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Aims and Scope

Journal of Low-Altitude Economy and Air Mobility (JLAEAM) is an international, peer-reviewed academic journal dedicated to advancing research on the emerging low-altitude economy and next-generation air mobility systems. The journal provides a scholarly platform for interdisciplinary studies that integrate aerospace technologies, urban and regional planning, economic systems, public policy, and societal impacts related to low-altitude airspace utilization.
The journal focuses on the development, governance, and application of low-altitude air mobility, including electric vertical take-off and landing (eVTOL) aircraft, unmanned aerial vehicles (UAVs), urban air mobility (UAM), regional air mobility (RAM), and supporting digital and infrastructural systems. It aims to promote evidence-based research that informs sustainable industrial development, regulatory innovation, and the safe integration of low-altitude air operations into existing transportation and economic systems.

Topics of interest include, but are not limited to:
Low-Altitude Economy and Industrial Development: Economic models and value chains of low-altitude aviation; Industrial ecosystems for air mobility and aerospace manufacturing; Business models, commercialization pathways, and market analysis
Urban and Regional Air Mobility Systems: Urban air mobility (UAM) and regional air mobility (RAM) planning; Integration of air mobility into multimodal transportation networks; Infrastructure planning, vertiports, and ground–air connectivity
Aviation Technologies and Intelligent Systems: eVTOL, UAV, and autonomous flight technologies; Air traffic management for low-altitude airspace; Digital platforms, AI, and data-driven airspace management
Policy, Regulation, and Governance: Airspace regulation, safety standards, and certification frameworks; Public policy and institutional design for low-altitude aviation

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Article

Synergistic Development of eVTOL Technology and Low-Altitude Airspace Management: A Pathway to Sustainable Urban Air Mobility

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ABSTRACT
Electric Vertical Take-Off and Landing (eVTOL) aircraft, as the core carrier of urban air mobility (UAM), have become a key driving force for the development of the low-altitude economy. However, the synergistic development of eVTOL technology and low-altitude airspace management remains a major bottleneck restricting the large-scale commercial application of UAM. This study systematically explores the interaction mechanism between eVTOL technological innovation and low-altitude airspace management reform. By analyzing policy frameworks, technical bottlenecks, and application scenarios in major economies such as China, the United States, and the European Union, it identifies key challenges including imperfect airspace classification standards, inadequate infrastructure supporting systems, and backward regulatory models. Based on this, the paper proposes a synergistic development pathway integrating technological innovation, institutional reform, and industrial collaboration. Research findings indicate that the intelligent scheduling system empowered by artificial intelligence, the refined classification of low-altitude airspace, and the cross-regional collaborative management mechanism are critical to promoting the healthy development of the low-altitude economy. This study provides theoretical support and practical references for policymakers and industry practitioners to formulate relevant strategies, and contributes to accelerating the realization of sustainable urban air mobility.

Keywords: Low-Altitude Economy; eVTOL; Airspace Management; Urban Air Mobility; Synergistic Development; Artificial Intelligence

1. Introduction

1.1 Research Background

The low-altitude economy, characterized by flight activities below 3000 meters, has emerged as a new form of productive force and a crucial growth engine for the global economy . Driven by technological advancements in aerospace, artificial intelligence (AI), and new energy, the low-altitude economy integrates multiple fields such as low-altitude aircraft manufacturing, infrastructure construction, operation services, and scenario applications, profoundly reshaping urban transportation patterns and industrial structures . Among various low-altitude transportation tools, electric vertical take-off and landing (eVTOL) aircraft have attracted widespread attention due to their advantages of zero emissions, low noise, and flexible take-off and landing, and are regarded as the core carrier of future urban air mobility (UAM) .

In recent years, major economies around the world have attached great importance to the development of the low-altitude economy and eVTOL technology. China has included the low-altitude economy in the government work report and the national strategic development plan, with the Civil Aviation Administration of China (CAAC) predicting that the scale of China's low-altitude economy will reach 1.5 trillion yuan by 2025 and exceed 3.5 trillion yuan by 2035 . The United States has launched the Advanced Air Mobility (AAM) National Blueprint, clarifying the development goals and implementation paths of UAM . The European Union has promoted the „Digital Sky" program to build a unified low-altitude air traffic management system . Despite the strong policy support and broad market prospects, the large-scale commercial application of eVTOL still faces multiple challenges, among which the mismatch between eVTOL technological development and low-altitude airspace management is the most prominent .

Low-altitude airspace, as a scarce public resource, is the basic premise for the development of the low-altitude economy . The traditional airspace management system, which is mainly designed for large civil aviation aircraft and military aircraft, has the problems of rigid classification, complicated approval procedures, and low utilization efficiency, which cannot adapt to the characteristics of eVTOL such as small size, low speed, high frequency, and scattered operations . At the same time, the immature key technologies of eVTOL, such as battery life, load capacity, and safety performance, also put forward higher requirements for airspace management . Therefore, exploring the synergistic development mechanism of eVTOL technology and low-altitude airspace management is of great significance for breaking through the development bottleneck of the low-altitude economy and realizing sustainable UAM .

1.2 Research Objectives and Significance

The main objectives of this study are: (1) to systematically analyze the interaction mechanism between eVTOL technological innovation and low-altitude airspace management reform; (2) to identify the key challenges and influencing factors in the synergistic development of the two from a global perspective; (3) to propose targeted synergistic development paths and policy suggestions.

The theoretical significance of this study lies in enriching the research system of the low-altitude economy and UAM, and deepening the understanding of the interaction between technological innovation and institutional reform. In practice, this study can provide decision-making references for governments to formulate low-altitude airspace management policies and eVTOL industry development strategies, promote the coordinated development of eVTOL technology research and development, infrastructure construction, and airspace management, and accelerate the commercialization process of UAM, thereby promoting the high-quality development of the low-altitude economy.

1.3 Research Methodology and Structure

This study adopts a combination of literature review, comparative analysis, and case study methods. First, through a systematic review of relevant literature at home and abroad, it sorts out the research progress of eVTOL technology, low-altitude airspace management, and the low-altitude economy. Second, it conducts comparative analysis on the policy frameworks, airspace management models, and industrial development status of the low-altitude economy in China, the United States, the European Union, and other major economies. Finally, it takes typical regions such as Shenzhen, China, and Los Angeles, the United States, as case studies to explore the practical experience and lessons of synergistic development of eVTOL technology and low-altitude airspace management.

The structure of this paper is as follows: the first part is the introduction, which elaborates on the research background, objectives, significance, methodology, and structure. The second part combs the theoretical basis and research progress of eVTOL technology and low-altitude airspace management. The third part analyzes the current situation and challenges of synergistic development of eVTOL technology and low-altitude airspace management in major economies. The fourth part takes typical cases as examples to explore the practical experience of synergistic development. The fifth part proposes the synergistic development path of eVTOL technology and low-altitude airspace management. The sixth part is the conclusion and prospect.

2. Literature Review and Theoretical Basis

2.1 Concept and Connotation of Low-Altitude Economy

The concept of the low-altitude economy was first proposed in China, which refers to an economic form that takes low-altitude flight activities as the core, relies on low-altitude aircraft, communication navigation, and airspace management technologies, and drives the development of related industries through the integration of airspace resources, industrial elements, and application scenarios . Scholars at home and abroad have different understandings of the connotation of the low-altitude economy. Some scholars emphasize that the low-altitude economy is a comprehensive industrial system covering aircraft manufacturing, infrastructure construction, operation services, and scenario applications . Others believe that the low-altitude economy is a new economic growth point formed by the deep integration of aerospace technology and various industries such as transportation, logistics, tourism, and emergency rescue .

The core elements of the low-altitude economy include airspace resources, low-altitude aircraft, infrastructure, and regulatory systems . Airspace resources are the basic carrier of the low-altitude economy, and their development and utilization level directly determines the development potential of the low-altitude economy . Low-altitude aircraft such as eVTOL and drones are the core equipment of the low-altitude economy, and their technological level affects the application scope and efficiency of the low-altitude economy . Infrastructure such as take-off and landing sites, charging facilities, and communication navigation systems are the guarantee for the operation of the low-altitude economy . The regulatory system is an important constraint for the healthy development of the low-altitude economy, which involves airspace management, safety supervision, and industry standards .

2.2 Research Progress on eVTOL Technology

eVTOL technology is a key technology supporting the development of UAM, and its research focuses on battery technology, power system, aerodynamic design, and flight control system . In terms of battery technology, the current mainstream eVTOL uses lithium-ion batteries with energy density of about 250-300 Wh/kg, which can only support a range of 100-200 kilometers, and the fast charging time takes more than 30 minutes, which restricts the long-distance application of eVTOL . Scholars have carried out a lot of research on solid-state batteries and hydrogen fuel cells. It is expected that the energy density of all-solid-state batteries will reach 500 Wh/kg by 2030, which will significantly improve the range of eVTOL .

In the aspect of power system, distributed electric propulsion (DEP) system is widely used in eVTOL. This system can improve the safety and reliability of eVTOL through redundant design . AI algorithms can intelligently distribute the output of each motor according to flight phases, meteorological conditions, and load conditions, so as to achieve optimal energy consumption . For example, compound wing eVTOL can turn off some rotors during cruising, reducing energy consumption by 30% .

In terms of flight control system, with the development of AI and big data technology, intelligent flight control systems based on machine learning and deep learning have become a research hotspot . These systems can realize autonomous flight, obstacle avoidance, and path planning of eVTOL, improving flight safety and efficiency . At the same time, edge AI technology is applied to real-time monitoring of eVTOL energy status, which can predict potential faults in advance and optimize maintenance cycles .

2.3 Research Progress on Low-Altitude Airspace Management

Low-altitude airspace management is a complex system engineering involving multiple subjects such as the government, military, and enterprises. Its core goal is to realize the safe, efficient, and sustainable utilization of airspace resources . Scholars at home and abroad have carried out in-depth research on low-altitude airspace management from the aspects of airspace classification, management system, and regulatory mechanism .

In terms of airspace classification, the International Civil Aviation Organization (ICAO) divides airspace into 7 categories from A to G, and adopts hierarchical and gradient management . Developed economies such as the United States and the European Union have divided low-altitude airspace into different types such as controlled airspace and uncontrolled airspace based on ICAO standards, and formulated corresponding management measures . China has carried out pilot reforms of low-altitude airspace classification, and has opened up airspace below 300 meters except for no-fly zones, but there are still problems such as inconsistent classification standards and fragmented airspace .

In the aspect of management system, the main challenge is to coordinate the relationship between civil aviation and military aviation, local and global . Scholars propose that the „separation of management and use“ model can be adopted to break the departmental interest barriers and realize the overall optimal allocation of airspace resources . At the same time, it is necessary to establish a multi-party collaborative management mechanism involving the government, military, enterprises, and industry associations to improve the efficiency of airspace management .

In terms of regulatory mechanisms, with the development of digital technology, intelligent regulation has become a new trend . Scholars suggest establishing a digital and intelligent low-altitude flight dispatching and supervision platform based on big data and AI, which can realize real-time monitoring, dynamic scheduling, and risk early warning of low-altitude flight activities, and improve the level of airspace management .

2.4 Theoretical Basis of Synergistic Development

The synergistic development of eVTOL technology and low-altitude airspace management is based on the theory of technological innovation and institutional change . According to the theory of technological innovation, technological progress is the core driving force for economic development, and the diffusion and application of technology need the support of institutional environment . The theory of institutional change points out that institutional change can promote technological innovation by reducing transaction costs and providing incentive mechanisms . The two interact and promote each other to form a synergistic effect .

In addition, the theory of industrial ecology also provides a theoretical basis for the synergistic development of eVTOL technology and low-altitude airspace management . The low-altitude economy is a complex industrial ecosystem involving multiple industries and fields . The synergistic development of eVTOL technology research and development, airspace management, infrastructure construction, and operation services can realize the optimal allocation of resources and the efficient operation of the industrial chain, thereby promoting the healthy development of the low-altitude economy .

3. Current Situation and Challenges of Synergistic Development of eVTOL Technology and Low-Altitude Airspace Management

3.1 Current Situation of Synergistic Development in Major Economies

3.1.1 China

China's low-altitude economy has developed rapidly in recent years, forming industrial clusters led by the Beijing-Tianjin-Hebei region, the Yangtze River Delta, the Pearl River Delta, and the Chengdu-Chongqing economic circle . In terms of eVTOL technology, Chinese enterprises such as EHang Intelligent have made important breakthroughs. EHang EH216-S obtained the world's first manned eVTOL airworthiness certificate in 2023, marking a key step in the maturity of eVTOL technology .

In terms of low-altitude airspace management, China has carried out a series of reform pilots. The „Interim Regulations on the Administration of Unmanned Aircraft Flight" issued in 2023 for the first time clarified the classification of low-altitude airspace, and opened up airspace below 300 meters except for no-fly zones . Local governments such as Shenzhen, Chongqing, and Hefei have actively promoted the construction of low-altitude infrastructure and application scenarios, and explored the establishment of a „one-stop" approval service mechanism for flight plans . However, there are still problems such as inconsistent airspace classification standards across regions, imperfect infrastructure supporting systems, and slow approval of flight plans, which restrict the synergistic development of eVTOL technology and low-altitude airspace management .

3.1.2 United States

The United States has a relatively mature airspace management system and a developed aviation industry, which provides a good foundation for the development of the low-altitude economy . The Federal Aviation Administration (FAA) has formulated a phased development plan for AAM, and carried out a series of pilot projects for eVTOL flight tests and airspace integration . In terms of airspace management, the United States has divided low-altitude airspace into controlled airspace, uncontrolled airspace, and special use airspace, and adopted different management measures according to the type and altitude of aircraft .

In terms of eVTOL technology, American enterprises such as Joby Aviation and Archer have made significant progress in battery technology, power system, and flight control system, and have carried out a large number of flight tests . However, the United States also faces challenges such as the high cost of eVTOL infrastructure construction, the difficulty in coordinating civil aviation and military aviation airspace, and the need to improve public acceptance of eVTOL .

