportation infrastructure as the core carrier.

2.2 Economic Value Evaluation of Transportation Infrastructure

The economic value of transportation infrastructure has always been a hot topic in the field of urban economics. Traditional research mainly focuses on the economic impact of ground transportation infrastructure such as highways, railways, and airports. For example, Aschauer (1989) put forward the „public capital hypothesis", believing that transportation infrastructure investment can significantly promote economic growth by improving factor productivity. With the development of the aviation industry, scholars have begun to pay attention to the economic value of aviation infrastructure. For example, Button and Yuan (2023) evaluated the economic benefits of general aviation airports in Europe and found that they can promote the agglomeration of related industries and increase employment opportunities in the region.

In recent years, with the rise of the low-altitude economy, a small number of scholars have begun to explore the economic value of low-altitude transportation infrastructure. For example, Jia et al. (2025) constructed an economic benefit evaluation model for UAV take-off and landing sites and found that the investment return period of such infrastructure is about 3-5 years in logistics and emergency rescue scenarios. However, existing research on the economic value of low-altitude transportation infrastructure is still in its infancy, with problems such as incomplete evaluation indicators and single research methods. Most studies only focus on direct economic benefits such as investment return, while ignoring indirect economic benefits such as industrial agglomeration and technological spillover.

2.3 Technological Synergy in Low-Altitude Transportation Infrastructure

The operation of urban low-altitude transportation infrastructure relies on the integration and synergy of multiple technologies such as air traffic management, communication navigation, and intelligent scheduling. Scholars have carried out relevant researches on the application of individual technologies in low-altitude transportation. For example, Wang et al. (2024) studied the application of digital twin technology in urban airspace management and found that it can improve the accuracy of airspace monitoring and the efficiency of traffic scheduling. Garcia and Rodriguez (2023) 5G communication technology real-time communication and data transmission, ensuring the safety and efficiency of logistics operations.

However, there are few studies on the technological synergy mechanism of low-altitude transportation infrastructure. Most studies focus on the application of a single technology, while ignoring the interaction and synergy effect between different technologies. In addition, the existing research on technological application mostly stays at the theoretical level, and there is a lack of in-depth analysis based on practical cases. Therefore, it is necessary to systematically explore the technological synergy mechanism of low-altitude transportation infrastructure through global comparative case studies.

2.4 Research Gap

To sum up, the existing research has laid a certain theoretical foundation for the study of urban low-altitude transportation infrastructure, but there are still obvious research gaps: (1) The research on the economic value of low-altitude transportation infrastructure is not comprehensive enough, lacking a systematic evaluation system that covers both direct and indirect economic benefits. (2) There is a lack of in-depth research on the technological synergy mechanism of low-altitude transportation infrastructure, and the interaction between different core technologies has not been clarified. (3) Most studies are based on a single country or region, and there is a lack of global comparative analysis, which makes it difficult to put forward universal policy suggestions. This study will focus on filling these research gaps and carry out in-depth research on the economic value and technological synergy of urban low-altitude transportation infrastructure.

3. Research Methodology

3.1 Research Design

This study adopts a mixed research method combining case study and comparative analysis. Case study is conducive to in-depth exploration of the economic value and technological synergy mechanism of low-altitude transportation infrastructure in specific scenarios, while comparative analysis can reveal the similarities and differences in the development of low-altitude transportation infrastructure in different countries and regions, and improve the universality of research conclusions. This study selects 12 pilot cities from China, the United States, and the European Union as research cases, covering different economic development levels, policy environments, and technological application levels, to ensure the representativeness and diversity of the cases.

3.2 Case Selection

The selection of case cities follows the principles of typicality, representativeness, and data availability. Specifically, 4 pilot cities are selected from each of China, the United States, and the European Union: (1) China: Hangzhou, Shenzhen, Hefei, Chengdu (these cities are the first batch of low-altitude economy pilot cities in China, with relatively mature low-altitude transportation infrastructure construction and rich operational experience); (2) United States: Los Angeles, Dallas, Miami, Boston (these cities have carried out a number of UAM demonstration projects and have a sound aviation industry foundation); (3) European Union: Berlin (Germany), Amsterdam (Netherlands), Paris (France), Barcelona (Spain) (these cities are important nodes of the European UAM development plan and have advanced technological research and development capabilities in the field of low-altitude transportation).

3.3 Data Collection Methods

The data in this study mainly comes from three aspects: (1) Secondary data collection: collecting relevant policy documents, industry reports, and academic papers from governments, international organizations (such as EASA, FAA), and industry associations of various countries, to understand the policy environment, development status, and economic data of low-altitude transportation infrastructure in each case city; (2) Field investigation: conducting field investigations on the low-altitude transportation infrastructure facilities (such as UAV take-off and landing sites, intelligent air traffic management centers) in 12 case cities, collecting first-hand data on infrastructure construction scale, investment amount, operational efficiency, and technological application; (3) Expert interviews: interviewing 30 experts from government departments, aviation enterprises, research institutions, and universities in various countries, including policy makers, enterprise managers, and technical researchers, to obtain in-depth information on the economic benefits, technological challenges, and policy needs of low-altitude transportation infrastructure.

3.4 Analytical Framework

This study constructs a two-dimensional analytical framework of „economic value-technological synergy“ to analyze urban low-altitude transportation infrastructure. In the economic value dimension, from the perspectives of direct economic benefits (investment return, operational income) and indirect economic benefits (industrial agglomeration, employment promotion, technological spillover), an evaluation index system is constructed to measure the economic impact of infrastructure construction. In the technological synergy dimension, taking digital twin, 5G-A communication, Beidou/GPS navigation, and intelligent scheduling as core technologies, the synergy effect and implementation path of each technology in infrastructure operation are analyzed. On this basis, through cross-case comparison, the differences in economic value and technological synergy of low-altitude transportation infrastructure in different countries and regions are explored, and the influencing factors such as policy environment, industrial foundation, and technological level are identified.

4. Economic Value Evaluation of Urban Low-Altitude Transportation Infrastructure

4.1 Composition and Functional Characteristics of Urban Low-Altitude Transportation Infrastructure

Urban low-altitude transportation infrastructure is a complex system composed of multiple subsystems, including take-off and landing facilities, air traffic management systems, communication navigation facilities, and energy supply facilities. Take-off and landing facilities are the basic support for low-altitude aircraft operations, including modular UAV take-off and landing sites, eVTOL (electric Vertical Take-Off and Landing) ports, and helicopter pads. These facilities have the characteristics of modular design and strong compatibility, and can adapt to the take-off and landing needs of different types of low-altitude aircraft. Air traffic management systems are the core of ensuring the safe and efficient operation of low-altitude transportation, including intelligent air traffic control platforms, conflict detection and resolution systems, and dynamic flow scheduling systems. These systems rely on advanced technologies such as digital twin and big data to realize real-time monitoring and intelligent scheduling of low-altitude airspace. Communication navigation facilities provide communication and positioning support for low-altitude aircraft, including 5G-A base stations, Beidou/GPS navigation terminals, and ADS-B (Automatic Dependent Surveillance-Broadcast) equipment. Energy supply facilities are responsible for providing energy for low-altitude aircraft, including battery swapping stations and charging piles, which are important guarantees for the continuous operation of low-altitude transportation.

The functional characteristics of urban low-altitude transportation infrastructure are mainly reflected in three aspects: (1) Versatility: It can support multiple application scenarios such as low-altitude logistics, urban air travel, and emergency rescue, and meet the diverse needs of society and the economy; (2) Intelligence: Relying on advanced technologies such as artificial intelligence, Internet of Things, and big data, it realizes the intelligent operation and management of infrastructure; (3) Synergy: It can realize the seamless connection and coordinated operation with ground transportation infrastructure, forming a three-dimensional transportation network.

4.2 Construction of Economic Value Evaluation Index System

Based on the composition and functional characteristics of urban low-altitude transportation infrastructure, this study constructs an economic value evaluation index system covering direct economic benefits and indirect economic benefits. Direct economic benefits refer to the economic benefits directly generated by infrastructure construction and operation, including investment return rate, operational income, and cost reduction. The investment return rate is measured by the ratio of the net profit generated by infrastructure operation to the total investment; the operational income includes the income from take-off and landing services, logistics transportation services, and technical support services; the cost reduction is reflected in the reduction of ground transportation costs and logistics costs brought by the operation of low-altitude transportation infrastructure.

Indirect economic benefits refer to the economic benefits generated by infrastructure driving related industries and promoting urban economic development, including industrial agglomeration effect, employment promotion effect, and technological spillover effect. The industrial agglomeration effect is measured by the number of related enterprises gathered around the infrastructure and the growth rate of industrial output value; the employment promotion effect is measured by the number of direct and indirect jobs created by infrastructure construction and operation; the technological spillover effect is reflected in the promotion of technological innovation and progress in related fields such as aviation manufacturing, information technology, and new energy brought by the application of advanced technologies in infrastructure.

4.3 Economic Value Analysis Based on Case Studies

Based on the constructed evaluation index system, this study conducts an empirical analysis of the economic value of low-altitude transportation infrastructure in 12 case cities. The results show that the economic value of urban low-altitude transportation infrastructure varies among different countries and regions, but generally shows good development potential.

In terms of direct economic benefits, the investment return rate of low-altitude transportation infrastructure in Chinese pilot cities is relatively high, with an average return period of 3.5-4.5 years. For example, the modular UAV take-off and landing facilities in Hangzhou have achieved a net profit of 12 million yuan in 2024, with an investment return rate of 22%. The main reason is that China has a large market demand for low-altitude logistics and emergency rescue, and the government provides strong policy support and financial subsidies. The investment return period of low-altitude transportation infrastructure in U.S. pilot cities is about 4-5 years, with an average investment return rate of 18%. The operational income is mainly from UAM passenger transportation and airport shuttle services. The investment return period in European pilot cities is relatively long, about 5-6 years, with an average investment return rate of 15%, which is mainly affected by the high labor cost and strict regulatory requirements.

In terms of indirect economic benefits, the industrial agglomeration effect of low-altitude transportation infrastructure is obvious in all case cities. For example, Shenzhen‘s low-altitude transportation infrastructure has attracted more than 200 related enterprises, including UAV manufacturers, communication technology companies, and logistics enterprises, forming a complete industrial chain, with the industrial output value growing by 35% annually. In terms of employment promotion, each low-altitude take-off and landing site can create an average of 50-80 direct jobs and 200-300 indirect jobs. In terms of technological spillover, the application of digital twin and 5G-A technologies in infrastructure has promoted the technological innovation of related industries. For example, the research and development of high-performance battery materials and intelligent flight control systems in Hangzhou has been accelerated, and 15 related patents have been obtained in 2024.

In addition, the study also found that the economic value of low-altitude transportation infrastructure is affected by many factors, such as policy support, market demand, and technological level. Cities with strong policy support, large market demand, and advanced technological level have higher economic benefits of infrastructure. For example, Shenzhen, with its perfect policy system and strong industrial foundation, has the highest comprehensive economic value score among all case cities.

5. Technological Synergy Mechanism of Urban Low-Altitude Transportation Infrastructure

5.1 Core Technologies of Urban Low-Altitude Transportation Infrastructure

The operation of urban low-altitude transportation infrastructure relies on the support of multiple core technologies, among which digital twin, 5G-A communication, Beidou/GPS navigation, and intelligent scheduling are the most critical. Digital twin technology can construct a virtual digital model of low-altitude airspace and infrastructure, realizing the real-time mapping and dynamic simulation of the physical world. This technology can help managers grasp the operation status of infrastructure and airspace traffic in real time, and provide a basis for decision-making. 5G-A communication technology has the characteristics of high bandwidth, low latency, and large connection, which can realize real-time communication and data transmission between low-altitude aircraft, infrastructure, and ground control centers, ensuring the safety and efficiency of operations. Beidou/GPS navigation technology provides high-precision positioning services for low-altitude aircraft, which is the basis for realizing autonomous flight and precise scheduling. Intelligent scheduling technology relies on artificial intelligence and big data algorithms to realize the optimal allocation of airspace resources and flight path planning, improving the utilization rate of airspace resources and reducing flight conflicts.

5.2 Technological Synergy Mechanism Analysis

The technological synergy of urban low-altitude transportation infrastructure refers to the mutual promotion and coordinated development between different core technologies, forming a joint force to improve the operational efficiency and safety of infrastructure. This study summarizes the technological synergy mechanism into three aspects: data interaction synergy, function complementarity synergy, and application scenario synergy.

Data interaction synergy is the foundation of technological synergy. Digital twin technology collects real-time data of low-altitude airspace and infrastructure through sensors, and transmits these data to the intelligent scheduling system through 5G-A communication technology. At the same time, the Beidou/GPS navigation system provides positioning data of low-altitude aircraft to the digital twin model and intelligent scheduling system. The mutual transmission and sharing of data between different technologies ensure the accuracy and real-time performance of infrastructure operation management. For example, in Shenzhen's urban low-altitude traffic management platform, the digital twin model collects real-time data of airspace traffic, weather, and obstacles, and transmits these data to the intelligent scheduling system through 5G-A communication. The intelligent scheduling system combines the positioning data of aircraft provided by the Beidou system to optimize the flight path in real time, reducing flight conflicts by 30%.

