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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

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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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