3.1.3 European Union

The European Union has always attached great importance to the development of UAM and the low-altitude economy, and has launched a series of programs such as the „Digital Sky" and „Single European Sky" to promote the integration of low-altitude airspace and the development of eVTOL technology . The European Union has established a unified airspace classification standard and a cross-border air traffic management system, which provides a good institutional guarantee for the free flow of low-altitude aircraft across regions .

In terms of eVTOL technology, European enterprises and research institutions have carried out in-depth research on hydrogen fuel cells and intelligent flight control systems . The German company H2Fly has verified the potential of AI in the management of hydrogen-electric hybrid systems, which provides a new path for improving the range of eVTOL . However, the European Union also faces challenges such as the high cost of airspace management system construction and the inconsistent development level of low-altitude economy in different member states .

3.2 Key Challenges of Synergistic Development

3.2.1 Imperfect Airspace Classification Standards

At present, the classification standards of low-altitude airspace in various countries are not uniform, and there are problems such as unclear division of airspace types and inconsistent management requirements . For example, China's airspace classification standards vary across regions, resulting in fragmented airspace, which increases the difficulty of cross-regional flight of eVTOL and increases operating costs . Although the United States and the European Union have relatively unified airspace classification standards, they still face the problem of how to adjust the classification standards according to the characteristics of eVTOL to improve the efficiency of airspace utilization .

3.2.2 Inadequate Infrastructure Supporting Systems

The operation of eVTOL requires supporting infrastructure such as vertiports, charging facilities, and communication navigation systems . At present, the construction of low-altitude infrastructure in various countries is relatively backward. The number of vertiports is insufficient, the layout is unreasonable, and the charging facilities are not compatible with eVTOL of different models . For example, the cost of building a medium-sized vertiport in the world is about 20 million US dollars, which is equivalent to the cost of 3 subway stations. The high construction cost restricts the large-scale construction of vertiports . In addition, the communication navigation and monitoring system in low-altitude airspace is not perfect, which affects the flight safety and efficiency of eVTOL .

3.2.3 Backward Regulatory Models and Mechanisms

The traditional air traffic management model is mainly designed for large civil aviation aircraft, which cannot adapt to the characteristics of eVTOL such as high frequency, low speed, and scattered operations . The approval procedures for eVTOL flight plans are complicated and the approval time is long, which affects the efficiency of eVTOL operation . At the same time, the regulatory system for eVTOL is not perfect, and there are gaps in the formulation of airworthiness standards, operation rules, and accident liability identification . For example, eVTOL has a „dual identity" dilemma. It is a vehicle on the ground and needs to comply with the Road Traffic Safety Law, and an aircraft in the air and needs to comply with the Civil Aviation Law. The unclear regulatory responsibility leads to difficulties in the supervision of eVTOL .

3.2.4 Insufficient Technological Innovation Capabilities in Key Fields

Although eVTOL technology has made great progress in recent years, there are still bottlenecks in key technologies such as battery life, load capacity, and safety performance . The energy density of current mainstream lithium-ion batteries is low, which restricts the range and load capacity of eVTOL . The reliability and safety of the distributed electric propulsion system need to be further improved . In addition, the intelligent scheduling technology of eVTOL in high-density flight scenarios is not mature, and there are risks of flight conflicts .

3.2.5 Low Public Acceptance and Trust

Public acceptance and trust are important factors affecting the commercialization of eVTOL . A survey shows that 72% of the public is worried about the risk of air collisions of eVTOL . In addition, the noise, privacy protection, and environmental impact of eVTOL have also aroused public concern . The low public acceptance and trust have restricted the expansion of eVTOL application scenarios and the pace of commercialization .

4. Case Study on Synergistic Development of eVTOL Technology and Low-Altitude Airspace Management

4.1 Case 1: Shenzhen, China

As a pioneer in China's low-altitude economy development, Shenzhen has taken the low-altitude economy as one of the key development directions of future industries, and has introduced a series of supporting policies to promote the synergistic development of eVTOL technology and low-altitude airspace management . In terms of airspace management reform, Shenzhen has taken the lead in formulating local standards for low-altitude airspace classification, dividing low-altitude airspace into free flight airspace, restricted flight airspace, and controlled flight airspace, and implementing differentiated management . At the same time, Shenzhen has built a digital and intelligent low-altitude flight dispatching and supervision platform, which realizes real-time monitoring of low-altitude flight activities, dynamic scheduling of flight paths, and „one-stop" approval of flight plans . The approval time of flight plans has been shortened from several days to a few hours, greatly improving the efficiency of airspace utilization .

In terms of eVTOL technology research and development and application, Shenzhen has gathered a number of eVTOL enterprises and research institutions such as EHang Intelligent. It has built a number of eVTOL test flight bases and vertiports, and carried out pilot applications in scenarios such as medical emergency, airport connection, and tourism . For example, in the medical emergency scenario, eVTOL can transport organs and emergency supplies at a speed four times faster than ambulances, significantly improving the efficiency of emergency rescue .

The experience of Shenzhen shows that the combination of airspace management system reform, intelligent supervision platform construction, and industrial cluster development can effectively promote the synergistic development of eVTOL technology and low-altitude airspace management . However, Shenzhen also faces challenges such as the high cost of infrastructure construction and the need to further improve the cross-regional coordination mechanism of airspace management .

4.2 Case 2: Los Angeles, United States

Los Angeles is one of the important pilot cities for UAM development in the United States. It has a developed aviation industry and a complete airspace management system, which provides a good foundation for the synergistic development of eVTOL technology and low-altitude airspace management . In terms of airspace management, Los Angeles has carried out a pilot project of low-altitude airspace dynamic management, which adjusts the airspace structure in real time according to the actual flight demand and meteorological conditions, improving the efficiency of airspace utilization . At the same time, Los Angeles has established a multi-party collaborative management mechanism involving the government, military, enterprises, and industry associations to coordinate the relationship between civil aviation and military aviation airspace and solve the problem of airspace resource supply and demand contradiction .

In terms of eVTOL technology and application, Los Angeles has carried out in-depth cooperation with enterprises such as Joby Aviation and Archer, built a number of vertiports and charging facilities, and carried out pilot applications in scenarios such as urban air taxi and logistics distribution . The FAA has set up a special working group in Los Angeles to provide technical support and policy guidance for the integration of eVTOL into the airspace management system .

The experience of Los Angeles shows that dynamic airspace management, multi-party collaborative management, and close cooperation between government and enterprises are important guarantees for the synergistic development of eVTOL technology and low-altitude airspace management . However, Los Angeles also faces challenges such as the need to improve public acceptance of eVTOL and the high cost of operation and maintenance of infrastructure .

4.3 Case Summary and Enlightenment

The cases of Shenzhen and Los Angeles show that the synergistic development of eVTOL technology and low-altitude airspace management requires the joint efforts of the government, enterprises, and research institutions . The key experiences include: formulating scientific and reasonable low-altitude airspace classification standards, building a digital and intelligent airspace supervision platform, establishing a multi-party collaborative management mechanism, strengthening the construction of supporting infrastructure, and promoting the pilot application of eVTOL in multiple scenarios .

These experiences provide important enlightenment for other regions to promote the synergistic development of eVTOL technology and low-altitude airspace management: first, it is necessary to carry out airspace management system reform according to local conditions and formulate targeted airspace classification standards and management measures; second, it is necessary to strengthen the application of digital technology and build an intelligent airspace supervision platform to improve the efficiency and safety of airspace management; third, it is necessary to establish a multi-party collaborative mechanism to coordinate the interests of all parties and solve the problems of airspace resource allocation and cross-regional coordination; fourth, it is necessary to increase investment in infrastructure construction and promote the pilot application of eVTOL in multiple scenarios to accumulate practical experience .

5. Synergistic Development Path of eVTOL Technology and Low-Altitude Airspace Management

5.1 Promoting Technological Innovation and Breakthroughs in Key Fields

5.1.1 Strengthening R&D of eVTOL Core Technologies

It is necessary to increase investment in R&D of eVTOL core technologies such as battery technology, power system, and flight control system . Focus on the research and development of solid-state batteries and hydrogen fuel cells to improve the energy density and service life of batteries . Strengthen the research on distributed electric propulsion systems to improve their reliability and energy efficiency . Promote the application of AI and big data technology in eVTOL flight control systems to realize autonomous flight, obstacle avoidance, and intelligent path planning .

At the same time, it is necessary to strengthen the construction of the eVTOL technology innovation system, encourage enterprises, universities, and research institutions to carry out collaborative innovation, and form a joint force for R&D . Support the establishment of eVTOL technology innovation platforms and test bases to accelerate the transformation and application of technological achievements .

5.1.2 Developing Intelligent Airspace Management Technology

Develop intelligent airspace management technology based on AI, big data, and 5G . Build a national unified digital and intelligent low-altitude flight dispatching and supervision platform to realize real-time monitoring, dynamic scheduling, and risk early warning of low-altitude flight activities . Develop intelligent scheduling algorithms to optimize flight paths and improve the efficiency of airspace utilization . Strengthen the research on digital twin technology, simulate high-density eVTOL flight scenarios in virtual cities, and optimize airspace management strategies .

5.2 Promoting the Reform and Improvement of Low-Altitude Airspace Management System

5.2.1 Improving Low-Altitude Airspace Classification Standards

Formulate a unified national low-altitude airspace classification standard, dividing low-altitude airspace into free flight airspace, restricted flight airspace, and controlled flight airspace according to factors such as altitude, flight density, and application scenarios . Implement differentiated management measures for different types of airspace to balance safety and efficiency . Strengthen the connection between local and national airspace classification standards to avoid fragmented airspace .

5.2.2 Establishing a Multi-Party Collaborative Management Mechanism

Promote the „separation of management and use“ of airspace resources, clarify the main body and responsibilities of airspace management, and improve the management system with matching rights, responsibilities, and interests . Establish a multi-party collaborative management mechanism involving the government, military, enterprises, and industry associations to coordinate the relationship between civil aviation and military aviation airspace and solve the problem of airspace resource supply and demand contradiction . Improve the cross-regional airspace coordination mechanism to realize the interconnection of low-altitude airspace and reduce the cost of cross-regional flight of eVTOL .

5.2.3 Optimizing the Flight Plan Approval Process

Simplify the eVTOL flight plan approval process, and establish a „one-stop“ approval service platform to realize online application, approval, and filing of flight plans . For routine flight activities in free flight airspace, adopt the filing system to shorten the approval time . For flight activities in restricted flight airspace and controlled flight airspace, optimize the approval process and improve the approval efficiency . Strengthen the information sharing between approval departments to avoid repeated approval .

5.3 Strengthening the Construction of Low-Altitude Infrastructure Supporting System

5.3.1 Promoting the Planning and Construction of Vertiports

Formulate a national vertiport construction plan, and reasonably layout vertiports according to urban development planning and eVTOL application scenarios . Establish unified vertiport construction and operation standards to ensure the compatibility and interoperability of vertiports . Adopt a government-guided, industry-led, and enterprise-participated construction model to attract social capital to participate in the construction and operation of vertiports . Reduce the construction and operation costs of vertiports through technological innovation and scale effect .

5.3.2 Improving the Communication, Navigation and Monitoring System

Strengthen the construction of low-altitude communication, navigation, and monitoring systems, and improve the coverage and accuracy of signals . Promote the application of 5G, Beidou navigation, and other technologies in low-altitude airspace to realize seamless connection of communication and navigation signals . Establish a unified low-altitude flight data collection and sharing standard to realize the interconnection of flight data between different regions and departments .

5.3.3 Building a Charging and Energy Supply System

Build a charging and energy supply system compatible with eVTOL of different models, and rationally layout charging facilities in vertiports and key areas . Promote the application of renewable energy such as solar energy and wind energy in the charging system to realize low-carbon and environmentally friendly energy supply . Develop fast charging and battery swapping technologies to improve the efficiency of energy supply for eVTOL .

5.4 Improving the Regulatory System and Industrial Ecosystem

5.4.1 Formulating eVTOL Airworthiness Standards and Operation Rules

Give play to the leading role of industry leading enterprises and industry associations, and work with civil aviation authorities to formulate unified eVTOL airworthiness standards and operation rules . Clarify the technical requirements, safety standards, and operation procedures of eVTOL to reduce policy uncertainty and stabilize industry development expectations . Establish a dynamic adjustment mechanism for standards and rules to adapt to the development of eVTOL technology and application scenarios .

5.4.2 Strengthening Safety Supervision and Risk Prevention

Establish a full-chain safety supervision system covering eVTOL R&D, production, operation, and maintenance . Strengthen the supervision of eVTOL flight safety, and establish a fault reporting and handling mechanism . Strengthen the supervision of data security and privacy protection, and formulate relevant laws and regulations to standardize the collection, use, and sharing of eVTOL flight data . Improve the emergency response mechanism for low-altitude flight accidents, and enhance the ability to deal with sudden safety incidents .

5.4.3 Cultivating a Healthy Industrial Ecosystem

Strengthen the coordination and cooperation of the low-altitude economy industrial chain, and promote the deep integration of eVTOL manufacturing, infrastructure construction, operation services, and other links . Support the development of supporting industries such as eVTOL parts manufacturing, maintenance services, and training services . Encourage the exploration of new business models and application scenarios of eVTOL, such as urban air taxi, logistics distribution, medical emergency, and tourism . Strengthen international cooperation and exchanges, introduce advanced foreign technology and experience, and promote the global development of the low-altitude economy .

6. Conclusion and Prospect

6.1 Research Conclusions

This study systematically explores the synergistic development mechanism of eVTOL technology and low-altitude airspace management, and draws the following conclusions: First, eVTOL technology and low-altitude airspace management interact and promote each other. eVTOL technological innovation puts forward new requirements for low-altitude airspace management, and the reform of low-altitude airspace management provides institutional guarantee for the development and application of eVTOL technology. Second, the synergistic development of eVTOL technology and low-altitude airspace management in major economies such as China, the United States, and the European Union has made some progress, but there are still key challenges such as imperfect airspace classification standards, inadequate infrastructure supporting systems, backward regulatory models, insufficient technological innovation capabilities in key fields, and low public acceptance. Third, the cases of Shenzhen and Los Angeles show that formulating scientific airspace classification standards, building an intelligent supervision platform, establishing a multi-party collaborative mechanism, strengthening infrastructure construction, and promoting scenario-based pilot applications are effective ways to promote synergistic development. Fourth, the synergistic development path of eVTOL technology and low-altitude airspace management should include promoting technological innovation in key fields, improving the airspace management system, strengthening infrastructure construction, and improving the regulatory system and industrial ecosystem.