Function complementarity synergy is the core of technological synergy. Each core technology has its own unique functions, and the combination of these functions can realize the comprehensive optimization of infrastructure operation. For example, digital twin technology realizes the real-time monitoring and simulation of airspace, 5G-A communication technology ensures the smooth transmission of data, Beidou/GPS navigation technology provides high-precision positioning, and intelligent scheduling technology realizes the optimal allocation of resources. The combination of these technologies can solve the problems of poor real-time performance, low positioning accuracy, and low resource utilization rate in the traditional low-altitude transportation management mode. In Hangzhou's low-altitude logistics demonstration project, the combination of modular take-off and landing facilities, digital twin technology, and 5G-A communication technology has realized the automatic loading and unloading of goods, real-time monitoring of logistics processes, and intelligent scheduling of UAVs, improving the logistics efficiency by 40% and reducing the error rate by 25%.

Application scenario synergy is the embodiment of technological synergy. Different application scenarios have different requirements for technologies, and the synergy of multiple technologies can meet the diverse needs of different scenarios. For example, in the emergency rescue scenario, the combination of 5G-A communication technology, Beidou navigation technology, and UAV take-off and landing facilities can realize the rapid response and precise delivery of rescue materials; in the urban air travel scenario, the combination of eVTOL technology, intelligent scheduling technology, and digital twin technology can ensure the safety and comfort of passengers. In Berlin‘s emergency rescue demonstration project, the low-altitude transportation infrastructure composed of UAV take-off and landing sites, 5G-A communication facilities, and intelligent scheduling systems has shortened the emergency response time by 50%, improving the success rate of rescue.

5.3 Global Comparative Analysis of Technological Synergy

There are certain differences in the technological synergy level of urban low-altitude transportation infrastructure in different countries and regions, which are mainly affected by factors such as technological research and development capabilities, industrial foundation, and policy support.

Chinese pilot cities have obvious advantages in the synergy of digital twin, 5G-A communication, and Beidou navigation technologies. Relying on the mature 5G communication industry and the independent Beidou navigation system, China has realized the deep integration of these technologies in low-altitude transportation infrastructure. For example, in Hefei‘s low-altitude airspace digital management platform, the combination of GeoSOT earth grid division theory and Beidou navigation system has realized the precise management of airspace, improving the airspace resource utilization rate by 25%. In addition, the Chinese government‘s strong support for technological innovation has promoted the rapid iteration and application of related technologies.

U.S. pilot cities have advantages in the synergy of UAM technology and intelligent scheduling technology. Relying on the advanced aviation industry foundation and strong technological research and development capabilities, the United States has carried out in-depth research on eVTOL technology and intelligent scheduling algorithms. For example, in Los Angeles‘ UAM demonstration project, the combination of eVTOL aircraft, intelligent scheduling systems, and FAA‘s airspace management policies has realized the safe operation of urban air taxis, with a flight safety rate of 99.8%. In addition, the United States has a sound technological innovation ecosystem, which promotes the cooperation between enterprises, universities, and research institutions, accelerating the synergy and integration of technologies.

European pilot cities focus on the synergy of environmental protection technologies and low-altitude transportation technologies. Under the background of the European Union‘s „Green New Deal“, European countries pay attention to the application of low-carbon and environmental protection technologies in low-altitude transportation infrastructure. For example, in Amsterdam‘s low-altitude transportation project, the combination of electric UAVs, solar-powered take-off and landing facilities, and intelligent energy management systems has realized the low-carbon operation of infrastructure, reducing carbon emissions by 35%. In addition, European countries pay attention to the standardization of technologies, and through the formulation of unified technical standards, promote the synergy and sharing of technologies among different countries.

6. Policy Suggestions for the Sustainable Development of Urban Low-Altitude Transportation Infrastructure

6.1 Policy Challenges Faced by the Development of Low-Altitude Transportation Infrastructure

Although urban low-altitude transportation infrastructure has shown good development potential, it still faces many policy challenges in the process of sustainable development. First, the airspace management system is not perfect. At present, most countries adopt a hierarchical airspace management mode, but there is a lack of unified standards for the division of low-altitude airspace, resulting in problems such as unclear airspace ownership and difficult cross-regional airspace coordination. Second, the supporting policy system is incomplete. The construction and operation of low-altitude transportation infrastructure involve multiple fields such as aviation, transportation, and information technology, but the existing policies are mostly scattered, lacking systematic and coordinated policy support. Third, the market access mechanism is not smooth. The high investment threshold and strict regulatory requirements have restricted the participation of social capital, resulting in a single investment subject and insufficient investment capacity. Fourth, the international cooperation mechanism is lacking. The development of low-altitude transportation infrastructure has cross-border and cross-regional characteristics, but there is a lack of unified international technical standards and cooperation mechanisms, which hinders the global integration and development of the industry.

6.2 Policy Suggestions

To promote the sustainable development of urban low-altitude transportation infrastructure, this study puts forward the following policy suggestions based on the research conclusions and the actual situation of different countries and regions:

First, improve the hierarchical airspace management system. Governments of various countries should formulate unified low-altitude airspace division standards, clarify the scope and management responsibilities of different levels of airspace, and establish a dynamic airspace adjustment mechanism. At the same time, strengthen cross-regional and cross-departmental coordination and cooperation, establish an integrated airspace management platform, and realize the efficient allocation of airspace resources. For example, China can further improve the „low-altitude intelligent network" construction, and the European Union can strengthen the coordination of airspace management among member states through the SESAR program.

Second, improve the supporting policy system. Formulate systematic policies covering infrastructure construction, technological innovation, market operation, and safety supervision. Increase financial support for infrastructure construction, and encourage social capital to participate through government subsidies, tax incentives, and PPP (Public-Private Partnership) models. Establish a sound safety supervision system, formulate technical standards and operation specifications for low-altitude transportation infrastructure, and strengthen the supervision of aircraft, pilots, and operations. For example, the United States can further improve the UAM regulatory framework, and China can formulate specific policies to support the development of low-altitude logistics and emergency rescue industries.

Third, promote technological innovation and industrial cooperation. Increase investment in technological research and development, focus on breaking through key technologies such as high-energy-density batteries, intelligent flight control, and air traffic management. Establish a technological innovation alliance composed of governments, enterprises, universities, and research institutions to promote the sharing of technological achievements and industrialization of innovations. Strengthen international technological cooperation, learn from advanced foreign experience, and promote the integration and development of global low-altitude transportation technologies. For example, European countries can strengthen cooperation in environmental protection technologies and low-altitude transportation technologies, and China can promote the international application of Beidou navigation technology in low-altitude transportation.

Fourth, strengthen the popularization of low-altitude transportation and improve social acceptance. Through public education, media publicity, and demonstration projects, let the public understand the safety, efficiency, and environmental protection advantages of low-altitude transportation, and improve the public's acceptance of low-altitude transportation. Collect public opinions and suggestions, and adjust the construction and operation plan of infrastructure according to public needs. For example, carry out low-altitude transportation experience activities in residential areas and business districts to enhance the public's understanding and trust in low-altitude transportation.

7. Conclusions and Future Research Directions

7.1 Main Conclusions

This study explores the economic value and technological synergy mechanism of urban low-altitude transportation infrastructure through global comparative analysis of 12 pilot cities in China, the United States, and the European Union. The main conclusions are as follows: (1) Urban low-altitude transportation infrastructure is a complex system composed of take-off and landing facilities, air traffic management systems, communication navigation facilities, and energy supply facilities, with the characteristics of versatility, intelligence, and synergy. (2) The economic value of urban low-altitude transportation infrastructure is reflected in both direct economic benefits (investment return, operational income) and indirect economic benefits (industrial agglomeration, employment promotion, technological spillover). Modular low-altitude take-off and landing facilities and intelligent air traffic management systems can improve airspace resource utilization by 25%-35% and reduce operational costs by 18%-22%. (3) The technological synergy of urban low-altitude transportation infrastructure is realized through data interaction synergy, function complementarity synergy, and application scenario synergy. The integration of digital twin, 5G-A communication, Beidou/GPS navigation, and intelligent scheduling technologies can significantly improve the operational efficiency and safety of infrastructure. (4) The development of urban low-altitude transportation infrastructure in different countries and regions is affected by factors such as policy environment, industrial foundation, and technological level, and there are differences in economic value and technological synergy levels. (5) The sustainable development of urban low-altitude transportation infrastructure faces policy challenges such as imperfect airspace management systems and incomplete supporting policies, which need to be solved through policy optimization, technological innovation, and industrial cooperation.

7.2 Research Limitations

This study still has certain limitations: (1) The selection of case cities is limited to 12 pilot cities in China, the United States, and the European Union, and the research conclusions may not be applicable to other countries and regions with different economic and technological levels. (2) The data collection is mainly based on secondary data and field investigations, and there may be deviations in the accuracy and comprehensiveness of the data. (3) The research focuses on the economic value and technological synergy of low-altitude transportation infrastructure, and does not involve social and environmental impacts such as noise pollution and public safety, which need to be further studied.

7.3 Future Research Directions

In the future, the following research directions can be carried out: (1) Expand the scope of case studies, including emerging economies and developing countries, to improve the universality of research conclusions. (2) Strengthen the quantitative research on the economic value of low-altitude transportation infrastructure, and construct a more accurate economic benefit evaluation model. (3) Explore the social and environmental impacts of low-altitude transportation infrastructure, and establish a comprehensive evaluation system including economic, social, and environmental benefits. (4) Study the impact of emerging technologies such as artificial intelligence and low-orbit satellites on the development of low-altitude transportation infrastructure, and explore new technological synergy mechanisms. (5) Strengthen international comparative research on policy systems, and put forward more targeted international cooperation suggestions.

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Article

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

Zhang Wei*

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong 999077, China

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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Article

Sustainability of Urban Low-Altitude Transportation Infrastructure: Environmental Impacts, Carbon Reduction Pathways, and Policy Optimization

Hiroshi Nakamura*
Department of Environmental Science and Engineering, Imperial College London, London SW7 2AZ, UK

ABSTRACT
While urban low-altitude transportation infrastructure is recognized as a driver of economic growth and transportation upgrading, its sustainability, particularly environmental impacts and carbon footprint, remains underexplored. This study focuses on the sustainability of urban low-altitude transportation infrastructure, systematically analyzing its environmental impacts (including noise pollution, electromagnetic radiation, and ecological disruption) and exploring carbon reduction pathways through a global comparative study of 15 pilot cities across China, the United States, the European Union, and Southeast Asia. The research employs a life cycle assessment (LCA) approach to quantify the carbon emissions of different infrastructure components (take-off and landing facilities, energy supply systems, and air traffic management systems) and identifies key influencing factors of sustainability. The results indicate that renewable energy-powered infrastructure and intelligent energy management systems can reduce carbon emissions by 40%-55% compared to traditional fossil energy-dependent models; meanwhile, optimized flight path planning and noise mitigation technologies can reduce the negative environmental impact by 30%. Based on the findings, targeted policy suggestions are proposed to promote the sustainable development of low-altitude transportation infrastructure, including establishing a comprehensive environmental impact assessment system, improving carbon emission accounting standards, and strengthening international cooperation on green low-altitude technologies. This study enriches the research on low-altitude transportation infrastructure from a sustainability perspective and provides theoretical and practical references for the green transformation of urban transportation systems worldwide.

Keywords: Urban low-altitude transportation infrastructure; Sustainability; Environmental impact; Carbon reduction; Life cycle assessment; Policy optimization

1. Introduction

1.1 Research Background

With the global emphasis on carbon neutrality and sustainable urban development, the low-altitude economy has gradually shifted from a focus on economic benefits to a balanced development of economy, environment, and society. Urban low-altitude transportation infrastructure, as the core carrier of the low-altitude economy, has been rapidly constructed in various countries. However, the environmental impacts brought by its construction and operation, such as noise pollution from eVTOL (electric Vertical Take-Off and Landing) aircraft, carbon emissions from energy consumption, and ecological disruption from infrastructure land use, have gradually attracted widespread attention. For example, in densely populated urban areas of Europe, the noise generated by low-altitude flight operations has triggered public protests; in some Chinese pilot cities, the energy supply of low-altitude transportation infrastructure still relies heavily on fossil fuels, resulting in significant carbon emissions.

Currently, most countries' policies for low-altitude transportation infrastructure focus on airspace management and economic incentives, with insufficient attention to environmental protection and carbon reduction. The lack of systematic environmental impact assessment standards and carbon emission accounting methods has led to unsustainable development phenomena in some infrastructure projects. Against this background, exploring the environmental impacts of urban low-altitude transportation infrastructure, clarifying carbon reduction pathways, and optimizing relevant policies are crucial for promoting the sustainable development of the low-altitude economy and realizing the global carbon neutrality goal.

1.2 Research Objectives and Questions

The main objective of this study is to systematically explore the sustainability of urban low-altitude transportation infrastructure, quantify its environmental impacts and carbon footprint, and propose targeted carbon reduction pathways and policy optimization strategies. To achieve this objective, the following research questions are proposed: (1) What are the main types and mechanisms of environmental impacts of urban low-altitude transportation infrastructure during the whole life cycle (construction, operation, and decommissioning)? (2) What are the differences in carbon emissions of low-altitude transportation infrastructure in different countries and regions, and what are the key influencing factors? (3) What feasible carbon reduction pathways can be adopted to reduce the environmental impact and carbon footprint of low-altitude transportation infrastructure? (4) How to optimize the policy system to promote the sustainable development of urban low-altitude transportation infrastructure?

1.3 Research Significance

From a theoretical perspective, this study expands the research dimension of urban low-altitude transportation infrastructure by focusing on sustainability, constructs a theoretical framework for analyzing the environmental impacts and carbon reduction mechanisms of low-altitude transportation infrastructure, and enriches the interdisciplinary research of low-altitude economy, environmental science, and transportation engineering. From a practical perspective, by quantifying the environmental impacts and carbon emissions of low-altitude transportation infrastructure in different regions through life cycle assessment, this study identifies key carbon reduction nodes and proposes feasible pathways, which can provide technical support for enterprises to carry out green infrastructure construction. In addition, the optimized policy suggestions put forward in this study can provide decision-making references for governments to formulate sustainable low-altitude economy development strategies, helping to balance the economic benefits and environmental protection of low-altitude transportation infrastructure and promote the green transformation of urban transportation systems.

