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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

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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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