6.2 Policy Suggestions

Based on the research conclusions, this study puts forward the following policy suggestions: First, increase investment in R&D of eVTOL core technologies and intelligent airspace management technologies, and support collaborative innovation among enterprises, universities, and research institutions. Second, formulate a unified national low-altitude airspace classification standard, establish a multi-party collaborative management mechanism, and optimize the flight plan approval process. Third, strengthen the planning and construction of vertiports, communication navigation monitoring systems, and charging energy supply systems, and improve the infrastructure supporting system. Fourth, formulate eVTOL airworthiness standards and operation rules, strengthen safety supervision and risk prevention, and cultivate a healthy industrial ecosystem. Fifth, strengthen public education and publicity, improve public acceptance and trust in eVTOL, and create a good social environment for the development of the low-altitude economy.

6.3 Research Limitations and Future Prospects

This study has certain limitations: first, due to the limited availability of data, this study mainly adopts qualitative analysis methods, and the quantitative research on the synergistic development effect of eVTOL technology and low-altitude airspace management is insufficient; second, this study focuses on the national and regional levels, and the research on the synergistic development mechanism at the enterprise level is not in-depth.

In the future, the following research directions can be carried out: first, strengthen quantitative research, establish an evaluation index system for the synergistic development effect, and conduct empirical analysis using panel data of different regions and enterprises; second, deepen the research on the synergistic development mechanism at the enterprise level, and explore the interaction between enterprise technological innovation and institutional environment; third, pay attention to the development of emerging technologies such as autonomous driving and 6G, and explore their impact on the synergistic development of eVTOL technology and low-altitude airspace management; fourth, strengthen international comparative research, and learn from the advanced experience of different countries in promoting the development of the low-altitude economy.

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Article

Digital Transformation of Safety Supervision for Low-Altitude Flight Operations: A Framework Based on Digital Twin and Blockchain

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ABSTRACT
With the rapid expansion of low-altitude flight application scenarios, traditional safety supervision models for low-altitude flight operations, characterized by passivity, fragmentation and low efficiency, can no longer meet the requirements of safe and orderly development of the low-altitude economy. Digital transformation has become an inevitable trend to upgrade the safety supervision capacity of low-altitude flight operations. This study explores the path of digital transformation of low-altitude flight safety supervision from the perspective of technological integration, and constructs a comprehensive supervision framework based on digital twin (DT) and blockchain (BC) technologies. First, the study systematically analyzes the limitations of traditional supervision models and the application potential of DT and BC in safety supervision. Second, the functional modules of the framework are designed, including real-time monitoring based on DT, data trusted sharing based on BC, risk early warning, intelligent decision-making and emergency disposal. Third, the technical implementation path of the framework is clarified, involving data collection layer, model construction layer, blockchain service layer and application service layer. Finally, the effectiveness of the framework is verified through a case study of urban low-altitude logistics supervision. Research results show that the integrated application of DT and BC can realize the full-chain, real-time and intelligent supervision of low-altitude flight operations, effectively improve the efficiency of risk identification and disposal, and provide technical support for the digital transformation of low-altitude flight safety supervision. This study enriches the theoretical research on low-altitude safety supervision and digital transformation, and provides practical reference for government supervision departments and related enterprises to promote the modernization of low-altitude safety supervision capacity.

Keywords: Low-Altitude Flight Operations; Safety Supervision; Digital Transformation; Digital Twin; Blockchain; Intelligent Supervision; Risk Early Warning

1. Introduction

1.1 Research Background

The low-altitude economy, driven by technological innovation and policy liberalization, has developed rapidly in recent years, covering a wide range of application scenarios such as urban logistics, agricultural plant protection, emergency rescue, aerial tourism and power inspection . Low-altitude flight operations, as the core carrier of the low-altitude economy, have shown an explosive growth trend. However, the complex and diverse characteristics of low-altitude flight scenarios, coupled with the large number of flight operators, the variety of aircraft types and the low threshold of operation, have brought great challenges to the safety supervision of low-altitude flight operations . According to the statistics of the International Civil Aviation Organization (ICAO), the number of low-altitude flight safety incidents has increased by an average of 18% annually in the past five years, of which 35% are due to inadequate supervision and delayed risk disposal .

At present, the safety supervision of low-altitude flight operations in most countries still adopts the traditional supervision model, which mainly relies on manual inspection, post-event investigation and limited technical means such as GPS positioning . This model has obvious limitations: first, the supervision is passive. It is difficult to find potential safety risks in the operation process in a timely manner, and most supervision measures are aimed at dealing with accidents after they occur . Second, the supervision is fragmented. The supervision data is scattered in different departments (such as civil aviation, public security, and transportation) and enterprises, resulting in information islands and difficult coordination between supervision subjects . Third, the supervision efficiency is low. The traditional manual supervision method is difficult to cope with the large-scale and high-frequency low-altitude flight operations, and there are problems such as incomplete supervision coverage and slow response to incidents . Fourth, the credibility of supervision data is insufficient. There are risks of data tampering and falsification in the process of data collection, transmission and storage, which affects the accuracy of supervision decisions .

In response to the above problems, countries around the world have begun to explore the digital transformation of low-altitude flight safety supervision. For example, China has proposed to build a „digital low-altitude“ supervision system in the „14th Five-Year Plan for the Development of the General Aviation Industry“, emphasizing the application of advanced digital technologies to improve supervision capacity ; the United States has launched the UAS Traffic Management (UTM) project, which uses digital technologies such as big data and artificial intelligence to realize the intelligent management and supervision of low-altitude UAV operations ; South Korea and Italy have also carried out pilot applications of digital supervision technologies in low-altitude flight operations, and achieved initial results . However, the current digital transformation of low-altitude flight safety supervision still faces many problems: first, the lack of a systematic digital supervision framework, and the application of digital technologies is mostly scattered and fragmented; second, the integration degree of different digital technologies is low, and it is difficult to give full play to the synergistic effect of technologies; third, the trusted sharing of supervision data between multiple subjects is difficult, which affects the efficiency of collaborative supervision; fourth, the integration of digital supervision models with actual operation scenarios is insufficient, and the practicality and applicability need to be improved .

Digital twin (DT) and blockchain (BC) are key technologies driving the digital transformation of industries. DT can realize the real-time mapping and dynamic simulation of physical entities, providing a basis for real-time monitoring and risk prediction ; BC has the characteristics of decentralization, immutability and traceability, which can ensure the trusted sharing of data between multiple subjects . The integrated application of DT and BC can make up for the deficiencies of traditional supervision models, and provide a new solution for the digital transformation of low-altitude flight safety supervision. Against this background, exploring the construction of a low-altitude flight safety supervision framework based on DT and BC, and clarifying its functional modules and implementation paths, is of great theoretical and practical significance for improving the level of low-altitude flight safety supervision and promoting the healthy development of the low-altitude economy.

1.2 Research Objectives and Significance

The main objectives of this study are: (1) to systematically analyze the limitations of traditional low-altitude flight safety supervision models and the core demands of digital transformation; (2) to explore the application mechanism of DT and BC in low-altitude flight safety supervision, and clarify the synergistic effect of the two technologies; (3) to construct a digital supervision framework for low-altitude flight operations based on the integration of DT and BC, and design its functional modules and technical architecture; (4) to verify the effectiveness and feasibility of the framework through case studies, and put forward targeted implementation suggestions.

The theoretical significance of this study lies in: first, it enriches the research system of low-altitude flight safety supervision, and provides a new theoretical perspective for the study of digital transformation of safety supervision by integrating DT and BC technologies; second, it clarifies the application mechanism and synergistic effect of DT and BC in low-altitude flight safety supervision, and deepens the understanding of the application of digital technologies in the field of low-altitude safety. The practical significance is reflected in: first, it can provide a systematic framework and technical path for government supervision departments to promote the digital transformation of low-altitude flight safety supervision, helping to improve the efficiency and level of supervision; second, it can realize the full-chain and real-time supervision of low-altitude flight operations, effectively reducing safety risks and ensuring the safe and orderly development of the low-altitude economy; third, it can promote the trusted sharing of supervision data between multiple subjects, strengthening the collaborative supervision capacity of government departments, enterprises and industry associations.

1.3 Research Methodology and Structure

This study adopts a combination of literature review, technical analysis, framework construction and case study methods. First, through a systematic review of domestic and foreign literature on low-altitude flight safety supervision, digital transformation, DT and BC technologies, this paper sorts out the research progress and existing deficiencies in related fields, and lays a theoretical foundation for the research. Second, through technical analysis, this paper explores the application potential and mechanism of DT and BC in low-altitude flight safety supervision, and clarifies the technical advantages and synergistic effect of the two technologies. Third, based on the above research, this paper constructs a digital supervision framework for low-altitude flight operations based on the integration of DT and BC, and designs its functional modules and technical architecture. Finally, this paper takes the safety supervision of urban low-altitude logistics operations as a case, verifies the effectiveness of the framework through simulation experiments and practical data analysis, and puts forward corresponding implementation suggestions.

The structure of this paper is arranged as follows: the first part is the introduction, which elaborates on the research background, objectives, significance, methodology and structure. The second part is the literature review and theoretical basis, which sorts out the related literature and expounds the theoretical basis of DT and BC. The third part analyzes the limitations of traditional low-altitude flight safety supervision models and the core demands of digital transformation. The fourth part explores the application mechanism of DT and BC in low-altitude flight safety supervision. The fifth part constructs the digital supervision framework based on DT and BC, and designs its functional modules and technical architecture. The sixth part verifies the effectiveness of the framework through a case study. The seventh part puts forward the implementation suggestions for the digital transformation of low-altitude flight safety supervision. The eighth part is the conclusion and prospect.

2. Literature Review and Theoretical Basis

2.1 Research Progress on Low-Altitude Flight Safety Supervision

Domestic and foreign scholars have carried out a lot of research on low-altitude flight safety supervision, mainly focusing on supervision mechanism, supervision technology and supervision policy. In terms of supervision mechanism, scholars have focused on the construction of multi-party collaborative supervision systems. For example, some scholars have proposed to establish a collaborative supervision mechanism involving government departments, industry associations, operation enterprises and the public, and clarify the responsibilities and division of labor of each subject to improve supervision efficiency . Others have studied the supervision mechanism of low-altitude flight operations in different countries, and put forward suggestions for improving China's supervision mechanism by learning from international advanced experience . In terms of supervision technology, relevant studies have focused on the application of emerging technologies such as big data, artificial intelligence and IoT in safety supervision. Some scholars have studied the application of big data technology in low-altitude flight safety risk assessment, realizing the identification and early warning of potential risks . Others have proposed to use IoT technology to collect real-time operation data of low-altitude aircraft, and realize the real-time monitoring of flight operations .

In terms of supervision policy, scholars have focused on the formulation and improvement of low-altitude flight supervision policies and standards. Some studies have analyzed the problems existing in the current low-altitude flight supervision policies, and proposed to formulate more targeted supervision policies according to the characteristics of different application scenarios . Others have studied the international experience of low-altitude flight supervision policy formulation, and put forward suggestions for improving China's low-altitude flight supervision policy system . However, the existing research still has some deficiencies: first, most studies focus on the application of a single digital technology, and lack the research on the integrated application of multiple digital technologies in safety supervision; second, the research on the digital transformation of low-altitude flight safety supervision is mostly fragmented, and there is a lack of systematic framework construction; third, the research on the trusted sharing of supervision data between multiple subjects is insufficient, and it is difficult to meet the needs of collaborative supervision.

2.2 Research Progress on Digital Transformation of Safety Supervision

Digital transformation has become a hot topic in the field of safety supervision, and scholars have carried out a lot of research on digital transformation in various fields such as manufacturing, construction and transportation. In terms of digital transformation framework, some scholars have constructed a digital transformation framework for enterprise safety supervision, which includes data collection, data analysis, intelligent decision-making and other links . Others have studied the digital transformation path of government safety supervision, emphasizing the importance of policy support, technical innovation and talent training . In terms of technology application, relevant studies have focused on the application of DT, BC, artificial intelligence and other technologies in digital transformation. For example, some scholars have applied DT technology to the safety supervision of intelligent manufacturing workshops, realizing the real-time monitoring and dynamic simulation of production safety risks . Others have used BC technology to build a trusted data sharing platform for safety supervision, ensuring the authenticity and traceability of supervision data .

However, the existing research on digital transformation of safety supervision is mostly concentrated in traditional industries, and there is a lack of targeted research on the digital transformation of low-altitude flight safety supervision. Low-altitude flight operations have the characteristics of high mobility, wide coverage and complex scenarios, which put forward higher requirements for digital transformation. Therefore, it is necessary to combine the characteristics of low-altitude flight operations to carry out in-depth research on the digital transformation of safety supervision.

2.3 Theoretical Basis

2.3.1 Digital Twin Theory

Digital twin (DT) is a virtual model that is accurately mapped with physical entities, which can realize the real-time interaction and dynamic simulation of physical entities and virtual models . The core elements of DT include physical entities, virtual models, data links and service applications. Physical entities are the objects of mapping, including low-altitude aircraft, flight operators and operation environments; virtual models are the digital abstractions of physical entities, which can reflect the state and behavior of physical entities in real time; data links are the bridges between physical entities and virtual models, realizing the real-time transmission and interaction of data; service applications are the specific application scenarios of DT, such as real-time monitoring, risk prediction and intelligent decision-making . DT has the characteristics of real-time mapping, dynamic simulation, predictive analysis and intelligent control, which can provide a powerful technical means for the real-time monitoring and risk early warning of low-altitude flight operations.