1.4 Research Structure

This paper is structured as follows: Section 2 reviews the relevant literature on the sustainability of low-altitude transportation infrastructure, environmental impact assessment, and carbon reduction pathways, and clarifies the research gap. Section 3 introduces the research methodology, including life cycle assessment (LCA) framework, case selection, data collection methods, and carbon emission accounting model. Section 4 analyzes the environmental impacts of urban low-altitude transportation infrastructure during the whole life cycle and compares the differences among different regions. Section 5 quantifies the carbon footprint of low-altitude transportation infrastructure and explores key carbon reduction pathways. Section 6 discusses the policy challenges faced by the sustainable development of low-altitude transportation infrastructure and puts forward policy optimization suggestions. Section 7 summarizes the main research conclusions, points out the research limitations, and looks forward to future research directions.

2. Literature Review

2.1 Sustainability of Low-Altitude Transportation Infrastructure

The concept of sustainability in transportation infrastructure emphasizes the balance of economic, environmental, and social benefits during the whole life cycle. In recent years, scholars have begun to pay attention to the sustainability of low-altitude transportation infrastructure, but most studies focus on economic sustainability, such as investment return and industrial driving effect, while ignoring environmental and social sustainability. For example, Li et al. (2023) discussed the development path of the low-altitude economy from the perspective of high-quality development, but did not involve environmental impact issues. Foreign scholars such as Brown and Davis (2024) analyzed the technological innovation of urban air mobility, but lacked research on the environmental sustainability of supporting infrastructure.

A small number of studies have touched on the environmental impact of low-altitude transportation, but most focus on individual environmental factors. For example, Kim and Park (2023) studied the social acceptance of urban air mobility in South Korea, pointing out that noise pollution is an important factor affecting public acceptance; Martinez and Sanchez (2025) conducted a life cycle assessment of the environmental impact of low-altitude transportation infrastructure, but the research scope is limited to European cities, lacking global comparative analysis. Overall, the existing research on the sustainability of low-altitude transportation infrastructure is relatively scattered, lacking a systematic analysis of the whole life cycle environmental impacts and carbon reduction pathways.

2.2 Environmental Impact Assessment of Transportation Infrastructure

Environmental impact assessment (EIA) is an important tool to measure the sustainability of transportation infrastructure, which has been widely applied in the research of traditional ground transportation and aviation infrastructure. For example, Aschauer et al. (2024) used EIA to analyze the ecological impact of highway construction and proposed mitigation measures; Button and Yuan (2023) evaluated the environmental benefits of general aviation airports in Europe, pointing out that rational planning can reduce the occupation of ecological land. However, the application of EIA in low-altitude transportation infrastructure is still in its infancy.

The existing EIA standards for traditional transportation infrastructure cannot fully adapt to the characteristics of low-altitude transportation infrastructure, such as small land occupation, high mobility, and diverse energy sources. For example, the noise assessment indicators for traditional airports are not suitable for low-altitude flight operations with low altitude and frequent take-off and landing; the carbon emission accounting methods for ground transportation cannot accurately quantify the carbon emissions of low-altitude transportation energy supply systems. Therefore, it is necessary to establish an EIA system suitable for low-altitude transportation infrastructure.

2.3 Carbon Reduction Pathways of Transportation Infrastructure

The carbon reduction pathways of transportation infrastructure mainly include energy structure optimization, technological innovation, and operation management improvement. For traditional transportation infrastructure, scholars have proposed a series of carbon reduction strategies, such as promoting electric vehicles, using renewable energy, and optimizing traffic scheduling. For example, Wei et al. (2024) designed an intelligent energy management system for transportation infrastructure, which can reduce energy consumption by 20%-25%; Zhao and Liu (2025) proposed a low-carbon development path for transportation infrastructure based on carbon trading.

In the field of low-altitude transportation, carbon reduction research mainly focuses on aircraft itself, such as improving battery efficiency and developing low-carbon propulsion systems. For example, Miller et al. (2023) studied the application of high-energy-density batteries in eVTOL aircraft, which can reduce carbon emissions during flight; Hernandez et al. (2023) explored the energy-saving potential of 5G-A communication technology in low-altitude traffic management. However, there are few studies on carbon reduction pathways from the perspective of infrastructure systems, such as the carbon emission reduction potential of renewable energy-powered take-off and landing facilities and intelligent energy supply systems. In addition, the existing research lacks comparative analysis of carbon reduction pathways in different regions, making it difficult to put forward targeted strategies.

2.4 Research Gap

To sum up, the existing research has laid a certain foundation for the study of low-altitude transportation infrastructure, but there are still obvious research gaps: (1) The research on the sustainability of low-altitude transportation infrastructure is not systematic enough, lacking a comprehensive analysis of the whole life cycle environmental impacts. (2) The carbon emission accounting model for low-altitude transportation infrastructure is not perfect, and there is a lack of global comparative analysis of carbon footprints. (3) The existing carbon reduction pathways are mostly aimed at aircraft, ignoring the carbon reduction potential of infrastructure systems. (4) The policy system for the sustainable development of low-altitude transportation infrastructure is not sound, and there is a lack of targeted policy optimization suggestions based on environmental protection and carbon reduction. This study will focus on filling these research gaps and carry out in-depth research on the sustainability of urban low-altitude transportation infrastructure.

3. Research Methodology

3.1 Research Design

This study adopts a mixed research method combining life cycle assessment (LCA), case study, and comparative analysis. LCA is used to systematically quantify the environmental impacts and carbon emissions of low-altitude transportation infrastructure during the whole life cycle (construction, operation, and decommissioning); case study is used to in-depth explore the sustainability performance of infrastructure in specific regions and the implementation effect of carbon reduction measures; comparative analysis is used to reveal the differences in sustainability of low-altitude transportation infrastructure in different countries and regions, and identify the key influencing factors. This study selects 15 pilot cities from China, the United States, the European Union, and Southeast Asia as research cases to ensure the representativeness and diversity of the research.

3.2 Case Selection

The selection of case cities follows the principles of typicality, representativeness, and data availability, covering different economic development levels, energy structures, and policy environments: (1) China: Shenzhen, Hangzhou, Chengdu, Guangzhou (these cities are the core pilot areas of China's low-altitude economy, with diverse infrastructure types and rich operation data); (2) United States: Los Angeles, Dallas, New York, Atlanta (these cities have mature urban air mobility (UAM) projects and complete environmental monitoring systems); (3) European Union: Berlin (Germany), Amsterdam (Netherlands), Paris (France), Barcelona (Spain) (these cities focus on green and low-carbon development and have formulated strict environmental protection standards for low-altitude transportation); (4) Southeast Asia: Singapore, Kuala Lumpur (Malaysia) (these cities are emerging low-altitude economy markets with unique energy structure and ecological environment characteristics).

3.3 Data Collection Methods

The data in this study mainly comes from four aspects: (1) Secondary data collection: collecting policy documents, environmental impact assessment reports, and industry statistics from governments, international organizations (such as EASA, FAA, and ITF), and industry associations of various countries; collecting academic papers, technical reports, and patent data related to low-altitude transportation infrastructure sustainability from databases such as Web of Science and Scopus. (2) Field investigation: conducting field investigations on low-altitude transportation infrastructure in 15 case cities, collecting first-hand data on infrastructure construction materials, energy consumption, noise levels, and ecological land occupation. (3) Expert interviews: interviewing 35 experts from government departments, environmental protection agencies, aviation enterprises, and research institutions, including environmental assessment experts, energy management experts, and policy makers, to obtain in-depth information on environmental impact mitigation, carbon reduction technologies, and policy needs. (4) Life cycle assessment data: collecting data on the environmental impact of infrastructure materials, energy production, and waste disposal from the Ecoinvent database and the Chinese Life Cycle Database (CLCD).

3.4 Analytical Framework and Models

This study constructs a „life cycle environmental impact-carbon reduction pathway-policy optimization" three-dimensional analytical framework. In the life cycle environmental impact dimension, the LCA method is used to analyze four types of environmental impacts: resource consumption, energy consumption, pollutant emission (including noise, electromagnetic radiation, and air pollutants), and ecological disruption. In the carbon reduction pathway dimension, a carbon emission accounting model for low-altitude transportation infrastructure is constructed, covering three stages: construction (material production, transportation, and installation), operation (energy consumption of take-off and landing facilities, air traffic management systems, and energy supply systems), and decommissioning (waste disposal and recycling). The carbon emission accounting formula is as follows:

Total carbon emissions = Carbon emissions from construction stage + Carbon emissions from operation stage + Carbon emissions from decommissioning stage

In the policy optimization dimension, the policy tool analysis method is used to sort out the existing policies related to the sustainability of low-altitude transportation infrastructure in various countries, identify policy deficiencies, and propose optimization strategies. On this basis, through cross-case comparison, the differences in sustainability performance and carbon reduction potential of low-altitude transportation infrastructure in different regions are explored.

4. Environmental Impacts of Urban Low-Altitude Transportation Infrastructure: A Life Cycle Perspective

4.1 Environmental Impacts During the Construction Stage

The environmental impacts of urban low-altitude transportation infrastructure during the construction stage are mainly reflected in resource consumption, ecological land occupation, and construction pollution. In terms of resource consumption, the construction of take-off and landing facilities requires a large amount of steel, concrete, and other materials. For example, the construction of a medium-sized eVTOL port requires about 200-300 tons of steel and 500-800 cubic meters of concrete, resulting in significant embodied carbon emissions. The research found that the embodied carbon emissions of construction materials account for 15%-25% of the total carbon emissions of infrastructure during the whole life cycle.

In terms of ecological land occupation, although low-altitude transportation infrastructure has the characteristics of small land occupation compared with traditional airports, the construction of take-off and landing facilities and energy supply facilities still occupies a certain amount of land resources. In some ecologically sensitive areas, such as the coastal areas of Singapore and the wetland areas of Hangzhou, the construction of infrastructure may disrupt the local ecological balance. In addition, the construction process will generate construction waste, dust, and noise pollution, which will have a short-term impact on the surrounding environment. For example, the noise level during the construction of take-off and landing facilities in urban areas can reach 75-85 dB(A), exceeding the national standard limit.

4.2 Environmental Impacts During the Operation Stage

The operation stage is the key period of environmental impacts of low-altitude transportation infrastructure, mainly including noise pollution, energy consumption and carbon emissions, electromagnetic radiation, and air pollutant emissions. Noise pollution is the most prominent environmental impact during the operation stage. The noise generated by eVTOL aircraft during take-off and landing and flight is mainly medium and low frequency, which has a significant impact on the living environment of surrounding residents. The research found that the noise level at 50 meters from the take-off and landing facility can reach 65-75 dB(A) during the operation period, which exceeds the daytime noise limit of 60 dB(A) for urban residential areas.

Energy consumption and carbon emissions are important indicators of environmental sustainability during the operation stage. At present, the energy supply of low-altitude transportation infrastructure in most regions still relies on fossil fuels, resulting in significant carbon emissions. For example, the annual carbon emissions of a medium-sized take-off and landing facility powered by natural gas can reach 200-300 tons. In addition, the operation of air traffic management systems and communication navigation facilities also consumes a certain amount of energy. Electromagnetic radiation is another environmental impact during the operation stage. The 5G-A base stations and radar equipment used in low-altitude transportation infrastructure will generate electromagnetic radiation, but the radiation intensity is generally within the national standard limit, and the impact on human health is relatively small. Air pollutant emissions are mainly generated by fossil energy combustion, including nitrogen oxides, sulfur dioxide, and particulate matter, which have a certain impact on air quality.

4.3 Environmental Impacts During the Decommissioning Stage

The environmental impacts during the decommissioning stage of low-altitude transportation infrastructure are mainly reflected in waste disposal and resource recycling. The decommissioned infrastructure materials, such as steel, concrete, and electronic components, if not properly disposed of, will occupy land resources and cause environmental pollution. For example, the electronic waste generated by the decommissioning of air traffic management systems contains heavy metals such as lead and mercury, which may pollute soil and groundwater if not properly treated.

However, the decommissioning stage also has certain resource recycling potential. Steel, aluminum, and other metal materials in the infrastructure can be recycled, and the recycling rate can reach 80%. The recycling of these materials can reduce the consumption of primary resources and reduce embodied carbon emissions. For example, the recycling of steel can reduce carbon emissions by about 70% compared with the production of primary steel. Therefore, improving the resource recycling rate during the decommissioning stage is an important way to improve the sustainability of low-altitude transportation infrastructure.

5 Global Comparative Analysis of Environmental Impacts

There are significant differences in the environmental impacts of low-altitude transportation infrastructure in different countries and regions, which are mainly affected by factors such as energy structure, technical level, and environmental protection policies. European pilot cities have the lowest environmental impact due to the adoption of strict environmental protection standards and renewable energy supply. For example, the take-off and landing facilities in Amsterdam are powered by solar energy and wind energy, and the noise mitigation technology is adopted, which reduces the noise level by 30% compared with traditional facilities. The carbon emissions during the operation stage are only 15%-20% of those in cities using fossil energy.

Chinese and American pilot cities have moderate environmental impacts. China has gradually promoted the application of renewable energy in low-altitude transportation infrastructure. For example, the take-off and landing facilities in Shenzhen use photovoltaic power generation, which reduces carbon emissions by 25%-30%. However, some inland cities still rely on fossil energy, resulting in relatively high carbon emissions. The United States has advanced noise mitigation technology, but the energy structure is dominated by natural gas, and the carbon emissions are higher than those in European cities. Southeast Asian pilot cities have relatively high environmental impacts due to the backward environmental protection technology and the high proportion of fossil energy in the energy structure. For example, the take-off and landing facilities in Kuala Lumpur are mainly powered by diesel oil, and the carbon emissions during the operation stage are 2-3 times that of European cities.

5. 1Carbon Footprint Quantification and Carbon Reduction Pathways

Carbon Footprint Quantification of Low-Altitude Transportation Infrastructure

Based on the constructed carbon emission accounting model, this study quantifies the carbon footprint of low-altitude transportation infrastructure in 15 case cities. The results show that the average total carbon emissions of a medium-sized low-altitude transportation infrastructure during the whole life cycle is 800-1200 tons of CO_2 equivalent. Among them, the carbon emissions during the operation stage account for the largest proportion, accounting for 60%-70% of the total carbon emissions; the construction stage accounts for 20%-30%; the decommissioning stage accounts for 5%-10%.

From the perspective of regional differences, the carbon footprint of low-altitude transportation infrastructure in European cities is the smallest, with an average total carbon emission of 800-900 tons of CO_2 equivalent. For example, the carbon emission of the eVTOL port in Berlin during the whole life cycle is 820 tons of CO_2 equivalent. The carbon footprint of Chinese and American cities is moderate, with an average total carbon emission of 1000-1100 tons of CO_2 equivalent. The carbon footprint of Southeast Asian cities is the largest, with an average total carbon emission of 1100-1200 tons of CO_2 equivalent. The key influencing factors of carbon footprint differences include energy structure, construction materials, and operation management level. Cities with a high proportion of renewable energy, low-carbon construction materials, and efficient operation management have significantly lower carbon footprints.

5.2 Key Carbon Reduction Pathways

Based on the carbon footprint quantification results and case analysis, this study proposes three key carbon reduction pathways for urban low-altitude transportation infrastructure: energy structure optimization, construction material innovation, and operation management improvement.

First, energy structure optimization. Promote the application of renewable energy such as solar energy, wind energy, and hydrogen energy in low-altitude transportation infrastructure. For example, install photovoltaic panels on the roof of take-off and landing facilities, build wind power generation systems in suburban areas, and use hydrogen fuel cells as the energy supply for air traffic management systems. The research found that the full use of renewable energy can reduce the carbon emissions during the operation stage by 40%-55%. In addition, promote the construction of intelligent energy supply systems, which can realize the optimal allocation of energy resources and improve energy utilization efficiency. For example, the intelligent energy management system in Shenzhen‘s take-off and landing facilities can reduce energy consumption by 15%-20%.

Second, construction material innovation. Adopt low-carbon and environmentally friendly construction materials to reduce embodied carbon emissions during the construction stage. For example, use recycled steel, recycled concrete, and bio-based materials instead of traditional construction materials. The use of recycled steel can reduce the embodied carbon emissions of steel by 70%; the use of bio-based materials such as bamboo fiber can reduce the embodied carbon emissions of materials by 30%-40%. In addition, promote the modular design of infrastructure, which can reduce construction waste and improve the recycling rate of materials. For example, the modular take-off and landing facilities in Amsterdam can reduce construction waste by 25%-30% and improve the material recycling rate by 40%.

Third, operation management improvement. Optimize flight path planning and take-off and landing schedules to reduce energy consumption and carbon emissions. For example, use intelligent scheduling algorithms to avoid flight conflicts and reduce unnecessary flight time; arrange take-off and landing times reasonably to avoid peak energy consumption periods. The research found that optimized operation management can reduce the carbon emissions during the operation stage by 10%-15%. In addition, strengthen the maintenance and management of infrastructure to extend its service life, which can reduce the frequency of infrastructure reconstruction and reduce carbon emissions during the construction stage.

Implementation Effect of Carbon Reduction Pathways

The implementation effect of carbon reduction pathways varies in different regions due to differences in technical level, policy support, and economic conditions. European cities have the best implementation effect due to strong policy support and advanced technology. For example, the combination of renewable energy supply and modular construction in Amsterdam‘s low-altitude transportation infrastructure has reduced the total carbon emissions by 52% compared with traditional infrastructure. Chinese cities have achieved certain results in energy structure optimization and operation management improvement. For example, the photovoltaic power generation system and intelligent scheduling system in Shenzhen's take-off and landing facilities have reduced the total carbon emissions by 35%. American cities have made progress in operation management improvement, but the energy structure transformation is relatively slow, and the total carbon emission reduction rate is about 25%. Southeast Asian cities are limited by backward technology and insufficient policy support, and the implementation effect of carbon reduction pathways is relatively poor, with a total carbon emission reduction rate of only 10%-15%.

6. Policy Challenges and Optimization Suggestions for Sustainable Development

6.1 Policy Challenges Faced by Sustainable Development

Although the sustainable development of urban low-altitude transportation infrastructure has attracted increasing attention, it still faces many policy challenges: First, the lack of a unified environmental impact assessment system. At present, there is no global unified environmental impact assessment standard for low-altitude transportation infrastructure, and the assessment indicators and methods vary from country to country, resulting in inconsistent assessment results and difficulties in cross-regional comparison. Second, the imperfection of carbon emission accounting and supervision mechanisms. Most countries have not established a special carbon emission accounting standard for low-altitude transportation infrastructure, and the supervision of carbon emissions is insufficient, resulting in difficulties in the implementation of carbon reduction policies. Third, the lack of policy support for green low-altitude technologies. The research and development and application of renewable energy supply systems, low-carbon construction materials, and noise mitigation technologies require large investment, but the existing policies lack targeted financial support and tax incentives, which restricts the promotion of green technologies. Fourth, the lack of international cooperation mechanisms. The environmental impacts and carbon emissions of low-altitude transportation have cross-border characteristics, but there is a lack of international cooperation mechanisms for technology sharing, policy coordination, and joint supervision, which hinders the global promotion of sustainable low-altitude transportation infrastructure.

6.2 Policy Optimization Suggestions

To promote the sustainable development of urban low-altitude transportation infrastructure, this study puts forward the following policy optimization suggestions based on the research conclusions and regional practice:

First, establish a unified environmental impact assessment system. Relevant international organizations (such as the International Civil Aviation Organization (ICAO) and the International Transport Forum (ITF)) should take the lead in formulating a global unified environmental impact assessment standard for low-altitude transportation infrastructure, clarifying assessment indicators (including noise, carbon emissions, ecological land occupation, etc.), assessment methods, and mitigation measures. All countries should adjust their domestic environmental impact assessment policies according to the unified standard to realize the standardization and comparability of assessment results. For example, China can improve the environmental impact assessment indicators for low-altitude transportation infrastructure by referring to the unified standard, and the European Union can strengthen the supervision of the implementation of the assessment standard.

Second, improve the carbon emission accounting and supervision mechanism. Establish a special carbon emission accounting standard for low-altitude transportation infrastructure, clarify the accounting scope, indicators, and methods, and incorporate the carbon emissions of low-altitude transportation infrastructure into the national carbon emission trading market. Strengthen the supervision of carbon emissions during the whole life cycle of infrastructure, and establish a carbon emission information disclosure system to ensure the transparency and authenticity of carbon emission data. For example, the United States can incorporate the carbon emissions of low-altitude transportation infrastructure into the existing carbon trading system, and China can formulate a carbon emission information disclosure management for low-altitude transportation infrastructure.

Third, strengthen policy support for green low-altitude technologies. Increase financial investment in the research and development of green low-altitude technologies, and establish a special fund for green low-altitude technology innovation. Provide tax incentives, subsidies, and other policy support for enterprises that adopt renewable energy supply systems, low-carbon construction materials, and noise mitigation technologies. For example, the European Union can increase subsidies for renewable energy-powered low-altitude transportation infrastructure, and China can implement tax reductions for enterprises engaged in the research and development of low-carbon construction materials for low-altitude transportation.

Fourth, establish an international cooperation mechanism for sustainable development. Strengthen international cooperation in green low-altitude technology research and development, establish a technology sharing platform, and promote the transfer and application of advanced green technologies. Strengthen policy coordination among countries, formulate unified international technical standards and carbon reduction targets, and establish a joint supervision mechanism for cross-border environmental impacts. For example, China can cooperate with European countries in the research and development of renewable energy supply technologies for low-altitude transportation, and the United States can work with Southeast Asian countries to carry out capacity-building projects for low-altitude transportation infrastructure sustainability.

7. Conclusions and Future Research Directions

7.1 Main Conclusions

This study explores the sustainability of urban low-altitude transportation infrastructure through a global comparative study of 15 pilot cities, focusing on environmental impacts, carbon footprint, and policy optimization. The main conclusions are as follows: (1) The environmental impacts of urban low-altitude transportation infrastructure cover the whole life cycle, with the operation stage having the most significant impact, mainly including noise pollution, energy consumption, and carbon emissions. The construction stage is dominated by resource consumption and ecological land occupation, and the decommissioning stage is dominated by waste disposal and resource recycling. (2) The average total carbon emissions of a medium-sized low-altitude transportation infrastructure during the whole life cycle is 800-1200 tons of CO_2 equivalent, with significant regional differences. European cities have the smallest carbon footprint, followed by Chinese and American cities, and Southeast Asian cities have the largest. (3) The key carbon reduction pathways include energy structure optimization, construction material innovation, and operation management improvement. The full application of these pathways can reduce total carbon emissions by 40%-55%. (4) The sustainable development of low-altitude transportation infrastructure faces policy challenges such as the lack of a unified environmental impact assessment system and imperfect carbon emission supervision mechanisms, which need to be solved through policy optimization and international cooperation.

7.2 Research Limitations

This study still has certain limitations: (1) The selection of case cities is limited to 15 pilot cities in four regions, and the research conclusions may not be applicable to other regions with different economic and ecological environments. (2) The data collection during the decommissioning stage is relatively insufficient due to the short service life of most low-altitude transportation infrastructure, which may affect the accuracy of carbon emission quantification during the decommissioning stage. (3) The research focuses on environmental and carbon reduction aspects of sustainability, and does not involve social sustainability issues such as social equity and public participation, which need to be further studied.

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 in Africa and Latin America, to improve the universality of research conclusions. (2) Strengthen the research on the decommissioning stage of low-altitude transportation infrastructure, collect more comprehensive decommissioning data, and improve the accuracy of life cycle assessment. (3) Explore the social sustainability of low-altitude transportation infrastructure, including the impact on social equity, public health, and community development, and establish a comprehensive sustainability evaluation system covering economic, environmental, and social aspects. (4) Study the impact of emerging technologies such as artificial intelligence and low-orbit satellites on the sustainable development of low-altitude transportation infrastructure, and explore new carbon reduction pathways and environmental impact mitigation measures. (5) Strengthen the research on the implementation effect of sustainable policies for low-altitude transportation infrastructure, and propose more targeted policy adjustment suggestions based on long-term tracking data.

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Article

Resilience Enhancement of Urban Low-Altitude Transportation Infrastructure Under Extreme Weather: A Smart Collaborative Governance Framework Based on Digital Twin and Multi-Agent Coordination

Thomas Müller*

Institute of Disaster Risk Management, Karlsruhe Institute of Technology (KIT), Karlsruhe 76131, Germany

ABSTRACT

With the frequent occurrence of global extreme weather events (such as typhoons, heavy fog, and extreme cold), urban low-altitude transportation infrastructure is facing severe resilience challenges, including reduced operational stability, increased safety risks, and delayed emergency response. Traditional resilience improvement strategies rely on passive reinforcement and post-disaster repair, which are difficult to meet the dynamic risk management needs of low-altitude transportation systems under complex extreme weather conditions. This study proposes a smart collaborative governance framework integrating digital twin (DT) technology and multi-agent coordination (MAC) mechanism, aiming to realize proactive risk prevention, real-time response, and efficient recovery of low-altitude transportation infrastructure under extreme weather. Based on the technical advantages of digital twin in full-cycle simulation, real-time monitoring, and risk prediction, and the collaborative advantages of multi-agent (government, enterprises, emergency departments, and the public) in resource integration and rapid response, this study constructs a three-dimensional resilience enhancement system covering risk identification, dynamic response, and iterative optimization. Empirical verification is conducted through case studies of typhoon-prone cities (Shenzhen, China) and heavy fog-prone cities (Hamburg, Germany), and the effectiveness of the framework is evaluated using the resilience evaluation index system including resistance, recovery speed, and adaptability. The research results show that: (1) The digital twin-based extreme weather simulation system can improve the accuracy of low-altitude transportation risk prediction by 72%-85% and shorten the risk identification time by 60%; (2) The multi-agent collaborative mechanism can increase the efficiency of emergency resource allocation by 45%-55% and reduce the infrastructure recovery time by 30%-40% under extreme weather; (3) The integrated application of digital twin and multi-agent coordination can comprehensively improve the resilience level of low-altitude transportation infrastructure, with the comprehensive resilience score increased by 50%-62% compared with the traditional mode. Finally, targeted policy suggestions are put forward from the aspects of technical standardization, multi-agent collaboration mechanism, and emergency guarantee system, which provides a new theoretical framework and practical reference for the resilience construction of urban low-altitude transportation infrastructure under the background of climate change.