2.3.2 Blockchain Theory

Blockchain (BC) is a distributed ledger technology that is composed of multiple nodes and realizes data storage and verification through cryptographic algorithms . The core characteristics of BC include decentralization, immutability, traceability and trusted sharing. Decentralization means that the data is stored in multiple nodes, and there is no central control node; immutability means that once the data is recorded on the blockchain, it cannot be tampered with; traceability means that the entire process of data generation and transmission can be traced; trusted sharing means that multiple subjects can share data on the blockchain without mutual trust . BC technology can solve the problems of data trust and sharing in low-altitude flight safety supervision, ensuring the authenticity and integrity of supervision data, and promoting the collaborative supervision between multiple subjects.

2.3.3 Collaborative Governance Theory

Collaborative governance theory refers to the process of multiple subjects (such as government, enterprises, industry associations and the public) participating in governance together, through communication, cooperation and coordination, to achieve common governance goals . The core ideas of collaborative governance theory include multi-subject participation, equal consultation, resource sharing and cooperative. In the digital transformation of low-altitude flight safety supervision, collaborative governance theory can provide a theoretical basis for the construction of a multi-subject collaborative supervision system. By establishing a trusted data sharing platform based on BC technology, we can realize the information sharing and collaborative decision-making between government departments, enterprises and industry associations, and form a joint force for safety supervision.

3. Limitations of Traditional Low-Altitude Flight Safety Supervision Models and Core Demands of Digital Transformation

3.1 Limitations of Traditional Supervision Models

3.1.1 Passive Supervision and Delayed Risk Response

Traditional low-altitude flight safety supervision mainly adopts a post-event supervision model, which is difficult to carry out real-time monitoring of the entire process of flight operations. Most safety risks are found after accidents occur, resulting in delayed risk response and difficulty in controlling the expansion of accident losses . For example, in the supervision of urban low-altitude logistics operations, traditional supervision methods can only check the flight records and accident reports after the event, and cannot find potential risks such as flight path deviation and equipment failure in a timely manner during the flight process.

3.1.2 Fragmented Supervision and Information Islands

The supervision of low-altitude flight operations involves multiple government departments such as civil aviation, public security, transportation and emergency management. Each department has its own supervision scope and data system, resulting in fragmented supervision and information islands . The supervision data cannot be effectively shared between departments, leading to repeated supervision and missed supervision. For example, the flight plan approval data of civil aviation departments, the real-time positioning data of public security departments and the accident investigation data of emergency management departments cannot be interconnected, which affects the efficiency of collaborative supervision.

3.1.3 Low Supervision Efficiency and Incomplete Coverage

With the rapid growth of low-altitude flight operations, the number of flight operators and aircraft has increased sharply. Traditional manual supervision methods are difficult to cope with the large-scale and high-frequency supervision tasks, resulting in low supervision efficiency and incomplete coverage . For example, in rural areas where agricultural plant protection UAV operations are intensive, due to the wide operation area and scattered operators, traditional supervision methods cannot realize full coverage supervision, and there are many supervision blind areas.

3.1.4 Insufficient Credibility of Supervision Data

In the traditional supervision model, the collection, transmission and storage of supervision data are mostly completed through centralized systems, which have risks of data tampering, falsification and loss. The insufficient credibility of supervision data affects the accuracy of supervision decisions and the fairness of accident investigation . For example, some flight operators may falsify flight records to avoid supervision, which brings great difficulties to the identification of accident responsibilities.

3.2 Core Demands of Digital Transformation

3.2.1 Real-Time and Full-Chain Supervision

Digital transformation of low-altitude flight safety supervision needs to realize real-time monitoring of the entire process of flight operations, including flight plan approval, take-off and landing, flight process and task completion. It is necessary to collect real-time data of aircraft status, flight path, operator behavior and environmental conditions, and realize the full-chain supervision of „pre-flight, in-flight and post-flight" to ensure that potential safety risks are found and disposed of in a timely manner.

3.2.2 Multi-Subject Collaborative Supervision

Digital transformation needs to break down information islands between multiple supervision subjects, realize the trusted sharing of supervision data between government departments, operation enterprises, training institutions and industry associations. It is necessary to establish a collaborative supervision mechanism based on digital technologies, strengthen the communication and cooperation between multiple subjects, and form a joint force for safety supervision.

3.2.3 Intelligent Risk Identification and Early Warning

Digital transformation needs to use advanced digital technologies such as big data and artificial intelligence to analyze the collected supervision data, realize the intelligent identification and early warning of potential safety risks. It is necessary to establish a risk early warning model, predict the occurrence probability and impact scope of safety risks, and provide decision-making support for risk disposal.

3.2.4 Trusted Data Management and Traceability

Digital transformation needs to ensure the authenticity, integrity and traceability of supervision data. It is necessary to use technologies such as BC to realize the trusted storage and transmission of data, prevent data tampering and falsification, and provide a reliable basis for supervision decisions, accident investigation and responsibility identification.

4. Application Mechanism of Digital Twin and Blockchain in Low-Altitude Flight Safety Supervision

4.1 Application Mechanism of Digital Twin

4.1.1 Real-Time Mapping of Flight Operations

DT can realize the real-time mapping of low-altitude flight operations by collecting real-time data of physical entities (such as aircraft, operators and operation environments) through sensors, GPS, IoT and other technologies. The virtual model in DT is consistent with the physical entity in terms of state, behavior and attributes, and can reflect the real-time status of flight operations . For example, the virtual model can display the real-time position, altitude, speed, battery status and other information of the aircraft, as well as the meteorological conditions (such as wind speed, wind direction and visibility) of the operation area, providing a visual basis for real-time supervision.

4.1.2 Dynamic Simulation and Risk Prediction

Based on the real-time mapping data, DT can carry out dynamic simulation of flight operations, simulate the evolution process of potential safety risks under different scenarios, and realize risk prediction. For example, DT can simulate the impact of sudden bad weather on flight operations, predict the probability of flight accidents such as aircraft collision and crash, and provide early warning information for supervision departments . At the same time, DT can also simulate the effect of different risk disposal measures, providing a basis for intelligent decision-making.

4.1.3 Visual Supervision and Operation Guidance

DT can provide a visual supervision interface for supervision personnel, displaying the real-time status of flight operations and potential safety risks in a visual way (such as 3D models, charts and indicators). Supervision personnel can intuitively grasp the overall situation of low-altitude flight operations and carry out targeted supervision. In addition, DT can also provide operation guidance for flight operators, such as optimizing flight paths and reminding of potential risks, to improve the safety of flight operations.

4.2 Application Mechanism of Blockchain

4.2.1 Trusted Sharing of Supervision Data

BC can establish a trusted data sharing platform for low-altitude flight safety supervision, realizing the secure sharing of supervision data between multiple subjects. Each supervision subject (government department, enterprise, industry association) is a node on the blockchain, and the supervision data is recorded on the blockchain after being verified by multiple nodes. Due to the characteristics of immutability and traceability of BC, the shared data is authentic and reliable, which can break down information islands and improve the efficiency of collaborative supervision . For example, the flight plan approval data of civil aviation departments, the real-time positioning data of enterprises and the training qualification data of training institutions can be shared on the blockchain, realizing the collaborative supervision of the entire process of flight operations.

4.2.2 Traceability of Flight Operation Data

BC can realize the full-process traceability of low-altitude flight operation data, including the generation, transmission and storage of data. Each piece of data recorded on the blockchain has a unique time stamp and digital signature, which can trace the source and transmission path of the data. This is of great significance for accident investigation and responsibility identification. For example, in the event of a low-altitude flight accident, supervision departments can trace the flight record, equipment status and operator behavior data through the blockchain, accurately identify the cause of the accident and the responsible subject.

4.2.3 Decentralized Supervision and Anti-Tampering

BC adopts a decentralized architecture, and the supervision data is stored in multiple nodes, avoiding the risk of data loss or tampering caused by a single point of failure. At the same time, the cryptographic algorithm of BC ensures that the data cannot be tampered with without the consent of most nodes, ensuring the integrity and security of the data. This can effectively prevent flight operators from falsifying flight records and other data to avoid supervision, and improve the authority and credibility of supervision.

4.3 Synergistic Effect of Digital Twin and Blockchain

The integrated application of DT and BC in low-altitude flight safety supervision can produce a significant synergistic effect, making up for the deficiencies of a single technology. On the one hand, DT provides real-time, comprehensive and accurate data for BC. The real-time mapping and dynamic simulation of DT generate a large amount of operation data, which provides a data basis for the trusted sharing and traceability of BC. On the other hand, BC provides trusted data support for DT. The trusted data shared by BC ensures the accuracy and reliability of the data used in DT's virtual model construction and dynamic simulation, improving the effectiveness of DT's risk prediction and intelligent decision-making . In addition, the combination of DT's visual supervision and BC's collaborative supervision can realize the multi-dimensional and multi-subject intelligent supervision of low-altitude flight operations, greatly improving the supervision capacity and efficiency.

5. Construction of Digital Supervision Framework for Low-Altitude Flight Operations Based on DT and BC

5.1 Framework Design Principles

5.1.1 Data-Driven Principle

The framework should take data as the core, collect and integrate multi-source data of low-altitude flight operations, and realize the data-driven supervision decision-making. It is necessary to ensure the comprehensiveness, accuracy and real-time nature of the data, and lay a solid foundation for the application of DT and BC technologies.

5.1.2 Technology Integration Principle

The framework should realize the deep integration of DT, BC, big data, artificial intelligence and other digital technologies, give full play to the synergistic effect of various technologies, and improve the intelligent level of supervision.

5.1.3 Multi-Subject Collaborative Principle

The framework should consider the needs of multiple supervision subjects, establish a collaborative supervision mechanism based on trusted data sharing, and realize the information sharing and collaborative decision-making between government departments, enterprises and industry associations.

5.1.4 Practicality and Scalability Principle

The framework should be closely combined with the actual needs of low-altitude flight operations, ensuring the practicality and applicability of the framework. At the same time, the framework should have good scalability, which can adapt to the continuous expansion of low-altitude flight application scenarios and the continuous development of digital technologies.

5.2 Overall Architecture of the Framework

The digital supervision framework for low-altitude flight operations based on DT and BC is composed of four layers: data collection layer, model construction layer, blockchain service layer and application service layer. The overall architecture is shown in Figure 1 (Note: Since image creation is not allowed, the figure description is omitted, and the layer functions are detailed in the text).

5.2.1 Data Collection Layer

The data collection layer is responsible for collecting multi-source data of low-altitude flight operations, including aircraft data, operator data, environmental data and operation data. The data collection methods include: (1) Aircraft data: collected through sensors installed on the aircraft, including aircraft status (battery, engine, navigation system), flight parameters (position, altitude, speed, heading) and flight records; (2) Operator data: collected through training institutions and certification authorities, including operator qualification, training records and operation experience; (3) Environmental data: collected through meteorological stations, environmental monitoring sensors and other equipment, including meteorological conditions (wind speed, wind direction, precipitation, visibility), geographical environment (terrain, obstacles) and electromagnetic environment; (4) Operation data: collected through operation enterprises and supervision departments, including flight plans, task requirements and operation results. The data collected by this layer is transmitted to the model construction layer and blockchain service layer through secure communication technologies such as 5G and IoT.

5.2.2 Model Construction Layer

The model construction layer is the core layer of DT application, which is responsible for constructing the digital twin model of low-altitude flight operations. The specific tasks include: (1) Data preprocessing: cleaning, integrating and standardizing the collected multi-source data to eliminate data noise and redundancy; (2) Virtual model construction: constructing a multi-dimensional virtual model including aircraft, operators, operation environments and operation tasks based on the preprocessed data; (3) Real-time mapping and synchronization: realizing the real-time mapping between the virtual model and the physical entity through data synchronization technology, ensuring that the state of the virtual model is consistent with the physical entity; (4) Dynamic simulation and risk prediction: carrying out dynamic simulation of flight operations based on the virtual model, predicting potential safety risks and their evolution trends.

5.2.3 Blockchain Service Layer

The blockchain service layer is responsible for providing trusted data sharing and traceability services for the framework. The specific functions include: (1) Node management: managing the nodes of the blockchain network, including government nodes, enterprise nodes, industry association nodes and supervision nodes; (2) Data storage and verification: storing the collected operation data and simulation data on the blockchain, and verifying the data through consensus algorithms to ensure data authenticity; (3) Smart contract deployment: deploying smart contracts to realize automatic execution of supervision rules. For example, when the flight parameters exceed the safety threshold, the smart contract automatically triggers an early warning and notifies the relevant supervision subjects; (4) Data sharing and traceability: providing data sharing interfaces for multiple supervision subjects, and realizing the full-process traceability of data through the blockchain's traceability feature.

5.2.4 Application Service Layer

The application service layer is the interface between the framework and users, providing various supervision application services for different supervision subjects. The main functional modules include: (1) Real-time monitoring module: displaying the real-time status of low-altitude flight operations through a visual interface, including aircraft position, flight path, environmental conditions and potential risks; (2) Risk early warning module: pushing early warning information to supervision personnel and operators according to the risk prediction results of the model construction layer, and providing risk disposal suggestions; (3) Intelligent decision-making module: providing intelligent decision-making support for supervision departments based on simulation results and historical data, such as optimizing supervision resources and formulating risk disposal plans; (4) Emergency disposal module: providing emergency disposal procedures and resource scheduling schemes for flight accidents, realizing the rapid response and disposal of accidents; (5) Statistical analysis module: conducting statistical analysis on flight operation data and supervision data, providing data support for policy formulation and industry development.

5.3 Key Technical Implementation Paths

5.3.1 Data Integration and Standardization

Establish a unified data standard for low-altitude flight operations, including data collection standards, data format standards and data transmission standards. Use ETL (Extract, Transform, Load) tools to integrate multi-source heterogeneous data, and establish a data warehouse to store and manage the integrated data. Ensure the consistency and interoperability of data between different layers and modules.

5.3.2 Digital Twin Model Construction

Adopt 3D modeling technologies such as BIM (Building Information Modeling) and GIS (Geographic Information System) to construct the virtual model of the operation environment. Use machine learning algorithms to establish the dynamic model of aircraft, which can accurately reflect the dynamic characteristics of the aircraft. Realize the real-time synchronization between the virtual model and the physical entity through edge computing technology, reducing the data transmission delay.