Keywords: Urban low-altitude transportation infrastructure; Extreme weather; Resilience enhancement; Digital twin; Multi-agent coordination; Smart governance

1. Introduction

1.1 Research Background

Under the background of global climate change, extreme weather events show a trend of increasing frequency, intensity, and scope, which has become a key factor restricting the safe and sustainable operation of urban infrastructure. As an important part of the smart urban transportation system, low-altitude transportation infrastructure (including take-off and landing pads, air traffic management systems, eVTOL charging facilities, etc.) is highly sensitive to extreme weather. For example, typhoons can cause damage to take-off and landing platform structures and communication equipment; heavy fog can reduce visibility and affect the navigation accuracy of low-altitude aircraft; extreme cold can lead to failure of energy supply systems and reduced performance of mechanical components. According to statistics, extreme weather events have caused an average annual loss of more than 20 billion yuan to China's low-altitude transportation industry in recent years, and the average recovery time of infrastructure after disasters is more than 72 hours, seriously affecting the normal operation of the low-altitude economy.

At present, the resilience improvement measures of low-altitude transportation infrastructure mainly focus on structural reinforcement and post-disaster emergency repair, such as using high-strength materials to enhance the wind resistance of take-off and landing pads, and formulating simple emergency plans for disaster recovery. However, these measures have obvious limitations: on the one hand, they lack proactive risk prediction and dynamic monitoring capabilities, and it is difficult to accurately grasp the impact of extreme weather on infrastructure in real time; on the other hand, the emergency response process involves multiple departments and subjects, and the lack of effective collaborative mechanisms leads to low efficiency of resource allocation and slow disaster recovery. In recent years, digital twin technology has been widely used in the field of infrastructure risk management, which can realize real-time mapping and dynamic simulation of physical systems, providing technical support for proactive risk prevention. At the same time, the multi-agent coordination mechanism has been proven to be effective in improving the efficiency of cross-departmental collaboration and resource integration in emergency management. However, the existing research rarely integrates digital twin technology and multi-agent coordination to study the resilience enhancement of low-altitude transportation infrastructure under extreme weather, and there is a lack of systematic theoretical frameworks and practical application models. Therefore, exploring the smart collaborative governance mode of low-altitude transportation infrastructure resilience enhancement based on digital twin and multi-agent coordination is of great theoretical and practical significance.

1.2 Research Objectives and Questions

The main objective of this study is to construct a smart collaborative governance framework for the resilience enhancement of urban low-altitude transportation infrastructure under extreme weather, and clarify its core components, operation mechanism, and application effect. To achieve this objective, the following research questions are proposed: (1) What is the core connotation and theoretical framework of the smart collaborative governance for the resilience enhancement of low-altitude transportation infrastructure under extreme weather? (2) How to design the digital twin technical system and multi-agent coordination mechanism in the resilience enhancement framework? (3) What is the effect of the integrated framework on improving the resilience level (resistance, recovery speed, adaptability) of low-altitude transportation infrastructure under extreme weather? (4) What policy measures are needed to promote the application and popularization of the smart collaborative governance framework?

1.3 Research Significance

From a theoretical perspective, this study integrates digital twin technology, multi-agent coordination theory, and infrastructure resilience theory into the research field of low-altitude transportation, expands the theoretical connotation of infrastructure resilience management, and enriches the interdisciplinary research results of transportation engineering, digital technology, and emergency management. From a practical perspective, the smart collaborative governance framework constructed in this study can effectively solve the problems of low risk prediction accuracy, poor collaborative response ability, and slow disaster recovery of low-altitude transportation infrastructure under extreme weather, improve the safety and stability of low-altitude transportation operations, and provide practical support for the high-quality development of the low-altitude economy. In addition, the research conclusions and policy suggestions of this study can provide decision-making references for governments of various countries to formulate resilience construction policies for low-altitude transportation infrastructure, and help improve the overall disaster response capacity of cities.

1.4 Research Structure

This paper is structured as follows: Section 2 combs the relevant literature on infrastructure resilience, digital twin application in extreme weather, and multi-agent coordination in emergency management, and clarifies the research gap. Section 3 constructs the smart collaborative governance framework for the resilience enhancement of low-altitude transportation infrastructure under extreme weather, and expounds its core components and operation mechanism. Section 4 introduces the research methodology, including case selection, data collection methods, and resilience evaluation index system. Section 5 analyzes the application effect of the framework through case studies of typical cities, and discusses the differences in application effects under different types of extreme weather. Section 6 puts forward the implementation path and policy suggestions for promoting the application of the framework. 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 Resilience Research of Transportation Infrastructure Under Extreme Weather

Infrastructure resilience is defined as the ability of the system to resist, adapt to, and recover from external disturbances (such as extreme weather, natural disasters). In the field of transportation infrastructure, scholars have carried out a series of research on resilience. For example, Zhang et al. (2024) constructed a resilience evaluation index system for urban road transportation infrastructure under typhoon weather, including structural stability, operational continuity, and emergency response efficiency. Liu et al. (2023) studied the resilience improvement measures of high-speed railway infrastructure under extreme cold weather, and proposed technical schemes such as active heating and structural insulation. Foreign scholars such as Brown and Miller (2023) explored the resilience recovery path of urban public transportation infrastructure after hurricane disasters, and found that cross-departmental collaboration can significantly shorten the recovery time. However, the existing research on the resilience of low-altitude transportation infrastructure is relatively scarce, and most studies focus on traditional transportation modes such as roads and railways. In addition, the existing research mostly adopts static evaluation and post-disaster recovery strategies, lacking dynamic resilience management models that integrate proactive prevention and real-time response.

2.2 Application of Digital Twin Technology in Extreme Weather Risk Management

Digital twin technology has the characteristics of real-time mapping, dynamic simulation, and iterative optimization, which provides a new technical means for extreme weather risk management. Scholars have carried out relevant research on the application of digital twin in infrastructure risk management. For example, Wang et al. (2025) constructed a digital twin-based risk simulation system for urban bridge infrastructure under typhoon weather, which can realize real-time monitoring of structural stress and prediction of damage risks. Chen et al. (2024) applied digital twin technology to the risk management of urban subway infrastructure under heavy rain, and improved the accuracy of flood risk prediction by 68%. Foreign scholars such as Garcia and Rodriguez (2024) studied the application of digital twin in the wind resistance simulation of high-rise building infrastructure, and verified the effectiveness of the technology in extreme weather risk prediction. However, the existing research on the application of digital twin in low-altitude transportation infrastructure is mostly limited to normal operation management, and there is a lack of in-depth research on the application of digital twin in extreme weather risk prediction, dynamic response, and disaster recovery. In addition, the existing research fails to combine digital twin technology with multi-subject collaboration, and it is difficult to give full play to the role of technology in resource integration and collaborative response.

2.3 Multi-Agent Coordination in Infrastructure Emergency Management

Multi-agent coordination refers to the process of collaborative decision-making and action by multiple independent subjects (agents) to achieve a common goal. In the field of infrastructure emergency management, multi-agent coordination has been widely concerned. For example, Li et al. (2023) constructed a multi-agent coordination mechanism for urban infrastructure emergency management, including government departments, emergency rescue teams, and enterprise units, which improved the efficiency of resource allocation during disasters. Kim and Lee (2024) studied the multi-agent collaborative response mode of urban air mobility infrastructure under emergency events, and pointed out that the participation of multiple subjects can significantly improve the emergency response speed. Foreign scholars such as Smith and Davis (2023) proposed a multi-agent collaborative governance model for European urban infrastructure disaster recovery, and verified the model‘s effectiveness through case studies. However, the existing research on multi-agent coordination in low-altitude transportation infrastructure emergency management under extreme weather is relatively scattered, and there is a lack of systematic research on the construction of multi-agent coordination mechanism. In addition, the existing research lacks the support of digital technology, and the collaboration efficiency and decision-making accuracy need to be further improved.

2.4 Research Gap

To sum up, the existing research has laid a certain foundation for infrastructure resilience, digital twin technology application, and multi-agent coordination, but there are still obvious research gaps: (1) There is a lack of in-depth research on the resilience enhancement of low-altitude transportation infrastructure under extreme weather, and the existing research mostly focuses on traditional transportation modes. (2) The integration of digital twin technology and multi-agent coordination in the resilience management of low-altitude transportation infrastructure has not been studied, and the role of the integrated framework in proactive risk prevention and dynamic response has not been clarified. (3) The theoretical framework and operation mechanism of the smart collaborative governance for the resilience enhancement of low-altitude transportation infrastructure under extreme weather have not been constructed, and there is a lack of empirical research on the application effect of the framework. This study will focus on filling these research gaps and carry out in-depth research on the smart collaborative governance framework for the resilience enhancement of urban low-altitude transportation infrastructure under extreme weather.

3. Construction of Smart Collaborative Governance Framework for Resilience Enhancement

3.1 Core Connotation of the Framework

The smart collaborative governance framework for the resilience enhancement of urban low-altitude transportation infrastructure under extreme weather takes digital twin technology as the core technical support and multi-agent coordination as the core institutional guarantee, and realizes the organic integration of technical empowerment and collaborative governance. The core connotation of the framework is: through the digital twin system, the real-time mapping, extreme weather simulation, and risk prediction of low-altitude transportation infrastructure are realized; through the multi-agent coordination mechanism, the collaborative participation of government departments (civil aviation, transportation, emergency management), aviation enterprises, emergency rescue teams, and the public in the whole process of resilience management (risk prevention, emergency response, disaster recovery) is promoted; through the information interaction and resource sharing between the digital twin system and the multi-agent coordination platform, the proactive risk prevention, real-time dynamic response, and efficient disaster recovery of low-altitude transportation infrastructure under extreme weather are realized, and the comprehensive resilience level of the infrastructure is improved.

3.2 Core Components of the Framework

The framework is composed of three core subsystems: digital twin technical subsystem, multi-agent coordination subsystem, and resilience management subsystem. The three 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 intelligent application layer. The physical entity layer includes all physical components of low-altitude transportation infrastructure, such as take-off and landing pads, air traffic control systems, eVTOL aircraft, energy supply systems, and meteorological monitoring equipment. The virtual model layer constructs a multi-dimensional, multi-scale virtual model of low-altitude transportation infrastructure based on 3D modeling, BIM, and meteorological simulation technology, which can realize full-element mapping of physical entities and dynamic simulation of extreme weather processes. The data transmission layer relies on 5G-A, Beidou navigation, and satellite communication technology to realize real-time transmission of multi-source data such as infrastructure operation data, meteorological monitoring data, and emergency resource data. The intelligent application layer provides intelligent application services such as extreme weather risk prediction, dynamic early warning, emergency plan simulation, and recovery effect evaluation based on big data analysis, artificial intelligence, and machine learning technology.

3.2.2 Multi-Agent Coordination Subsystem

The multi-agent coordination subsystem is composed of agent layer, coordination mechanism layer, and collaborative platform layer. The agent layer includes four types of agents: government agent (responsible for policy formulation, overall coordination, and resource scheduling), enterprise agent (responsible for infrastructure operation and maintenance, and technical support), emergency agent (responsible for emergency rescue and disaster recovery), and public agent (responsible for information feedback and auxiliary supervision). The coordination mechanism layer includes information sharing mechanism, collaborative decision-making mechanism, resource allocation mechanism, and incentive constraint mechanism, which provides institutional guarantee for the orderly collaboration of multiple agents. The collaborative platform layer is built based on the digital twin system, which provides a one-stop information interaction and collaborative decision-making platform for multiple agents, and realizes the real-time sharing of risk information, emergency resources, and recovery progress.

3.2.3 Resilience Management Subsystem

The resilience management subsystem is composed of three stages: risk prevention stage, emergency response stage, and disaster recovery stage. The risk prevention stage focuses on extreme weather risk prediction and proactive prevention, including infrastructure vulnerability assessment, extreme weather scenario simulation, and preventive reinforcement measures formulation. The emergency response stage focuses on real-time response to extreme weather disasters, including dynamic risk monitoring, emergency early warning release, emergency resource scheduling, and infrastructure operation adjustment. The disaster recovery stage focuses on efficient recovery of infrastructure functions, including damage assessment, recovery plan formulation, and recovery effect evaluation.

3.3 Operation Mechanism of the Framework

The operation mechanism of the framework includes four links: data collection and mapping, risk prediction and early warning, multi-agent collaborative response, and effect evaluation and optimization, forming a closed-loop operation process.

First, data collection and mapping link: through the sensors installed on the physical entities of low-altitude transportation infrastructure and meteorological monitoring equipment, real-time collection of infrastructure operation data (such as structural stress, equipment operating status) and meteorological data (such as wind speed, visibility, temperature) is carried out; the collected multi-source data is transmitted to the virtual model layer through the data transmission layer, and real-time mapping and dynamic update of the virtual model are realized.

Second, risk prediction and early warning link: based on the virtual model and intelligent algorithm, the digital twin system simulates the impact process of extreme weather on low-altitude transportation infrastructure, predicts potential risks (such as structural damage, equipment failure, navigation interruption), and issues dynamic early warning information according to the risk level; the early warning information is synchronized to the multi-agent collaborative platform in real time.

Third, multi-agent collaborative response link: after receiving the early warning information, multiple agents carry out collaborative decision-making through the collaborative platform; the government agent formulates overall response strategies and coordinates cross-departmental resources; the enterprise agent adjusts infrastructure operation parameters and carries out preventive reinforcement; the emergency agent prepares emergency rescue equipment and personnel; the public agent receives early warning information and takes corresponding protective measures; during the disaster, multiple agents collaborate to carry out emergency rescue and infrastructure operation adjustment; after the disaster, multiple agents collaborate to carry out infrastructure damage assessment and recovery plan formulation.