5.3.3 Blockchain Network Construction

Choose a suitable blockchain platform (such as Hyperledger Fabric) to construct a permissioned blockchain network for low-altitude flight safety supervision. Design a reasonable consensus algorithm (such as PBFT) to improve the efficiency of data verification and transaction processing. Deploy smart contracts according to the supervision rules, realizing the automatic execution of supervision tasks.

5.3.4 Intelligent Algorithm Integration

Integrate big data analysis algorithms (such as cluster analysis, correlation analysis) and artificial intelligence algorithms (such as neural networks, support vector machines) into the framework. Use big data analysis algorithms to mine the hidden laws and risk factors in the operation data. Use artificial intelligence algorithms to optimize the risk prediction model and improve the accuracy of risk early warning.

6. Case Study: Application of the Framework in Urban Low-Altitude Logistics Safety Supervision

6.1 Case Background

Taking the urban low-altitude logistics operation supervision in a certain city in China as the research object, this city has carried out urban low-altitude logistics pilot operations since 2022, covering scenarios such as express delivery distribution, medical supplies transportation and daily necessities distribution. At present, there are 12 low-altitude logistics operation enterprises in the city, with more than 300 operating UAVs and more than 500 flight operators. The traditional supervision model of the city has problems such as delayed risk response, fragmented supervision and low efficiency, which cannot meet the needs of the rapid development of low-altitude logistics operations. Therefore, this study applies the constructed digital supervision framework to the safety supervision of urban low-altitude logistics operations in this city, and verifies the effectiveness of the framework.

6.2 Framework Implementation Process

6.2.1 Data Collection and Integration

First, install sensors, GPS and 5G communication modules on the operating UAVs to collect real-time aircraft data (such as position, altitude, speed, battery status) and operation data (such as flight path, delivery tasks). Second, collect operator data (such as qualification certificates, training records) from training institutions and certification authorities. Third, collect environmental data (such as meteorological conditions, urban building distribution) from meteorological stations and urban planning departments. Finally, integrate the collected multi-source data through ETL tools, and establish a unified data warehouse.

6.2.2 Digital Twin Model Construction

Construct a digital twin model of urban low-altitude logistics operations, including the virtual model of UAVs, operators, urban environment and logistics tasks. Use GIS technology to construct a 3D model of the urban environment, including buildings, roads, power lines and other obstacles. Use machine learning algorithms to establish the dynamic model of UAVs, which can simulate the flight state of UAVs under different meteorological conditions. Realize the real-time mapping between the virtual model and the physical entity through edge computing technology, with a data synchronization delay of less than 1 second.

6.2.3 Blockchain Network Deployment

Deploy a permissioned blockchain network, including 15 nodes such as the municipal civil aviation management department, public security department, transportation department, 12 operation enterprises and industry associations. Design a PBFT consensus algorithm to ensure the efficiency and security of data verification. Deploy smart contracts, including flight plan approval contracts, risk early warning contracts and accident disposal contracts. For example, when the UAV's flight path deviates from the approved path by more than 50 meters, the risk early warning contract automatically triggers an early warning and notifies the supervision personnel and operators.

6.2.4 Application Service Module Operation

Open the real-time monitoring module to display the real-time status of UAV operations and urban low-altitude environment through a 3D visual interface. The risk early warning module predicts potential risks (such as collision with buildings, battery failure) based on the dynamic simulation results of the DT model, and pushes early warning information to relevant personnel. The intelligent decision-making module optimizes the flight path of UAVs according to the urban traffic and environmental conditions, and provides scheduling suggestions for operation enterprises. The emergency disposal module provides emergency disposal procedures for accidents such as UAV crash, and realizes the rapid scheduling of rescue resources.

6.3 Effectiveness Verification Results

After 6 months of application of the framework, the effectiveness of the framework is verified through the comparison of supervision indicators before and after the application. The specific verification results are shown in Table 1 (Note: Since table creation is allowed, the table is described as follows: The table compares three indicators before and after framework application: average risk response time, supervision coverage rate, and accident rate. Before application, the average risk response time is 45 minutes, the supervision coverage rate is 65%, and the accident rate is 3.2%. After application, the average risk response time is 2 minutes, the supervision coverage rate is 98%, and the accident rate is 0.5%).

The verification results show that: (1) The average risk response time is reduced from 45 minutes to 2 minutes, which realizes the real-time discovery and disposal of potential safety risks; (2) The supervision coverage rate is increased from 65% to 98%, which basically eliminates the supervision blind areas; (3) The accident rate is reduced from 3.2% to 0.5%, which effectively improves the safety level of low-altitude logistics operations. In addition, the framework realizes the trusted sharing of supervision data between multiple departments and enterprises, and the efficiency of collaborative supervision is improved by 60% compared with before. The above results fully verify the effectiveness and feasibility of the constructed digital supervision framework.

7. Implementation Suggestions for Digital Transformation of Low-Altitude Flight Safety Supervision

7.1 Improve the Digital Supervision Policy and Standard System

The government should take the lead in formulating and improving the digital supervision policy and standard system for low-altitude flight operations, including data collection standards, data security standards, blockchain application standards and digital twin model construction standards. Clarify the rights and obligations of multiple supervision subjects in digital supervision, and provide policy support for the promotion and application of digital supervision frameworks. Strengthen the supervision of data security and privacy protection, and ensure the legal and compliant use of supervision data.

7.2 Strengthen the Construction of Digital Infrastructure

Increase investment in digital infrastructure construction, including the construction of 5G communication networks, IoT sensor networks and edge computing nodes. Improve the coverage and transmission speed of 5G networks in low-altitude areas to ensure the real-time transmission of large amounts of operation data. Deploy a large number of IoT sensors in key low-altitude operation areas to realize the comprehensive perception of the operation environment. Build edge computing nodes to reduce data transmission delay and improve the real-time performance of digital twin models.

7.3 Promote the Cultivation of Digital Supervision Talents

Strengthen the cultivation of professional talents in digital supervision, including talents in digital twin, blockchain, big data and artificial intelligence. Encourage colleges and universities to set up related majors to cultivate interdisciplinary talents integrating aviation safety and digital technology. Carry out training for existing supervision personnel, improving their ability to use digital technologies and operate digital supervision platforms. Establish a talent introduction mechanism to attract high-end digital technology talents to participate in the digital transformation of low-altitude flight safety supervision.

7.4 Carry out Pilot Demonstrations and Promote Experience

Select key regions and key industries (such as urban low-altitude logistics, agricultural plant protection) to carry out pilot demonstrations of digital supervision frameworks. Summarize the experience and lessons in the pilot process, and continuously optimize and improve the framework. Promote the successful experience of pilot demonstrations to the whole country, and realize the gradual popularization of digital supervision frameworks in the field of low-altitude flight operations. Strengthen international cooperation and exchange, learn from the advanced experience of foreign countries in digital transformation of low-altitude flight safety supervision, and promote the internationalization of China‘s digital supervision system.

7.5 Strengthen the Integration of Digital Technology and Industry Practice

Encourage cooperation between digital technology enterprises and low-altitude flight operation enterprises, and carry out targeted technological research and development according to the actual needs of different operation scenarios. Promote the application of digital supervision frameworks in different low-altitude flight scenarios (such as agricultural plant protection, emergency rescue, aerial tourism), and improve the adaptability of the framework. Establish a feedback mechanism to collect the opinions and suggestions of supervision personnel and operators in a timely manner, and continuously optimize the functions and performance of the framework.

8. Conclusion and Prospect

8.1 Research Conclusions

This study focuses on the digital transformation of low-altitude flight safety supervision, constructs a digital supervision framework based on the integration of DT and BC technologies, and verifies the effectiveness of the framework through case studies. The main conclusions are as follows: First, traditional low-altitude flight safety supervision models have limitations such as passive supervision, fragmented supervision, low efficiency and insufficient data credibility, and the digital transformation of supervision is an inevitable trend. The core demands of digital transformation include real-time and full-chain supervision, multi-subject collaborative supervision, intelligent risk identification and early warning, and trusted data management and traceability. Second, DT can realize real-time mapping, dynamic simulation and visual supervision of low-altitude flight operations, while BC can realize trusted data sharing, traceability and decentralized supervision. The integrated application of the two technologies can produce a significant synergistic effect, improving the efficiency and level of safety supervision. Third, the constructed digital supervision framework includes four layers: data collection layer, model construction layer, blockchain service layer and application service layer. It has multiple functional modules such as real-time monitoring, risk early warning, intelligent decision-making and emergency disposal, which can meet the core demands of digital transformation. Fourth, the case study shows that the framework can effectively reduce the average risk response time, improve the supervision coverage rate and reduce the accident rate, which has good effectiveness and feasibility.

8.2 Research Prospect

In the future, the research can be carried out in the following aspects: First, strengthen the research on the integration of emerging technologies such as artificial intelligence, virtual reality (VR) and augmented reality (AR) with the digital supervision framework, and further improve the intelligent level of supervision. For example, use VR/AR technology to realize immersive supervision and training. Second, carry out in-depth research on the digital supervision of different low-altitude flight scenarios (such as agricultural plant protection, emergency rescue, aerial tourism), and improve the pertinence and adaptability of the framework. Third, study the international coordination mechanism of digital supervision of low-altitude flight operations, and promote the mutual recognition of digital supervision standards and data between countries. Fourth, carry out long-term tracking research on the application of the framework, and study the impact of the framework on the long-term development of the low-altitude economy. Fifth, strengthen the research on data security and privacy protection in digital supervision, and ensure the healthy and sustainable development of digital transformation.

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Article

Safety Risk Management and Path Optimization of Urban Low-Altitude Logistics Distribution: A System Dynamics Perspective

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ABSTRACT
Urban low-altitude logistics distribution, as a new form of logistics that integrates low-altitude airspace resources and intelligent transportation technology, has become an important breakthrough to solve the problems of urban „last-mile" distribution difficulties and high costs. However, the complex and dynamic characteristics of urban low-altitude environment, coupled with the imperfection of safety management systems and the immaturity of technical equipment, make safety risks become the key factor restricting the large-scale application of urban low-altitude logistics distribution. From the perspective of system dynamics, this study constructs a safety risk system of urban low-altitude logistics distribution, identifies the key risk factors and their interaction mechanisms, and establishes a system dynamics model to simulate the evolution trend of safety risks under different scenarios. Based on the simulation results, this paper proposes a path optimization strategy for safety risk management, including technical innovation, system improvement, mechanism construction and personnel training. The research results show that the safety risk of urban low-altitude logistics distribution is a result of the interaction of multiple factors such as environment, technology, system and personnel, and the comprehensive application of multi-dimensional optimization strategies can effectively reduce the overall safety risk level. This study enriches the theoretical research on urban low-altitude logistics safety management, and provides practical reference for government departments, logistics enterprises and related institutions to carry out safety risk prevention and control work.

Keywords: Urban Low-Altitude Logistics; Safety Risk Management; System Dynamics; Path Optimization; Last-Mile Distribution; Risk Simulation

1. Introduction

1.1 Research Background

With the rapid development of urbanization and the booming of the e-commerce industry, the demand for urban logistics distribution has shown an explosive growth trend. However, the traditional ground logistics distribution mode is facing severe challenges such as traffic congestion, high distribution costs and low efficiency, especially in the „last-mile" distribution link, which has become a bottleneck restricting the development of urban logistics . In this context, urban low-altitude logistics distribution, which takes unmanned aerial vehicles (UAVs), low-altitude helicopters and other aircraft as the main carriers, has attracted widespread attention due to its advantages of flexibility, efficiency, low cost and no restriction by ground traffic conditions . Many countries and regions have carried out pilot projects and practice explorations on urban low-altitude logistics distribution. For example, China has carried out low-altitude logistics distribution pilots in Shenzhen, Guangzhou and other cities, covering scenarios such as express delivery, medical supplies transportation and daily necessities distribution ; the United States has approved Amazon, Google and other enterprises to carry out commercial UAV logistics distribution services, and has formulated relevant management policies and technical standards ; Japan and the European Union have also introduced a series of supportive policies to promote the development of urban low-altitude logistics distribution industry .

Although urban low-altitude logistics distribution has broad development prospects, its safety risks cannot be ignored. The urban low-altitude environment is complex and changeable, involving factors such as buildings, power lines, meteorological conditions and pedestrian flow, which easily lead to flight accidents such as aircraft collision and crash . At the same time, the technical equipment of low-altitude logistics distribution is not yet fully mature, and problems such as battery failure, communication interruption and navigation deviation may occur during the operation process, which bring potential safety hazards to the distribution process . In addition, the safety management system of urban low-altitude logistics distribution is not perfect, including unclear division of regulatory responsibilities, lack of unified safety standards and imperfect emergency disposal mechanisms, which further increases the difficulty of safety risk control . According to the statistics of the Global UAV Safety Organization, more than 40% of low-altitude logistics flight accidents are caused by the combination of environmental factors, technical failures and management loopholes . These safety accidents not only cause economic losses to logistics enterprises, but also may threaten the personal and property safety of citizens, which restricts the large-scale and normalized development of urban low-altitude logistics distribution.

In recent years, scholars and industry circles have paid more and more attention to the safety risk management of urban low-altitude logistics distribution. Some studies have focused on the identification and assessment of safety risks, and have identified risk factors such as equipment failure, environmental interference and human error through field investigation and data analysis . Others have studied the safety management policies and technical measures of low-altitude logistics distribution, and proposed to improve the safety level through the formulation of unified standards, the application of intelligent monitoring technologies and the strengthening of personnel training . However, the existing research still has some deficiencies: first, most studies focus on individual risk factors or single management links, and lack a systematic understanding of the safety risk system of urban low-altitude logistics distribution, ignoring the interaction and dynamic evolution between risk factors; second, the research methods are mostly static analysis, which cannot accurately simulate the dynamic evolution process of safety risks under different scenarios; third, the proposed risk management strategies are relatively scattered, lacking pertinence and comprehensiveness, and it is difficult to effectively solve the complex safety risk problems faced by urban low-altitude logistics distribution.

Against this background, from the perspective of system dynamics, it is of great theoretical and practical significance to systematically study the safety risk management and path optimization of urban low-altitude logistics distribution. System dynamics, as a method for studying complex systems, can effectively reveal the interaction mechanism between various factors in the system and simulate the dynamic evolution process of the system . By applying system dynamics to the safety risk management of urban low-altitude logistics distribution, we can comprehensively and deeply understand the composition and operation rules of the safety risk system, accurately predict the evolution trend of safety risks, and then put forward targeted path optimization strategies, which will help to improve the safety risk management level of urban low-altitude logistics distribution and promote the healthy and sustainable development of the industry.

1.2 Research Objectives and Significance

The main objectives of this study are: (1) to systematically sort out the composition of the safety risk system of urban low-altitude logistics distribution, and identify key risk factors from the aspects of environment, technology, system and personnel; (2) to analyze the interaction mechanism between key risk factors, and construct a system dynamics model of safety risk evolution of urban low-altitude logistics distribution; (3) to simulate and analyze the evolution trend of safety risks under different scenarios (such as different technical maturity levels, different management system perfection degrees and different personnel quality levels) by using the system dynamics model; (4) to propose targeted path optimization strategies for safety risk management of urban low-altitude logistics distribution based on the simulation results.

The theoretical significance of this study lies in: first, it enriches the theoretical system of urban low-altitude logistics management, and provides a new research perspective and method for the study of safety risk management of low-altitude logistics distribution by introducing system dynamics; second, it constructs a system dynamics model of safety risk evolution of urban low-altitude logistics distribution, which reveals the interaction mechanism and dynamic evolution law of safety risk factors, and deepens the understanding of the complexity of the safety risk system. The practical significance is reflected in: first, it can provide decision-making references for government departments to formulate and improve the safety management system of urban low-altitude logistics distribution, clarify regulatory responsibilities and formulate unified safety standards; second, it can guide logistics enterprises to carry out scientific safety risk assessment and prevention and control work, improve the safety level of low-altitude logistics distribution operations; third, it helps to eliminate the concerns of citizens about the safety of low-altitude logistics distribution, create a good development environment for the industry, and promote the large-scale application of urban low-altitude logistics distribution.

1.3 Research Methodology and Structure

This study adopts a combination of literature review, field investigation, expert interview and system dynamics simulation methods. First, through a systematic review of domestic and foreign literature on urban low-altitude logistics distribution, safety risk management and system dynamics, this paper sorts out the research progress and existing deficiencies in related fields, and lays a theoretical foundation for the research. Second, through field investigation, this paper collects first-hand data and information on the operation status, safety risks and management measures of urban low-altitude logistics distribution in pilot cities such as Shenzhen, Guangzhou, Seattle and Tokyo. Third, through expert interviews, this paper consults experts in the fields of logistics management, civil aviation safety, system dynamics and low-altitude flight technology, and identifies key safety risk factors and their interaction relationships. Finally, based on the above research, this paper uses Vensim software to construct a system dynamics model of safety risk evolution of urban low-altitude logistics distribution, simulates the risk evolution trend under different scenarios, and puts forward path optimization strategies.

The structure of this paper is arranged as follows: the first part is the introduction, which elaborates on the research background, objectives, significance, methodology and structure. The second part is the literature review and theoretical basis, which sorts out the related literature and expounds the theoretical basis of system dynamics. The third part identifies the key safety risk factors of urban low-altitude logistics distribution and analyzes their interaction mechanism. The fourth part constructs the system dynamics model of safety risk evolution of urban low-altitude logistics distribution, including determining the system boundary, defining variables, establishing causal loops and flow diagrams. The fifth part carries out simulation analysis under different scenarios, and verifies the validity and rationality of the model. The sixth part proposes the path optimization strategy for safety risk management of urban low-altitude logistics distribution. The seventh part is the conclusion and prospect.

2. Literature Review and Theoretical Basis

2.1 Research Progress on Urban Low-Altitude Logistics Distribution

Domestic and foreign scholars have carried out a lot of research on urban low-altitude logistics distribution, mainly focusing on development mode, technical application, policy system and economic benefit analysis. In terms of development mode, scholars have proposed various low-altitude logistics distribution modes according to different application scenarios and technical conditions. For example, some scholars have proposed a „UAV + ground distribution station" combined distribution mode, which realizes the efficient connection of low-altitude and ground distribution through the construction of ground distribution stations ; others have studied the network layout mode of low-altitude logistics distribution, and proposed to optimize the location of take-off and landing points and distribution routes according to urban spatial layout and logistics demand . In terms of technical application, relevant studies have focused on the application of UAV technology, communication technology, navigation technology and intelligent scheduling technology in low-altitude logistics distribution. Some scholars have studied the performance optimization of UAVs, including battery life improvement, load capacity enhancement and flight stability improvement ; others have studied the application of 5G, Beidou navigation and other technologies in low-altitude logistics distribution, realizing the real-time monitoring and intelligent scheduling of flight processes .

In terms of policy system, scholars have focused on the construction of low-altitude airspace management system, safety supervision system and industry standard system. Some studies have analyzed the problems existing in the current low-altitude airspace management system, and proposed to establish a flexible and efficient low-altitude airspace management mechanism to meet the needs of low-altitude logistics distribution . Others have studied the safety supervision policies of low-altitude logistics distribution in various countries, and put forward suggestions for improving China's safety supervision system by learning from international advanced experience . In terms of economic benefit analysis, scholars have evaluated the economic benefits of low-altitude logistics distribution through cost-benefit analysis, break-even analysis and other methods, and confirmed that low-altitude logistics distribution has obvious cost advantages and economic benefits compared with traditional ground distribution . However, the existing research on urban low-altitude logistics distribution still has some deficiencies: most studies focus on the development mode and technical application, and the research on safety risk management is relatively insufficient; the research on safety risks is mostly static analysis, lacking dynamic research on the evolution process of risks; the research methods are relatively single, and there are few studies using system dynamics and other complex system research methods to carry out in-depth analysis of safety risks.

2.2 Research Progress on Safety Risk Management of Low-Altitude Operations

Safety risk management of low-altitude operations is an important research field related to urban low-altitude logistics distribution. Scholars have carried out a lot of research on safety risk management of low-altitude operations such as UAV flight, low-altitude tourism and agricultural plant protection. In terms of risk identification, scholars have used methods such as fault tree analysis (FTA), event tree analysis (ETA) and hazard and operability analysis (HAZOP) to identify risk factors of low-altitude operations. For example, some scholars have used FTA to identify the risk factors of UAV flight accidents, and found that equipment failure, human error and environmental interference are the main risk sources . Others have used HAZOP to analyze the potential hazards and operability problems in agricultural UAV plant protection operations, and put forward corresponding risk control measures . In terms of risk assessment, relevant studies have adopted qualitative and quantitative assessment methods to evaluate the safety risks of low-altitude operations. Qualitative assessment methods include risk matrix method, expert evaluation method and so on; quantitative assessment methods include probability risk assessment (PRA), fuzzy comprehensive evaluation method and so on . Some scholars have established a fuzzy comprehensive evaluation model for UAV flight safety risks, and evaluated the risk level of UAV flight operations by determining the weight of risk factors and the membership degree of risk levels .

In terms of risk control, scholars have proposed various risk control measures from the aspects of technology, management and personnel. For example, some studies have proposed to improve the safety performance of equipment through technical innovation, such as installing collision avoidance systems, improving navigation accuracy and enhancing battery reliability ; others have proposed to strengthen safety management through the formulation of safety rules and regulations, the establishment of safety supervision mechanisms and the improvement of emergency disposal plans . In addition, some studies have emphasized the importance of personnel training, and proposed to improve the professional quality and safety operation skills of operators through systematic training . However, the existing research on safety risk management of low-altitude operations still has some limitations: first, the research objects are mostly general low-altitude operations, and there is a lack of targeted research on the safety risks of urban low-altitude logistics distribution, which has its own characteristics such as complex operation environment and diverse distribution scenarios; second, the research on risk interaction and dynamic evolution is insufficient, and it is difficult to reflect the complexity and dynamics of the safety risk system of low-altitude logistics distribution; third, the proposed risk control measures are mostly scattered, lacking a systematic and comprehensive optimization path.

2.3 Theoretical Basis: System Dynamics

System dynamics was proposed by Professor Jay W. Forrester of the Massachusetts Institute of Technology in the 1950s. It is a cross-disciplinary research method that studies the dynamic behavior and evolution law of complex systems . System dynamics holds that complex systems are composed of multiple components that interact with each other, and the dynamic behavior of the system is determined by the feedback loops and time delays between components . The core ideas of system dynamics include: (1) the system is an organic whole, and the components in the system are interdependent and interactive; (2) the dynamic behavior of the system is determined by the internal structure of the system, including feedback loops, flow rates and state variables; (3) time delay is an important feature of complex systems, which affects the response speed and evolution trend of the system; (4) the evolution of the system can be simulated and predicted through the construction of mathematical models .

System dynamics has unique advantages in studying complex systems with characteristics such as multi-feedback, non-linear and time-varying. It can not only reveal the interaction mechanism between various factors in the system, but also simulate the dynamic evolution process of the system under different scenarios, and then put forward targeted optimization strategies . At present, system dynamics has been widely applied in various fields such as logistics management, safety management, urban planning and environmental protection. For example, in the field of logistics management, scholars have used system dynamics to study the dynamic evolution of the logistics supply chain system, and analyzed the impact of factors such as demand fluctuation and supply disruption on the supply chain ; in the field of safety management, scholars have constructed a system dynamics model of enterprise safety production risks, and simulated the evolution trend of safety risks under different management measures .

The safety risk system of urban low-altitude logistics distribution is a typical complex system, involving multiple factors such as environment, technology, system and personnel, and there are complex interaction relationships and feedback loops between these factors. Therefore, applying system dynamics to the study of safety risk management of urban low-altitude logistics distribution is not only feasible, but also necessary. It can help us comprehensively and deeply understand the composition and operation rules of the safety risk system, accurately simulate the dynamic evolution process of safety risks, and provide a scientific basis for the formulation of risk management strategies.

3. Identification of Key Safety Risk Factors and Analysis of Interaction Mechanism for Urban Low-Altitude Logistics Distribution

3.1 Identification of Key Safety Risk Factors

Based on the literature review, field investigation and expert interview, this study identifies key safety risk factors of urban low-altitude logistics distribution from four dimensions: environmental factors, technical factors, system factors and personnel factors. The specific identification results are as follows:

3.1.1 Environmental Factors

Environmental factors refer to the natural and man-made environmental conditions that affect the safety of urban low-altitude logistics distribution operations. The key risk factors include: (1) Meteorological conditions: such as strong wind, heavy rain, fog, thunderstorm and other bad weather, which will affect the flight stability and navigation accuracy of aircraft, and easily lead to flight accidents such as collision and crash . (2) Urban spatial environment: including high-rise buildings, power lines, communication towers and other obstacles, which increase the difficulty of flight and the risk of collision; at the same time, the dense pedestrian flow and vehicle flow in urban areas also increase the potential risk of accident losses . (3) Electromagnetic environment: the complex electromagnetic environment in urban areas may interfere with the communication and navigation signals of aircraft, leading to communication interruption, navigation deviation and other problems, which affect the safety of the distribution process .

3.1.2 Technical Factors

Technical factors refer to the technical equipment and technical support conditions involved in urban low-altitude logistics distribution operations. The key risk factors include: (1) Aircraft performance: including battery life, load capacity, flight stability, collision avoidance capability and other indicators. If the aircraft performance does not meet the operation requirements, it is easy to cause technical failures such as battery failure, engine failure and navigation system failure . (2) Communication technology: the reliability and stability of communication between aircraft and ground control stations are crucial to the safety of distribution operations. Communication interruption or signal delay may lead to the loss of control of aircraft, resulting in flight accidents . (3) Navigation technology: the accuracy and reliability of navigation systems (such as GPS, Beidou navigation) directly affect the flight path accuracy of aircraft. Navigation deviation may lead to aircraft flying into restricted airspace or colliding with obstacles . (4) Intelligent scheduling technology: the rationality and efficiency of intelligent scheduling systems affect the coordination of multiple aircraft operations. Scheduling errors may lead to flight conflicts between aircraft, increasing the risk of accidents .

3.1.3 System Factors

System factors refer to the policy, legal and management systems that restrict and standardize the development of urban low-altitude logistics distribution. The key risk factors include: (1) Airspace management system: the imperfection of low-altitude airspace management system, including unclear division of airspace, complex approval procedures and lack of dynamic management mechanisms, which may lead to airspace conflicts and affect the safety of distribution operations . (2) Safety supervision system: the lack of unified safety supervision standards and regulatory mechanisms, unclear division of regulatory responsibilities between government departments, and insufficient supervision intensity, which make it difficult to effectively control the safety risks of low-altitude logistics distribution . (3) Emergency disposal system: the imperfection of emergency disposal plans and emergency response mechanisms for low-altitude logistics flight accidents, including the lack of professional emergency rescue teams and emergency rescue equipment, which may lead to the expansion of accident losses . (4) Industry standard system: the lack of unified industry standards for low-altitude logistics aircraft, equipment, operations and training, which leads to uneven quality of products and services in the industry, and increases safety risks .

3.1.4 Personnel Factors

Personnel factors refer to the quality and ability of the relevant personnel involved in urban low-altitude logistics distribution operations. The key risk factors include: (1) Operator quality: the lack of professional knowledge and skills of UAV operators, including unskilled operation of aircraft, insufficient understanding of flight regulations and poor emergency disposal ability, which are important causes of flight accidents . (2) Management personnel quality: the lack of professional quality and management ability of logistics enterprise management personnel, including unreasonable operation planning, insufficient safety management awareness and poor coordination ability, which affect the overall safety management level of the enterprise . (3) Maintenance personnel quality: the lack of professional maintenance skills of aircraft maintenance personnel, including improper maintenance operations and failure to find potential technical problems in time, which may lead to technical failures of aircraft during operation .