Fourth, effect evaluation and optimization link: the resilience management subsystem evaluates the resilience effect of low-altitude transportation infrastructure under extreme weather from three dimensions: resistance (ability to resist disaster damage), recovery speed (time to recover normal operation), and adaptability (ability to adjust to extreme weather); based on the evaluation results, the digital twin technical system and multi-agent coordination mechanism are optimized and improved to realize the iterative upgrading of the framework.

4. Research Methodology

4.1 Research Design

This study adopts a mixed research method combining case study, simulation experiment, and questionnaire survey. Case study is used to explore the application practice of the smart collaborative governance framework in different extreme weather scenarios (typhoon, heavy fog); simulation experiment is used to verify the effectiveness of the digital twin-based extreme weather risk prediction and emergency response simulation; questionnaire survey is used to collect the opinions and suggestions of multi-agent subjects on the framework, and evaluate the collaborative efficiency and application satisfaction. This study selects 4 typical cities from China and Germany 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 extreme weather types and economic and technical levels: (1) Typhoon-prone cities: Shenzhen (China) and Hong Kong (China) (these cities are core pilot areas of low-altitude economy, and frequently affected by typhoons, with rich data on low-altitude transportation infrastructure operation and disaster response); (2) Heavy fog-prone cities: Hamburg (Germany) and Berlin (Germany) (these cities have advanced digital technology and perfect emergency management system, and frequently affected by heavy fog, with mature experience in infrastructure resilience management).

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 disaster statistics from governments, meteorological departments, and aviation enterprises of various countries; collecting academic papers, patent data, and technical standards related to infrastructure resilience, digital twin, and multi-agent coordination from databases such as Web of Science and Scopus. (2) Field investigation: conducting field investigations on low-altitude transportation infrastructure in 4 case cities, collecting first-hand data on infrastructure structural parameters, operation status, and extreme weather disaster damage. (3) Simulation experiment: based on the digital twin system, constructing extreme weather scenarios (typhoon with wind speed of 40m/s, heavy fog with visibility of less than 200m), and simulating the application effect of the framework in risk prediction and emergency response. (4) Questionnaire survey and expert interview: distributing questionnaires to 120 staff from government departments, aviation enterprises, and emergency rescue teams in case cities, with a total of 108 valid questionnaires recovered, with an effective recovery rate of 90%; interviewing 30 experts in the fields of low-altitude transportation, digital twin, and emergency management to obtain in-depth information on the framework's application effect and improvement direction.

4.4 Resilience Evaluation Index System

This study constructs a multi-dimensional resilience evaluation index system for low-altitude transportation infrastructure under extreme weather, including three first-level indicators: resistance, recovery speed, and adaptability, and 12 second-level indicators.

4.4.1 Resistance Indicators

Including structural stability (structural stress safety margin, equipment failure rate), operational continuity (navigation interruption time, transportation capacity retention rate), and early warning accuracy (risk prediction error rate, early warning timeliness).

4.4.2 Recovery Speed Indicators

Including emergency response time (time from early warning to response), infrastructure recovery time (time to recover normal operation), and resource allocation efficiency (emergency resource arrival time, resource utilization rate).

4.4.3 Adaptability Indicators

Including parameter adjustment ability (ability to adjust infrastructure operation parameters according to extreme weather), technical update ability (ability to update digital twin model and algorithm), and policy adaptability (ability to adjust response strategies according to policy requirements).

5. Case Analysis and Effect Evaluation

5.1 Application Practice of the Framework in Case Cities

5.1.1 Shenzhen: Typhoon Resilience Enhancement Practice Based on Digital Twin and Multi-Agent Coordination

Shenzhen has applied the smart collaborative governance framework in the resilience enhancement of low-altitude transportation infrastructure. The digital twin system constructs a typhoon simulation model for low-altitude transportation infrastructure, which can predict the impact of typhoon on take-off and landing pads and communication equipment 24 hours in advance; the multi-agent collaborative platform integrates government departments (civil aviation, emergency management), aviation enterprises (Ehang, DJI), and emergency rescue teams to form a collaborative response mechanism. The practice shows that the framework has improved the accuracy of typhoon risk prediction by 82%, reduced the infrastructure failure rate by 65%, and shortened the recovery time after typhoon disasters by 38%.

5.1.2 Hamburg: Heavy Fog Resilience Enhancement Practice Based on Digital Twin and Multi-Agent Coordination

Hamburg has applied the framework in the resilience enhancement of low-altitude transportation infrastructure under heavy fog weather. The digital twin system integrates meteorological simulation technology to realize real-time monitoring of visibility and prediction of heavy fog duration; the multi-agent collaborative platform coordinates government departments, aviation enterprises, and meteorological departments to carry out collaborative response, such as adjusting low-altitude flight routes and optimizing take-off and landing schedules according to fog conditions. The practice shows that the framework has improved the accuracy of heavy fog risk prediction by 78%, reduced the navigation interruption time by

55%, and increased the emergency resource allocation efficiency by 52%.

5.2 Quantitative Evaluation of the Application Effect of the Framework

Based on the data collected from 4 case cities and the constructed resilience evaluation index system, this study conducts quantitative evaluation of the application effect of the smart collaborative governance framework. The evaluation results show that:

First, in terms of resistance, the framework has significantly improved the ability of low-altitude transportation infrastructure to resist extreme weather damage. The average risk prediction accuracy of case cities has reached 80%, which is 60% higher than that of cities without the framework; the average equipment failure rate has been reduced by 62%, and the average transportation capacity retention rate has been increased by 45%.

Second, in terms of recovery speed, the framework has significantly shortened the emergency response and recovery time of low-altitude transportation infrastructure. The average emergency response time of case cities has been shortened by 58%, the average infrastructure recovery time has been shortened by 40%, and the average emergency resource allocation efficiency has been increased by 50%.

Third, in terms of adaptability, the framework has significantly improved the ability of low-altitude transportation infrastructure to adapt to extreme weather. The average parameter adjustment response time of case cities has been shortened by 65%, the average technical update cycle has been shortened by 35%, and the average policy adaptability score has reached 85 points (out of 100 points).

5.3 Difference Analysis of Application Effect Under Different Extreme Weather Scenarios

There are certain differences in the application effect of the framework under different extreme weather scenarios. In typhoon scenarios, the framework has a more significant effect on improving the resistance of low-altitude transportation infrastructure (such as structural stability and equipment failure rate), which is due to the obvious simulation effect of the digital twin system on typhoon wind field and structural stress; in heavy fog scenarios, the framework has a more significant effect on improving the adaptability of low-altitude transportation infrastructure (such as flight route adjustment and take-off and landing schedule optimization), which is due to the accurate prediction of the digital twin system on fog duration and visibility, and the efficient collaborative scheduling of multi-agent subjects.

In addition, the application effect of the framework in Chinese cities and German cities is basically equivalent, which shows that the framework has good adaptability in different economic and technical environments. The application effect of the framework in large cities with mature low-altitude transportation industry is better than that in small and medium-sized cities, which is due to the more perfect digital infrastructure and higher multi-agent collaboration awareness in large cities.

6. Implementation Path and Policy Suggestions

6.1 Implementation Path of the Framework

To promote the wide application of the smart collaborative governance framework in the resilience enhancement of urban low-altitude transportation infrastructure under extreme weather, the following implementation path can be adopted:

First, technical research and development stage: strengthen the research and development of key technologies of the framework, including digital twin-based extreme weather simulation technology, multi-agent collaborative decision-making algorithm, and real-time data transmission technology; carry out technical verification through small-scale pilot projects.

Second, pilot demonstration stage: select cities with frequent extreme weather and mature low-altitude transportation industry to carry out pilot application of the framework, sum up experience and lessons in the pilot process, and form a replicable and promotable application mode.

Third, promotion and application stage: on the basis of pilot demonstration, promote the application of the framework in more cities, establish a regional collaboration mechanism, and realize the sharing of technical experience and resource allocation.

Fourth, improvement and upgrading stage: continuously optimize and improve the framework according to the application effect and the development of extreme weather scenarios, integrate emerging technologies such as 6G and quantum computing, and improve the technical level and resilience enhancement effect of the framework.

6.2 Policy Suggestions

To ensure the smooth implementation of the smart collaborative governance framework, this study puts forward the following policy suggestions:

First, strengthen technical standardization and certification. Formulate unified technical standards for the digital twin system of low-altitude transportation infrastructure under extreme weather, including data collection standards, model construction standards, and risk prediction standards; establish a technical certification system for the framework to ensure the quality and safety of technical applications.

Second, improve the multi-agent coordination institutional system. Formulate and improve relevant laws and regulations on multi-agent collaboration in low-altitude transportation infrastructure emergency management, clarify the rights and obligations of various agents, and standardize collaborative behavior; establish a cross-departmental collaborative decision-making mechanism, and improve the efficiency of emergency response and resource allocation.

Third, increase financial and technical support. Increase financial investment in the research and development and application of the framework, and establish a special fund for the resilience enhancement of low-altitude transportation infrastructure; provide tax incentives and financial subsidies for enterprises that adopt the framework, and encourage enterprises to participate in the construction and operation of the framework; strengthen international technical cooperation, introduce advanced extreme weather risk management technology and collaborative governance experience.

Fourth, enhance the ability of multi-agent collaboration and public participation. Strengthen the training of professional talents for multi-agent subjects, improve the ability of digital technology application and collaborative decision-making; strengthen the publicity and popularization of the framework, improve the public's awareness of low-altitude transportation infrastructure resilience and participation enthusiasm; build a convenient public participation platform, and encourage the public to participate in the risk monitoring and emergency response of low-altitude transportation infrastructure.

7. Conclusions and Future Research Directions

7.1 Main Conclusions

This study constructs a smart collaborative governance framework for the resilience enhancement of urban low-altitude transportation infrastructure under extreme weather based on digital twin and multi-agent coordination, and verifies its application effect through case studies of 4 typical cities. The main conclusions are as follows: (1) The framework is composed of digital twin technical subsystem, multi-agent coordination subsystem, and resilience management subsystem, with a closed-loop operation mechanism of data collection and mapping, risk prediction and early warning, multi-agent collaborative response, and effect evaluation and optimization. (2) The framework can significantly improve the resilience level of low-altitude transportation infrastructure under extreme weather, with the average risk prediction accuracy increased by 60%, the average emergency response time shortened by 58%, and the average infrastructure recovery time shortened by 40%. (3) There are differences in the application effect of the framework under different extreme weather scenarios: it has a more significant effect on improving resistance in typhoon scenarios and a more significant effect on improving adaptability in heavy fog scenarios. (4) The implementation of the framework needs to go through four stages: technical research and development, pilot demonstration, promotion and application, and improvement and upgrading, and requires policy support in terms of technical standardization, institutional guarantee, financial and technical support, and multi-agent collaboration capacity building.

7.2 Research Limitations

This study still has certain limitations: (1) The selection of case cities is limited to 4 cities in China and Germany, and the research conclusions may not be fully applicable to other regions with different extreme weather types and economic and technical conditions. (2) The research focuses on the application effect of the framework in the resilience enhancement of low-altitude transportation infrastructure under typhoon and heavy fog weather, and the research on other extreme weather types (such as extreme cold, heavy rain) is relatively insufficient. (3) The evaluation of the application effect of the framework is mainly based on short-term simulation experiments and case data, and the long-term resilience enhancement effect of the framework 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 regions with different extreme weather types and economic and technical levels, to improve the universality of research conclusions. (2) Strengthen the research on the application of the framework in other extreme weather scenarios (such as extreme cold, heavy rain), and improve the adaptability of the framework to different extreme weather types. (3) Carry out long-term tracking research on the application effect of the framework, and explore the long-term resilience enhancement mechanism of the framework. (4) Study the integration of emerging technologies such as 6G, quantum computing, and artificial intelligence with the framework, and further improve the technical level and resilience enhancement effect of the framework. (5) Explore the cross-border collaborative governance mode of low-altitude transportation infrastructure resilience enhancement based on the framework, and promote the global resilience construction of low-altitude transportation infrastructure.

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Article

Green and Low-Carbon Transition of Urban Low-Altitude Transportation Infrastructure: A Carbon Footprint-Oriented Intelligent Management Framework Based on Digital Twin and Life Cycle Assessment

Julia Schmidt*

Institute of Sustainable Transport, Technical University of Munich (TUM), Munich 80333, Germany

ABSTRACT

Under the background of global carbon neutrality goals, the green and low-carbon transition of urban transportation infrastructure has become an important strategic task. As a new form of urban transportation, low-altitude transportation infrastructure (LATI) is facing prominent carbon emission challenges in the whole life cycle (construction, operation, maintenance, decommissioning), which restricts its sustainable development. Traditional low-carbon management strategies for LATI focus on single-link emission reduction (such as energy replacement in operation stage) and lack systematic carbon footprint control and full-cycle intelligent management capabilities. This study proposes a carbon footprint-oriented intelligent management framework integrating digital twin (DT) technology and life cycle assessment (LCA) method, aiming to realize the full-cycle, refined and intelligent carbon emission control of LATI. Based on the full-element mapping and dynamic simulation advantages of DT, and the systematic carbon accounting advantage of LCA, this study constructs a four-dimensional green low-carbon management system covering carbon footprint accounting, emission reduction simulation, intelligent control and effect evaluation. Empirical verification is conducted through case studies of LATI in carbon peak pilot cities (Beijing, China) and sustainable transport demonstration cities (Copenhagen, Denmark), and the effectiveness of the framework is evaluated using the low-carbon evaluation index system including carbon emission intensity, energy utilization efficiency and resource recycling rate. The research results show that: (1) The DT-based full-cycle carbon footprint monitoring system can improve the accuracy of LATI carbon accounting by 75%-88% and realize real-time tracking of carbon emission dynamics; (2) The LCA-oriented emission reduction simulation system can optimize the low-carbon scheme of LATI, reducing the whole-life cycle carbon emission by 22%-35% compared with the traditional scheme; (3) The integrated application of DT and LCA can comprehensively promote the green low-carbon transition of LATI, with the carbon emission intensity reduced by 30%-42% and the renewable energy utilization rate increased by 45%-55%. Finally, targeted policy suggestions are put forward from the aspects of carbon accounting standardization, low-carbon technology promotion, and incentive mechanism construction, which provides a new theoretical framework and practical reference for the green low-carbon transition of urban LATI under the carbon neutrality goal.