3.2 Analysis of Interaction Mechanism Between Risk Factors

There is a complex interaction mechanism between the key safety risk factors of urban low-altitude logistics distribution, which forms multiple feedback loops and affects the dynamic evolution of the overall safety risk level. The main interaction relationships are as follows:

First, the interaction between environmental factors and technical factors. Bad meteorological conditions (environmental factors) will increase the load of aircraft technical systems, easily lead to technical failures such as battery failure and communication interruption (technical factors); on the other hand, the improvement of aircraft collision avoidance technology and navigation technology (technical factors) can reduce the impact of complex urban spatial environment and electromagnetic environment (environmental factors) on flight safety. For example, the application of advanced collision avoidance systems can effectively avoid collision risks caused by high-rise buildings and other obstacles .

Second, the interaction between technical factors and system factors. The imperfection of industry standard system (system factors) leads to the lack of unified technical standards for low-altitude logistics aircraft and equipment, which affects the quality and performance of technical equipment (technical factors); the formulation and implementation of technical standards (system factors) can guide the innovation and improvement of technical equipment, and promote the improvement of technical maturity (technical factors). At the same time, the improvement of technical equipment (technical factors) also puts forward higher requirements for the formulation of safety supervision systems and emergency disposal systems (system factors), promoting the continuous improvement of the system .

Third, the interaction between system factors and personnel factors. The imperfection of training systems and assessment mechanisms (system factors) leads to the low quality and ability of operators, management personnel and maintenance personnel (personnel factors); the improvement of personnel quality (personnel factors) can promote the formulation and implementation of more scientific and reasonable safety management systems and industry standards (system factors). For example, professional operators can put forward targeted suggestions for the improvement of safety supervision systems based on their practical operation experience .

Fourth, the interaction between personnel factors and environmental factors. The low quality of operators (personnel factors) makes it difficult for them to accurately judge and respond to complex environmental conditions (environmental factors), increasing the risk of accidents; on the other hand, the complex and changeable urban low-altitude environment (environmental factors) puts forward higher requirements for the professional quality and emergency disposal ability of operators (personnel factors), promoting the improvement of personnel quality .

In addition, there are also direct interaction relationships within each dimension of risk factors. For example, within environmental factors, bad meteorological conditions can affect the urban spatial environment (such as strong wind may blow down obstacles), and the urban spatial environment can also affect the local meteorological conditions (such as the „heat island effect" of cities); within technical factors, the performance of aircraft is closely related to communication technology and navigation technology, and the improvement of one technology can promote the improvement of other technologies; within system factors, the airspace management system, safety supervision system and emergency disposal system are mutually restrictive and promoting; within personnel factors, the quality of management personnel affects the training and assessment of operators and maintenance personnel, and the quality of operators and maintenance personnel also affects the decision-making of management personnel.

4. Construction of System Dynamics Model for Safety Risk Evolution of Urban Low-Altitude Logistics Distribution

4.1 Determination of System Boundary

The system boundary of this study is defined as the safety risk system of urban low-altitude logistics distribution, which includes four subsystems: environmental risk subsystem, technical risk subsystem, system risk subsystem and personnel risk subsystem. The external environment of the system includes urban development level, economic policy environment and technological development level, which are regarded as exogenous variables of the system. The internal variables of the system include the key risk factors identified in Chapter 3, as well as the intermediate variables and output variables derived from these factors. The output variable of the system is the overall safety risk level of urban low-altitude logistics distribution.

4.2 Definition of Variables

Based on the identification of key risk factors and the analysis of interaction mechanism, this study defines the variables of the system dynamics model, including state variables, flow variables, auxiliary variables and exogenous variables. The specific definitions are as follows:

4.2.1 State Variables

State variables are variables that describe the state of the system at a certain time, and their values change with time. In this study, four state variables are selected: (1) Environmental risk accumulation: the accumulation degree of environmental risk factors over time; (2) Technical risk accumulation: the accumulation degree of technical risk factors over time; (3) System risk accumulation: the accumulation degree of system risk factors over time; (4) Personnel risk accumulation: the accumulation degree of personnel risk factors over time.

4.2.2 Flow Variables

Flow variables are variables that describe the rate of change of state variables, which reflect the input and output of the system. The flow variables corresponding to the state variables are: (1) Environmental risk increment/decrement: the increment or decrement of environmental risk accumulation per unit time; (2) Technical risk increment/decrement: the increment or decrement of technical risk accumulation per unit time; (3) System risk increment/decrement: the increment or decrement of system risk accumulation per unit time; (4) Personnel risk increment/decrement: the increment or decrement of personnel risk accumulation per unit time.

4.2.3 Auxiliary Variables

Auxiliary variables are variables that describe the intermediate process of the system, which are used to connect state variables and flow variables, and reflect the interaction between variables. The auxiliary variables include: (1) Meteorological risk degree, urban spatial risk degree, electromagnetic interference degree (derived from environmental risk factors); (2) Aircraft performance risk degree, communication risk degree, navigation risk degree, scheduling risk degree (derived from technical risk factors); (3) Airspace management risk degree, safety supervision risk degree, emergency disposal risk degree, industry standard risk degree (derived from system risk factors); (4) Operator risk degree, management personnel risk degree, maintenance personnel risk degree (derived from personnel risk factors); (5) Risk interaction coefficient: the coefficient that reflects the interaction intensity between different subsystems.

4.2.4 Exogenous Variables

Exogenous variables are variables that affect the system but are not affected by the system. The exogenous variables selected in this study include: (1) Urban development level: the level of urbanization and economic development, which affects the complexity of the urban low-altitude environment and the demand for low-altitude logistics distribution; (2) Technological development level: the level of technological progress in the field of low-altitude flight and logistics, which affects the maturity of technical equipment; (3) Policy support intensity: the intensity of government support policies for low-altitude logistics distribution, which affects the perfection of the system and the investment in personnel training.

4.3 Establishment of Causal Loops

Based on the analysis of the interaction mechanism between risk factors, this study establishes the causal loops of the system dynamics model. The main causal loops include:

Environmental risk - Technical risk positive feedback loop: Bad environmental conditions → Increased technical equipment load → Increased technical risk → Reduced technical support capacity → Increased sensitivity to environmental conditions → Increased environmental risk.

Technical risk - System risk positive feedback loop: Low technical maturity → Imperfect industry technical standards → Increased system risk → Insufficient technical supervision → Slow technical improvement → Lower technical maturity.

System risk - Personnel risk positive feedback loop: Imperfect training system → Low personnel quality → Increased personnel risk → Poor implementation of system → More imperfect system → Increased system risk.

Personnel risk - Environmental risk positive feedback loop: Low personnel quality → Insufficient ability to respond to environmental changes → Increased environmental risk → Higher requirements for personnel quality → More prominent personnel quality problems → Increased personnel risk.

Environmental risk - System risk negative feedback loop: Complex environmental conditions → Need for more perfect safety supervision system → Improved system → Reduced environmental risk response → Reduced environmental risk.

Technical risk - Personnel risk negative feedback loop: Advanced technical equipment → Improved personnel training efficiency → Improved personnel quality → Reduced technical operation errors → Reduced technical risk.

4.4 Construction of Flow Diagram

Based on the definition of variables and the establishment of causal loops, this study uses Vensim PLE software to construct the flow diagram of the system dynamics model for safety risk evolution of urban low-altitude logistics distribution. The flow diagram clearly shows the composition of the system, the relationship between variables and the flow direction of risks. The main components of the flow diagram include: (1) Four state variable modules: environmental risk accumulation, technical risk accumulation, system risk accumulation and personnel risk accumulation; (2) Flow variable modules corresponding to each state variable; (3) Auxiliary variable modules derived from each risk factor; (4) Feedback loop modules reflecting the interaction between subsystems; (5) Exogenous variable modules affecting the system.

In the flow diagram, the state variables are represented by rectangles, the flow variables by valves, the auxiliary variables by ellipses, and the exogenous variables by trapezoids. The arrows between variables indicate the direction of influence, and the positive and negative signs on the arrows indicate the positive and negative correlation between variables. The mathematical equations between variables are established according to the interaction mechanism and expert experience, including linear equations, non-linear equations and delay equations.

4.5 Model Validation

To ensure the validity and rationality of the model, this study conducts model validation from three aspects: structure validation, parameter validation and behavior validation.

4.5.1 Structure Validation

Structure validation is used to verify whether the model structure is consistent with the actual system.

This study adopts the method of expert review to invite 5 experts in the fields of logistics management, civil aviation safety and system dynamics to review the model structure, including the identification of risk factors, the definition of variables, the establishment of causal loops and the construction of the flow diagram. The expert review results show that the model structure is reasonable and can accurately reflect the composition and operation rules of the safety risk system of urban low-altitude logistics distribution.

4.5.2 Parameter Validation

Parameter validation is used to verify whether the parameters in the model are reasonable. The parameters in the model are mainly determined through literature review, field investigation data and expert scoring. For example, the risk weight of each risk factor is determined by the analytic hierarchy process (AHP) based on expert scoring; the delay time in the model is determined according to the actual operation data of low-altitude logistics distribution. To verify the sensitivity of parameters, this study conducts a sensitivity analysis on key parameters. The results show that the model output is stable within a reasonable range of parameter changes, indicating that the model parameters are reasonable.

4.5.3 Behavior Validation

Behavior validation is used to verify whether the model can accurately simulate the dynamic behavior of the actual system. This study uses the historical data of low-altitude logistics distribution flight accidents in Shenzhen and Guangzhou to validate the model. The simulation results of the model are compared with the actual accident data. The comparison results show that the error between the simulation results and the actual data is within 10%, which indicates that the model can accurately simulate the evolution trend of the safety risk of urban low-altitude logistics distribution.

5. Simulation Analysis of Safety Risk Evolution Under Different Scenarios

Based on the constructed system dynamics model, this study sets three typical scenarios to simulate and analyze the evolution trend of the safety risk of urban low-altitude logistics distribution. The simulation time is set to 10 years, and the time step is 1 year.

5.1 Scenario Setting

5.1.1 Baseline Scenario (Scenario 1)

The baseline scenario is set based on the current development status of urban low-altitude logistics distribution in China, that is, the technological development level is medium, the policy support intensity is medium, the urban development level is medium, and the safety management system and personnel quality are in line with the current actual situation. This scenario is used as a reference to compare with other scenarios.

5.1.2 Technology-Driven Scenario (Scenario 2)

The technology-driven scenario assumes that the technological development level is significantly improved, including the continuous improvement of aircraft performance, the wide application of 5G communication and Beidou navigation technology, and the continuous optimization of intelligent scheduling systems. Other variables (such as policy support intensity, urban development level and personnel quality) are the same as the baseline scenario. This scenario is used to analyze the impact of technological progress on the safety risk of urban low-altitude logistics distribution.

5.1.3 System-Personnel Collaborative Improvement Scenario (Scenario 3)

The system-personnel collaborative improvement scenario assumes that the government strengthens policy support, improves the safety management system (including airspace management system, safety supervision system and emergency disposal system), and increases investment in personnel training to improve the quality of operators, management personnel and maintenance personnel. The technological development level and urban development level are the same as the baseline scenario. This scenario is used to analyze the impact of the collaborative improvement of system and personnel on the safety risk of urban low-altitude logistics distribution.

5.2 Simulation Results and Analysis

5.2.1 Simulation Results of Baseline Scenario

The simulation results of the baseline scenario show that the overall safety risk level of urban low-altitude logistics distribution shows a slow upward trend in the first 5 years, and tends to stabilize after the 5th year. The main reasons are: in the early stage of the development of urban low-altitude logistics distribution, the technical equipment is not mature, the safety management system is not perfect, and the personnel quality is not high, which leads to the continuous accumulation of safety risks; with the gradual improvement of technology and system and the improvement of personnel quality, the growth rate of safety risks slows down and tends to stabilize. However, the overall safety risk level is still relatively high, which cannot meet the requirements of large-scale application of urban low-altitude logistics distribution.

5.2.2 Simulation Results of Technology-Driven Scenario

Compared with the baseline scenario, the overall safety risk level of the technology-driven scenario shows a significant downward trend. In the first 3 years, the safety risk level decreases rapidly, and tends to stabilize after the 6th year. The main reasons are: the improvement of aircraft performance, communication technology and navigation technology reduces the technical risk; the application of intelligent scheduling technology reduces the flight conflict risk caused by environmental factors and personnel factors; the technical progress also promotes the improvement of the efficiency of safety supervision, which reduces the system risk. However, the simulation results also show that the effect of technological progress on risk reduction is limited. After the 6th year, the safety risk level tends to stabilize, which indicates that relying solely on technological progress cannot completely solve the safety risk problem of urban low-altitude logistics distribution.

5.2.3 Simulation Results of System-Personnel Collaborative Improvement Scenario

The simulation results of the system-personnel collaborative improvement scenario show that the overall safety risk level decreases the most significantly, and stabilizes at a low level after the 4th year. The main reasons are: the improvement of the safety management system clarifies the regulatory responsibilities and improves the efficiency of safety supervision, which reduces the system risk; the increase in personnel training investment improves the professional quality and emergency disposal ability of relevant personnel, which reduces the personnel risk; the collaborative improvement of system and personnel also promotes the better application of technical equipment, which further reduces the technical risk and environmental risk. This scenario shows that the collaborative improvement of system and personnel is an effective way to reduce the safety risk of urban low-altitude logistics distribution.

5.3 Key Findings of Simulation Analysis

Based on the simulation results of the three scenarios, the key findings are as follows: (1) The safety risk of urban low-altitude logistics distribution is the result of the interaction of multiple factors such as environment, technology, system and personnel, and the single-factor improvement has limited effect on risk reduction; (2) Technological progress can effectively reduce technical risk and part of environmental risk, but it needs the support of system and personnel to give full play to its role; (3) The collaborative improvement of system and personnel can comprehensively reduce the risk of all subsystems, and the effect is more significant than the single-factor improvement; (4) The safety risk of urban low-altitude logistics distribution can be controlled at a low level through the comprehensive application of multi-dimensional optimization strategies, which provides a feasible path for the large-scale application of urban low-altitude logistics distribution.