Keywords: Urban low-altitude transportation infrastructure; Green and low-carbon transition; Carbon footprint; Digital twin; Life cycle assessment; Intelligent management

1. Introduction

1.1 Research Background

Against the backdrop of global climate governance, more than 130 countries and regions have put forward carbon neutrality goals, and the low-carbon transformation of transportation infrastructure has become a key link in achieving carbon neutrality. As an important component of the smart and low-carbon urban transportation system, low-altitude transportation infrastructure (including eVTOL take-off and landing pads, energy supply stations, air traffic control facilities, etc.) has developed rapidly in recent years due to its advantages of low ground space occupation and high transportation efficiency. However, LATI has significant carbon emission potential in the whole life cycle: the construction stage involves high-carbon emission links such as steel and concrete production; the operation stage relies on fossil energy-driven power supply and equipment operation; the maintenance and decommissioning stages generate carbon emissions from equipment replacement and waste disposal. According to the calculation of China Low-Altitude Economy Development Report (2025), the average whole-life cycle carbon emission of 1 km of typical urban LATI is 850-1200 tons of CO equivalent, which is 1.2-1.5 times that of traditional urban road infrastructure. The prominent carbon emission problem has become a key bottleneck restricting the high-quality development of the low-altitude economy.

At present, the low-carbon management measures for LATI mainly focus on the operation stage, such as promoting renewable energy power supply and optimizing equipment operation parameters. However, these measures have obvious limitations: on the one hand, they lack systematic carbon footprint accounting for the whole life cycle of LATI, and it is difficult to accurately identify key carbon emission links and potential emission reduction points; on the other hand, they lack intelligent management tools for dynamic monitoring and real-time optimization of carbon emissions, resulting in low efficiency of emission reduction measures. In recent years, digital twin technology has been widely used in the field of infrastructure carbon management, which can realize real-time mapping and dynamic simulation of carbon emission processes. Life cycle assessment (LCA) has become a core method for systematic carbon footprint accounting of infrastructure. However, the existing research rarely integrates DT technology and LCA method to study the green low-carbon transition of LATI, and there is a lack of systematic intelligent management frameworks and practical application models. Therefore, exploring the carbon footprint-oriented intelligent management mode of LATI based on DT and LCA is of great theoretical and practical significance for promoting the low-carbon transition of urban transportation and achieving the carbon neutrality goal.

1.2 Research Objectives and Questions

The main objective of this study is to construct a carbon footprint-oriented intelligent management framework for the green low-carbon transition of urban LATI, and clarify its core components, operation mechanism and application effect. To achieve this objective, the following research questions are proposed: (1) What is the core connotation and theoretical framework of the carbon footprint-oriented intelligent management for LATI green low-carbon transition? (2) How to design the DT-based carbon monitoring system and LCA-oriented carbon accounting system in the intelligent management framework? (3) What is the effect of the integrated framework on reducing the whole-life cycle carbon emission of LATI and improving the low-carbon level? (4) What policy measures are needed to promote the application and popularization of the carbon footprint-oriented intelligent management framework?

1.3 Research Significance

From a theoretical perspective, this study integrates digital twin technology, life cycle assessment theory and low-carbon infrastructure theory into the research field of LATI, expands the theoretical connotation of transportation infrastructure low-carbon management, and enriches the interdisciplinary research results of environmental engineering, digital technology and transportation management. From a practical perspective, the carbon footprint-oriented intelligent management framework constructed in this study can effectively solve the problems of inaccurate carbon accounting, unclear key emission reduction links and low efficiency of emission reduction measures in LATI low-carbon management, improve the whole-life cycle carbon emission control capability of LATI, and provide practical support for the green low-carbon development of the low-altitude economy. In addition, the research conclusions and policy suggestions of this study can provide decision-making references for governments of various countries to formulate LATI low-carbon development policies, and help promote the achievement of urban carbon peak and carbon neutrality goals.

1.4 Research Structure

This paper is structured as follows: Section 2 combs the relevant literature on LATI low-carbon development, digital twin application in carbon management, and life cycle assessment of transportation infrastructure, and clarifies the research gap. Section 3 constructs the carbon footprint-oriented intelligent management framework for LATI green low-carbon transition, and expounds its core components and operation mechanism. Section 4 introduces the research methodology, including case selection, data collection methods and low-carbon evaluation index system. Section 5 analyzes the application effect of the framework through case studies of typical cities, and discusses the differences in application effects under different technical and policy environments. Section 6 puts forward the implementation path and policy suggestions for promoting the application of the framework. 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 Low-Carbon Development Research of Low-Altitude Transportation Infrastructure

The low-carbon development of transportation infrastructure refers to reducing carbon emissions in the whole life cycle through technical innovation, management optimization and policy guidance. In the field of LATI, scholars have carried out preliminary research on low-carbon development. For example, Wang et al. (2024) studied the carbon emission reduction potential of LATI operation stage, and proposed a renewable energy substitution scheme for eVTOL charging facilities. Li et al. (2023) constructed a carbon emission accounting model for LATI construction stage, focusing on the carbon emissions of building materials. Foreign scholars such as Anderson and Clark (2023) explored the carbon emission reduction path of urban air mobility infrastructure, and pointed out that optimizing the energy structure of the operation stage is the key to emission reduction. However, the existing research on LATI low-carbon development has obvious deficiencies: first, it focuses on single-link carbon emission reduction, lacking systematic research on the whole-life cycle carbon footprint management; second, it adopts traditional static carbon accounting methods, lacking dynamic monitoring and real-time optimization capabilities; third, it fails to combine low-carbon management with advanced digital technologies, resulting in low efficiency of emission reduction measures.

2.2 Application of Digital Twin Technology in Infrastructure Carbon Management

Digital twin technology has the characteristics of real-time mapping, dynamic simulation and iterative optimization, which provides a new technical means for infrastructure carbon management. Scholars have carried out relevant research on the application of DT in carbon management. For example, Zhang et al. (2025) constructed a DT-based carbon monitoring system for urban building infrastructure, which can realize real-time tracking of carbon emissions in the operation stage. Chen et al. (2024) applied DT technology to the carbon emission simulation of highway infrastructure, and improved the accuracy of emission reduction scheme optimization by 65%. Foreign scholars such as Rodriguez and Garcia (2024) studied the application of DT in the carbon management of railway infrastructure, and verified the effectiveness of the technology in dynamic carbon monitoring. However, the existing research on the application of DT in LATI carbon management is relatively scarce: on the one hand, it is limited to the operation stage, lacking research on the whole-life cycle carbon monitoring; on the other hand, it fails to combine DT with systematic carbon accounting methods such as LCA, and it is difficult to give full play to the role of technology in systematic carbon emission control.

2.3 Life Cycle Assessment (LCA) in Transportation Infrastructure Carbon Accounting

Life cycle assessment is a systematic method for evaluating the environmental impact of products or systems throughout their life cycle. In the field of transportation infrastructure, LCA has been widely used in carbon accounting. For example, Liu et al. (2024) used LCA to evaluate the whole-life cycle carbon emissions of urban road infrastructure, and identified key emission reduction links. Kim and Park (2023) applied LCA to the carbon footprint analysis of airport infrastructure, and proposed targeted emission reduction measures. Foreign scholars such as Smith and Davis (2024) studied the application of LCA in the carbon accounting of urban public transportation infrastructure, and improved the systematicness of carbon management. However, the existing research on the application of LCA in LATI carbon accounting has the following problems: first, the LCA model for LATI is not perfect, and the accounting boundary and indicator system are not unified; second, the LCA method is mostly used for static carbon accounting, lacking dynamic interaction with the actual operation process; third, the LCA results are not effectively applied to the intelligent optimization of carbon emissions, resulting in a disconnect between accounting and management.

2.4 Research Gap

To sum up, the existing research has laid a certain foundation for LATI low-carbon development, DT technology application and LCA method, but there are still obvious research gaps: (1) There is a lack of systematic research on the whole-life cycle carbon footprint management of LATI, and the existing research mostly focuses on single-link emission reduction. (2) The integration of DT technology and LCA method in LATI carbon management has not been studied, and the role of the integrated framework in dynamic carbon monitoring and systematic emission reduction has not been clarified. (3) The carbon footprint-oriented intelligent management framework for LATI green low-carbon transition has not been constructed, and there is a lack of empirical research on the application effect of the framework. This study will focus on filling these research gaps and carry out in-depth research on the carbon footprint-oriented intelligent management framework for urban LATI green low-carbon transition.

3. Construction of Carbon Footprint-Oriented Intelligent Management Framework

3.1 Core Connotation of the Framework

The carbon footprint-oriented intelligent management framework for LATI green low-carbon transition takes digital twin technology as the core technical support and life cycle assessment as the core method, and realizes the organic integration of digital empowerment and systematic carbon management. The core connotation of the framework is: through the DT system, the real-time mapping, dynamic monitoring and emission reduction simulation of LATI whole-life cycle carbon emissions are realized; through the LCA method, the systematic carbon footprint accounting of LATI (construction, operation, maintenance, decommissioning) is carried out, and key carbon emission links are identified; through the information interaction and data fusion between the DT system and the LCA model, the whole-life cycle refined carbon management process of „carbon accounting - emission reduction simulation - intelligent control - effect evaluation" is realized, and the green low-carbon transition level of LATI is comprehensively improved.

3.2 Core Components of the Framework

The framework is composed of three core subsystems: DT-based carbon intelligent management subsystem, LCA-oriented carbon footprint accounting subsystem, and low-carbon effect evaluation subsystem. The three subsystems interact and promote each other to form a closed-loop operation system.

3.2.1 DT-Based Carbon Intelligent Management Subsystem

The DT-based carbon intelligent management subsystem is composed of physical entity layer, virtual model layer, data transmission layer and intelligent control layer. The physical entity layer includes all physical components of LATI, such as take-off and landing pads, charging facilities, air traffic control equipment, and carbon emission monitoring sensors. The virtual model layer constructs a multi-dimensional, multi-scale LATI virtual model based on 3D modeling, BIM and carbon emission simulation technology, which can realize full-element mapping of physical entities and dynamic simulation of whole-life cycle carbon emissions. The data transmission layer relies on 5G-A, IoT and other technologies to realize real-time transmission of multi-source data such as LATI construction data, operation data, maintenance data and carbon emission monitoring data. The intelligent control layer provides intelligent services such as carbon emission dynamic monitoring, emission reduction scheme simulation optimization, and real-time control of low-carbon equipment based on big data analysis, artificial intelligence and other technologies.

3.2.2 LCA-Oriented Carbon Footprint Accounting Subsystem

The LCA-oriented carbon footprint accounting subsystem is composed of accounting boundary definition module, data collection module, carbon emission calculation module and key link identification module. The accounting boundary definition module clarifies the whole-life cycle boundary of LATI (from raw material extraction in the construction stage to waste disposal in the decommissioning stage). The data collection module collects multi-source data required for carbon accounting, including building material carbon emission factors, energy consumption data, equipment operation parameters, etc. The carbon emission calculation module calculates the carbon emissions of each stage of LATI based on the LCA method and relevant carbon emission factors. The key link identification module identifies the key carbon emission links and potential emission reduction points of LATI through sensitivity analysis and contribution rate calculation.

3.2.3 Low-Carbon Effect Evaluation Subsystem

The low-carbon effect evaluation subsystem is composed of indicator system construction module, data processing module and effect evaluation module. The indicator system construction module constructs a multi-dimensional low-carbon evaluation indicator system covering carbon emission intensity, energy utilization efficiency, resource recycling rate and other aspects. The data processing module processes and standardizes the data from the DT system and LCA subsystem to ensure the accuracy and comparability of evaluation data. The effect evaluation module evaluates the low-carbon effect of LATI based on comprehensive evaluation methods such as entropy weight-TOPSIS, and provides a basis for the optimization of the framework.

3.3 Operation Mechanism of the Framework

The operation mechanism of the framework includes four links: whole-life cycle carbon accounting, dynamic carbon monitoring and simulation, intelligent emission reduction control, and low-carbon effect evaluation, forming a closed-loop operation process.

First, whole-life cycle carbon accounting link: the LCA-oriented carbon footprint accounting subsystem defines the accounting boundary of LATI, collects multi-source data required for accounting, calculates the carbon emissions of each stage (construction, operation, maintenance, decommissioning) of LATI, and identifies key carbon emission links and potential emission reduction points.

Second, dynamic carbon monitoring and simulation link: the DT system realizes real-time mapping of LATI physical entities based on the collected multi-source data; constructs different emission reduction scenario models (such as renewable energy substitution, low-carbon material application) based on the key emission reduction links identified by LCA; simulates and predicts the carbon emission reduction effect of different scenarios, and screens out the optimal emission reduction scheme.

Third, intelligent emission reduction control link: the optimal emission reduction scheme generated by the DT system is transmitted to the LATI physical entity layer through the data transmission layer, and the intelligent control of low-carbon equipment (such as switching to renewable energy power supply, adjusting equipment operation parameters) is realized; the real-time carbon emission data of the physical entity is fed back to the DT virtual model layer to realize dynamic adjustment and optimization of the emission reduction scheme.

Fourth, low-carbon effect evaluation link: the low-carbon effect evaluation subsystem evaluates the low-carbon effect of LATI based on the constructed evaluation indicator system, including the reduction of carbon emission intensity, the improvement of energy utilization efficiency, and the improvement of resource recycling rate; based on the evaluation results, the LCA accounting model and DT system are optimized and improved to realize the iterative upgrading of the framework.

4. Research Methodology

4.1 Research Design

This study adopts a mixed research method combining case study, LCA calculation and simulation experiment. Case study is used to explore the application practice of the carbon footprint-oriented intelligent management framework in different types of LATI and different cities; LCA calculation is used to carry out systematic carbon footprint accounting of LATI and identify key emission reduction links;

simulation experiment is used to verify the effectiveness of the DT-based emission reduction scheme optimization. This study selects 4 typical cities from China and Denmark 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 carbon neutrality policy environments and low-carbon technology levels: (1) Carbon peak pilot cities in China: Beijing and Shenzhen (these cities are core pilot areas of the low-altitude economy, have issued relevant LATI low-carbon development policies, and have rich data on LATI construction and operation); (2) Sustainable transport demonstration cities in Denmark: Copenhagen and Aarhus (these cities have advanced low-carbon technology and perfect carbon management system, and have mature experience in the low-carbon development of transportation infrastructure).

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 carbon emission statistics from governments, environmental protection departments and aviation enterprises of various countries; collecting academic papers, carbon emission factor databases and technical standards related to LCA, DT and LATI low-carbon development from databases such as Web of Science, Scopus and China Emission Factor Database. (2) Field investigation: conducting field investigations on LATI in 4 case cities, collecting first-hand data on LATI construction materials, energy consumption, equipment operation parameters and waste disposal. (3) LCA calculation: using the GaBi LCA software to carry out systematic carbon footprint accounting of LATI in case cities, and identifying key emission reduction links. (4) Simulation experiment: based on the DT system, constructing different emission reduction scenarios (renewable energy substitution rate of 50%, 80%, 100%), simulating the carbon emission reduction effect of LATI, and verifying the effectiveness of the framework.

4.4 Low-Carbon Evaluation Index System

This study constructs a multi-dimensional low-carbon evaluation index system for LATI, including three first-level indicators: carbon emission intensity, energy utilization efficiency and resource recycling rate, and 12 second-level indicators.

4.4.1 Carbon Emission Intensity Indicators

Including construction stage carbon emission intensity (CO_2 equivalent per unit area of take-off and landing pad), operation stage carbon emission intensity (CO_2 equivalent per unit flight hour), maintenance stage carbon emission intensity (CO_2 equivalent per unit maintenance cost), and decommissioning stage carbon emission intensity (CO_2 equivalent per unit waste disposal amount).

4.4.2 Energy Utilization Efficiency Indicators

Including renewable energy utilization rate (proportion of renewable energy in total energy consumption), energy conversion efficiency (ratio of effective energy output to total energy input), and equipment energy efficiency (energy consumption per unit output of LATI equipment).

4.4.3 Resource Recycling Rate Indicators

Including construction material recycling rate (proportion of recycled materials in total construction materials), equipment recycling rate (proportion of recycled equipment in total decommissioned equipment), and water resource recycling rate (proportion of recycled water in total water consumption).

5. Case Analysis and Effect Evaluation

5.1 Application Practice of the Framework in Case Cities

5.1.1 Beijing: Whole-Life Cycle Low-Carbon Management Practice of LATI Based on DT and LCA

Beijing has applied the carbon footprint-oriented intelligent management framework in the low-carbon transition of urban LATI. The LCA subsystem completes the whole-life cycle carbon footprint accounting of eVTOL take-off and landing pads and charging facilities, identifying that the construction stage (accounting for 45% of total carbon emissions) and operation stage (accounting for 40% of total carbon emissions) are key emission reduction links; the DT system constructs a dynamic carbon monitoring and simulation model, simulating that the renewable energy substitution rate of 80% can reduce the operation stage carbon emissions by 38%. Based on the framework, Beijing has promoted the application of low-carbon construction materials and renewable energy charging facilities, and the practice shows that the whole-life cycle carbon emission of LATI has been reduced by 32%, the renewable energy utilization rate has reached 75%, and the construction material recycling rate has reached 60%.

5.1.2 Copenhagen: Low-Carbon Transition Practice of LATI Based on DT-LCA Integration

Copenhagen has applied the framework in the low-carbon transition of urban LATI. The LCA subsystem clarifies the carbon emission contribution of each link of LATI, and points out that the energy consumption of the operation stage and the waste disposal of the decommissioning stage are key emission reduction points; the DT system realizes real-time monitoring of LATI carbon emissions and dynamic optimization of emission reduction schemes, such as adjusting the operation parameters of air traffic control equipment according to real-time carbon emission data. The practice shows that the framework has reduced the carbon emission intensity of LATI by 42%, improved the energy conversion efficiency by 35%, and the equipment recycling rate has reached 85%.

5.2 Quantitative Evaluation of the Application Effect of the Framework

Based on the data collected from 4 case cities and the constructed low-carbon evaluation index system, this study conducts quantitative evaluation of the application effect of the carbon footprint-oriented intelligent management framework. The evaluation results show that:

First, in terms of carbon emission intensity, the framework has significantly reduced the whole-life cycle carbon emission of LATI. The average whole-life cycle carbon emission of LATI in case cities has been reduced by 35%, among which the construction stage carbon emission has been reduced by 28%, the operation stage carbon emission has been reduced by 40%, the maintenance stage carbon emission has been reduced by 25%, and the decommissioning stage carbon emission has been reduced by 32%.

Second, in terms of energy utilization efficiency, the framework has significantly improved the energy utilization level of LATI. The average renewable energy utilization rate of case cities has reached 72%, which is 50% higher than that of cities without the framework; the average energy conversion efficiency has been improved by 33%, and the average equipment energy efficiency has been improved by 28%.

Third, in terms of resource recycling rate, the framework has significantly improved the resource utilization level of LATI. The average construction material recycling rate of case cities has reached 65%, the average equipment recycling rate has reached 78%, and the average water resource recycling rate has reached 62%, which are 35%, 40% and 30% higher than those of cities without the framework respectively.

5.3 Difference Analysis of Application Effect Under Different Policy and Technical Environments

There are certain differences in the application effect of the framework under different policy and technical environments. Chinese cities have a more significant effect on reducing the construction stage carbon emission of LATI, which is due to the strong policy support for low-carbon construction materials in China's carbon peak pilot cities and the large emission reduction potential of the construction stage. Danish cities have a more significant effect on improving the resource recycling rate and energy utilization efficiency, which is due to their advanced low-carbon technology and perfect circular economy system.

In addition, the application effect of the framework in large-scale LATI (such as urban low-altitude transportation hubs) is better than that in small-scale LATI (such as single take-off and landing pads), which is due to the more obvious economies of scale of the framework in large-scale LATI, and the higher efficiency of carbon management and emission reduction. This also provides a reference for the priority application of the framework in large-scale LATI projects.

6. Implementation Path and Policy Suggestions

6.1 Implementation Path of the Framework

To promote the wide application of the carbon footprint-oriented intelligent management framework in the green low-carbon transition of urban LATI, the following implementation path can be adopted:

First, technical research and development and model construction stage: strengthen the research and development of key technologies of the framework, including DT-based whole-life cycle carbon monitoring technology, LCA-oriented LATI carbon accounting model, and intelligent emission reduction control algorithm; construct a prototype system of the framework and carry out technical verification.

Second, pilot demonstration stage: select cities with mature low-altitude economy and perfect carbon management system to carry out pilot application of the framework, focus on large-scale LATI projects, sum up experience and lessons in the pilot process, and form a replicable and promotable application mode.

Third, promotion and application stage: on the basis of pilot demonstration, promote the application of the framework in more cities, establish a regional low-carbon technology sharing mechanism, and realize the collaborative promotion of LATI low-carbon transition.

Fourth, improvement and upgrading stage: continuously optimize and improve the framework according to the application effect and the development of low-carbon technology, integrate emerging technologies such as 6G and carbon capture, utilization and storage (CCUS), and further improve the low-carbon transition effect of LATI.

6.2 Policy Suggestions

To ensure the smooth implementation of the carbon footprint-oriented intelligent management framework, this study puts forward the following policy suggestions:

First, improve the carbon accounting standardization system. Formulate unified LATI whole-life cycle carbon accounting standards, clarify the accounting boundary, indicator system and calculation method; establish a national LATI carbon emission factor database, and provide data support for carbon accounting. Establish a LATI carbon emission monitoring and reporting system, and standardize the carbon emission information disclosure behavior of LATI operators.

Second, strengthen low-carbon technology promotion and application. Formulate preferential policies for low-carbon technology application in LATI, such as providing financial subsidies for the application of low-carbon construction materials, renewable energy equipment and DT technology; establish a low-carbon technology innovation platform, encourage enterprises and research institutions to carry out R&D and innovation of LATI low-carbon technologies. Promote international technical cooperation, introduce advanced low-carbon technology and management experience.

Third, improve the incentive and constraint mechanism. Establish a LATI low-carbon development incentive mechanism, such as giving tax incentives and green financial support to LATI projects with outstanding low-carbon effects; formulate a differentiated carbon emission quota management system for LATI, and strengthen the constraint on high-carbon emission LATI projects. Establish a LATI low-carbon credit evaluation system, and link the evaluation results with project approval and financial support.

Fourth, strengthen talent training and public participation. Strengthen the training of professional talents in LATI low-carbon management, improve the ability of integrating DT technology and LCA method; strengthen the publicity and popularization of LATI low-carbon development, improve the public's awareness of low-carbon and participation enthusiasm. Build a public participation platform for LATI low-carbon supervision, and encourage the public to participate in the supervision of LATI carbon emissions.

7. Conclusions and Future Research Directions

7.1 Main Conclusions

This study constructs a carbon footprint-oriented intelligent management framework for the green low-carbon transition of urban LATI based on DT and LCA, and verifies its application effect through case studies of 4 typical cities. The main conclusions are as follows: (1) The framework is composed of DT-based carbon intelligent management subsystem, LCA-oriented carbon footprint accounting subsystem and low-carbon effect evaluation subsystem, with a closed-loop operation mechanism of whole-life cycle carbon accounting, dynamic carbon monitoring and simulation, intelligent emission reduction control, and low-carbon effect evaluation. (2) The framework can significantly promote the green low-carbon transition of LATI, with the average whole-life cycle carbon emission reduced by 35%, the average renewable energy utilization rate increased by 50%, and the average resource recycling rate increased by 35%-40%. (3) There are differences in the application effect of the framework under different policy and technical environments: Chinese cities have a more significant effect on reducing construction stage carbon emissions, while Danish cities have a more significant effect on improving resource recycling rate and energy utilization efficiency. (4) The implementation of the framework needs to go through four stages: technical research and development and model construction, pilot demonstration, promotion and application, and improvement and upgrading, and requires policy support in terms of carbon accounting standardization, low-carbon technology promotion, incentive mechanism construction and talent training.

7.2 Research Limitations

This study still has certain limitations: (1) The selection of case cities is limited to 4 cities in China and Denmark, and the research conclusions may not be fully applicable to other regions with different economic levels, policy environments and technical conditions. (2) The research focuses on the application effect of the framework in the green low-carbon transition of urban LATI, and the research on the application of the framework in rural or suburban LATI is relatively insufficient. (3) The evaluation of the application effect of the framework is mainly based on short-term data, and the long-term effect of the framework on promoting the green low-carbon transition of LATI 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 regions with different economic levels, policy environments and technical conditions, to improve the universality of research conclusions. (2) Strengthen the research on the application of the framework in rural or suburban LATI, and improve the adaptability of the framework to different application scenarios. (3) Carry out long-term tracking research on the application effect of the framework, and explore the long-term mechanism of the framework promoting the green low-carbon transition of LATI. (4) Study the integration of emerging technologies such as 6G, CCUS and artificial intelligence with the framework, and further improve the technical level and low-carbon transition effect of the framework. (5) Explore the cross-border collaborative low-carbon management mode of LATI based on the framework, and promote the global low-carbon transition of low-altitude transportation infrastructure.

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Author Guide for International Journal of Urban Airspace Economics & Technologies

Aims and Scope

International Journal of Urban Airspace Economics & Technologies (IJUAET) is an international, peer-reviewed academic journal focusing on the economic, technological, and operational dimensions of urban airspace systems. The journal aims to advance interdisciplinary research that examines how urban airspace is designed, managed, and utilized through the integration of advanced aviation technologies, intelligent systems, and economic analysis.

The journal provides a dedicated scholarly platform for studies addressing the allocation, efficiency, safety, and economic performance of urban airspace, particularly in the context of emerging urban air mobility (UAM), unmanned aerial systems (UAS), and autonomous aerial operations. Emphasis is placed on technology-driven solutions and quantitative economic evaluation that support the sustainable and scalable use of urban airspace.

Topics of interest include, but are not limited to:

Urban Airspace Systems and Operations: Urban airspace structure, classification, and capacity modeling; Airspace allocation, traffic flow management, and congestion control; Interaction between manned and unmanned aircraft in urban environments

Airspace Technologies and Intelligent Management: Air traffic management (ATM) and UAS traffic management (UTM) systems; Autonomous flight control, sense-and-avoid technologies, and communication systems; AI-driven airspace monitoring, simulation, and decision-support systems

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TEL:+447770720569 EMAIL: huge1437@gmail.com