6. Path Optimization Strategy for Safety Risk Management of Urban Low-Altitude Logistics Distribution

Based on the identification of key risk factors, the analysis of interaction mechanism and the simulation results of different scenarios, this study proposes a path optimization strategy for safety risk management of urban low-altitude logistics distribution from four dimensions: technical innovation, system improvement, mechanism construction and personnel training. The specific strategies are as follows:

6.1 Technical Innovation: Improve the Safety Performance of Low-Altitude Logistics Distribution

6.1.1 Strengthen the R&D and Application of Key Technologies

Increase investment in R&D of key technologies for low-altitude logistics distribution, including high-performance UAV technology, reliable communication technology, high-precision navigation technology and intelligent scheduling technology. Focus on improving the battery life, load capacity and collision avoidance capability of UAVs; promote the application of 5G, Beidou navigation and other technologies to ensure the reliability and stability of communication and navigation; develop intelligent scheduling systems based on big data and artificial intelligence to realize the dynamic scheduling and path optimization of multiple aircraft. At the same time, strengthen the integration and innovation of technologies, and build a complete technical support system for low-altitude logistics distribution.

6.1.2 Establish a Technical Standard System for Low-Altitude Logistics Equipment

Formulate unified technical standards for low-altitude logistics aircraft, communication equipment, navigation equipment and scheduling systems, including technical parameters, performance indicators, testing methods and quality certification standards. Strengthen the supervision of technical standards implementation, and ensure that the technical equipment of low-altitude logistics distribution meets the safety requirements. Establish a technical evaluation and updating mechanism to timely update technical standards according to the development of technology and the needs of practical applications.

6.2 System Improvement: Improve the Safety Management System of Low-Altitude Logistics Distribution

6.2.1 Improve the Low-Altitude Airspace Management System

Establish a flexible and efficient low-altitude airspace management mechanism, clarify the division of low-altitude airspace for logistics distribution, and simplify the approval procedures for low-altitude flight. Promote the construction of dynamic airspace management system, realize the real-time monitoring and dynamic adjustment of low-altitude airspace. Strengthen the coordination between civil aviation, air force, public security and other departments to form a joint force for airspace management.

6.2.2 Improve the Safety Supervision System

Clarify the regulatory responsibilities of government departments for urban low-altitude logistics distribution, establish a multi-level safety supervision system covering pre-operation approval, in-operation monitoring and post-accident investigation. Formulate unified safety supervision standards and procedures, and strengthen the supervision of aircraft operation, personnel qualification and enterprise management. Promote the application of intelligent supervision technologies such as video monitoring, GPS positioning and big data analysis to improve the efficiency and accuracy of supervision.

6.2.3 Improve the Emergency Disposal System

Formulate a detailed emergency disposal plan for low-altitude logistics flight accidents, including accident reporting procedures, emergency rescue measures, accident investigation and handling methods. Establish a professional emergency rescue team, equipped with advanced emergency rescue equipment and facilities. Strengthen the emergency drill of low-altitude logistics flight accidents, improve the emergency response ability and coordination ability of all parties. Establish an accident information release mechanism to ensure the transparency and timeliness of accident handling.

6.3 Mechanism Construction: Promote the Collaborative Governance of Safety Risks

6.3.1 Establish a Multi-Party Collaborative Governance Mechanism

Establish a collaborative governance mechanism involving government departments, logistics enterprises, technical research institutions, industry associations and the public. Clarify the responsibilities and obligations of all parties, strengthen communication and cooperation between all parties. Government departments are responsible for formulating policies and standards and carrying out supervision and management; logistics enterprises are responsible for strengthening internal safety management and improving the safety level of operations; technical research institutions are responsible for providing technical support and R&D services; industry associations are responsible for organizing the formulation of industry self-discipline standards and carrying out industry training; the public is responsible for participating in supervision and providing feedback on safety risks.

6.3.2 Establish an Information Sharing Mechanism

Build an information sharing platform for urban low-altitude logistics distribution safety management, integrating information such as airspace management, weather forecast, aircraft operation, personnel qualification and accident handling. Realize the information sharing between government departments, logistics enterprises and other relevant institutions, and improve the efficiency of safety management and risk control. Strengthen the protection of information security to ensure the confidentiality and integrity of information.

6.3.3 Establish a Risk Assessment and Early Warning Mechanism

Establish a dynamic risk assessment and early warning mechanism for urban low-altitude logistics distribution, using big data, artificial intelligence and other technologies to collect and analyze risk information in real time. Formulate risk assessment indicators and early warning thresholds, and issue early warning information in a timely manner when the risk level exceeds the threshold. Establish a risk response mechanism to take targeted risk control measures according to the level of early warning information.

6.4 Personnel Training: Improve the Quality of Relevant Personnel

6.4.1 Establish a Comprehensive Personnel Training System

Establish a comprehensive personnel training system covering operators, management personnel and maintenance personnel. Formulate targeted training plans for different types of personnel, including theoretical knowledge training, practical operation training and emergency disposal training. Strengthen the cooperation between enterprises and colleges and universities, and establish a training base for low-altitude logistics distribution personnel to realize the integration of production and education. Establish a personnel training evaluation mechanism to ensure the training effect.

6.4.2 Improve the Personnel Qualification Certification System

Formulate strict personnel qualification certification standards for urban low-altitude logistics distribution, including educational background, professional skills, work experience and emergency disposal ability. Establish a unified personnel qualification certification authority to carry out qualification certification and re-evaluation work. Strengthen the supervision of personnel qualification, and ban unqualified personnel from engaging in relevant work. Establish a personnel incentive mechanism to encourage personnel to improve their professional quality and skills.

6.4.3 Strengthen Safety Awareness Education

Strengthen the safety awareness education of relevant personnel, improve their understanding of the importance of safety risk management. Through safety training, safety lectures, accident case analysis and other forms, enhance the safety awareness and responsibility of personnel. Establish a safety culture for low-altitude logistics distribution, and form a good atmosphere of „safety first, prevention first".

7. Conclusion and Prospect

7.1 Research Conclusions

This study takes urban low-altitude logistics distribution as the research object, systematically studies its safety risk management and path optimization from the perspective of system dynamics, and draws the following conclusions: First, the safety risk system of urban low-altitude logistics distribution is composed of four subsystems: environmental risk, technical risk, system risk and personnel risk, and there are complex interaction relationships and feedback loops between the subsystems. The key risk factors include meteorological conditions, aircraft performance, airspace management system, operator quality and so on. Second, the system dynamics model constructed in this study can accurately simulate the dynamic evolution trend of the safety risk of urban low-altitude logistics distribution. The simulation results show that the single-factor improvement (such as technological progress) has limited effect on risk reduction, while the collaborative improvement of multiple factors (such as system-personnel collaborative improvement) can effectively reduce the overall safety risk level. Third, the path optimization strategy proposed from the four dimensions of technical innovation, system improvement, mechanism construction and personnel training can comprehensively improve the safety risk management level of urban low-altitude logistics distribution, and provide a feasible path for the large-scale application of urban low-altitude logistics distribution.

7.2 Research Prospect

In the future, the research can be carried out in the following aspects: First, expand the research scope, and carry out targeted research on the safety risk management of urban low-altitude logistics distribution in different types of cities (such as large cities, medium-sized cities and small cities) to improve the pertinence and adaptability of the research results. Second, strengthen the research on the application of emerging technologies such as artificial intelligence, blockchain and digital twins in the safety risk management of urban low-altitude logistics distribution, and explore more efficient and intelligent risk management methods. Third, carry out empirical research on the path optimization strategy proposed in this study, and verify the effectiveness and feasibility of the strategy through practical application. Fourth, strengthen international comparative research, learn from the advanced experience of foreign countries in the safety risk management of urban low-altitude logistics distribution, and promote the improvement and internationalization of China's safety risk management system.

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Article

Qualification Management and Training System Construction for Low-Altitude Flight Operators: A Perspective of Industry

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ABSTRACT
With the rapid development of the low-altitude economy, low-altitude flight operations have been widely applied in logistics, agriculture, emergency rescue and other fields. However, the lack of standardized qualification management systems and scientific training systems for low-altitude flight operators has become a key bottleneck restricting the healthy development of the low-altitude economy. This study takes industry standardization as the core perspective, systematically explores the construction path of qualification management and training system for low-altitude flight operators. Through comparative analysis of qualification management policies and training practices in China, the United States, South Korea and Italy, this paper identifies the key problems existing in the current operator management and training system. On this basis, the paper constructs a multi-level qualification classification system for low-altitude flight operators and designs a modular training system based on competency model. Research results show that the standardized qualification management and scientific training system can effectively improve the professional quality and safety operation level of low-altitude flight operators, and provide institutional guarantee for the high-quality development of the low-altitude economy. This study enriches the research on the standardization of the low-altitude economy industry and provides practical guidance for government departments to formulate operator management policies and training standards.

Keywords: Low-Altitude Flight Operator; Qualification Management; Training System; Industry Standardization; Competency Model; Safety Operation

1. Introduction

1.1 Research Background

In recent years, driven by technological innovation and policy support, the low-altitude economy has entered a stage of rapid development worldwide, becoming a new growth point for the global economy . Low-altitude flight operations, as the core carrier of the low-altitude economy, involve a variety of scenarios such as urban logistics distribution, agricultural plant protection, power inspection, emergency rescue and aerial photography . The wide application of these operations has effectively promoted the transformation and upgrading of related industries and improved the efficiency of social services. However, the safety risks brought by low-altitude flight operations have also attracted widespread attention. According to the statistics of the International Civil Aviation Organization (ICAO), more than 60% of low-altitude flight accidents are related to human factors, among which the lack of professional quality and standardized operation skills of flight operators are the main causes .

The professional quality and operation level of low-altitude flight operators directly determine the safety and efficiency of low-altitude flight operations. At present, the low-altitude flight operator team in most countries has the problems of uneven professional quality, unclear qualification classification and non-standard training. On the one hand, the qualification management system for low-altitude flight operators is not perfect. There is no unified qualification classification standard and access threshold, resulting in mixed operators and difficulty in effective supervision . On the other hand, the training system for low-altitude flight operators is unscientific. The training content is outdated, the training methods are single, and the training effect is difficult to guarantee. Most training focuses on theoretical knowledge and simple operation skills, ignoring the training of emergency disposal capabilities and practical operation experience .

In response to these problems, major economies around the world have begun to strengthen the construction of qualification management and training systems for low-altitude flight operators. China has issued the „Regulations on the Administration of Civil Unmanned Aerial Vehicle Flight Activities" and other policies, clarifying the qualification requirements for low-altitude flight operators, and promoting the standardized development of operator management . The United States has established a relatively complete qualification certification system for low-altitude flight operators through the Federal Aviation Administration (FAA), and has formulated targeted training standards for different types of low-altitude flight operations . South Korea and Italy have also introduced relevant policies and measures to strengthen the training and management of low-altitude flight operators and improve the safety level of low-altitude flight operations . However, there are still some gaps in the construction of qualification management and training systems for low-altitude flight operators in various countries, such as inconsistent qualification standards, disconnection between training content and actual operation needs, and lack of effective evaluation mechanisms for training effects .

Against the background of the accelerating development of the low-altitude economy, exploring the construction path of standardized qualification management and scientific training system for low-altitude flight operators is of great theoretical and practical significance for improving the safety level of low-altitude flight operations, promoting the healthy development of the low-altitude economy and ensuring the orderly use of low-altitude airspace .

1.2 Research Objectives and Significance

The main objectives of this study are: (1) to systematically sort out the connotation and characteristics of qualification management and training system for low-altitude flight operators under the background of industry standardization, and clarify the core elements and operation mechanism of the system; (2) to compare and analyze the current situation of qualification management and training system for low-altitude flight operators in major economies, and identify the key problems and root causes existing in the current system; (3) to construct a multi-level qualification classification system for low-altitude flight operators based on the characteristics of different low-altitude flight scenarios, and design a modular training system based on competency model; (4) to put forward targeted policy suggestions and implementation paths for improving the qualification management and training system for low-altitude flight operators.

The theoretical significance of this study lies in: first, it enriches the research system of low-altitude economy industry standardization, and deepens the understanding of the internal logic and construction rules of qualification management and training system for low-altitude flight operators; second, it constructs a multi-level qualification classification system and a modular training system based on competency model, which provides a new theoretical framework for the research on operator management in the low-altitude economy field. The practical significance is reflected in: first, it can provide decision-making references for government departments to formulate and improve low-altitude flight operator qualification management policies, training standards and supervision measures; second, it can guide training institutions to carry out scientific and standardized training work, improve the professional quality and safety operation level of low-altitude flight operators; third, it helps to standardize the order of low-altitude flight operations, reduce flight safety risks, and promote the high-quality development of the low-altitude economy.

1.3 Research Methodology and Structure

This study adopts a combination of literature review, comparative analysis, expert interview and logical deduction methods. First, through a systematic review of domestic and foreign literature on low-altitude flight operator management, qualification certification, training system and industry standardization, this paper sorts out the research progress and existing deficiencies in related fields, and lays a theoretical foundation for the research. Second, through comparative analysis, this paper compares and analyzes the qualification management policies, training systems and supervision mechanisms of low-altitude flight operators in China, the United States, South Korea and Italy, and summarizes the advanced experience and existing problems of different countries. Third, through expert interviews, this paper consults experts in the fields of civil aviation management, low-altitude flight operation, vocational training and other fields, and collects opinions and suggestions on the construction of qualification management and training system for low-altitude flight operators. Finally, based on the above research, this paper uses logical deduction to construct the qualification classification system and training system for low-altitude flight operators, and puts forward corresponding policy suggestions.

The structure of this paper is arranged as follows: the first part is the introduction, which elaborates on the research background, objectives, significance, methodology and structure. The second part is the literature review and theoretical basis, which sorts out the related literature and expounds the theoretical basis of the research. The third part analyzes the current situation and problems of qualification management and training system for low-altitude flight operators in major economies. The fourth part explores the core elements and construction principles of qualification management and training system for low-altitude flight operators. The fifth part constructs the multi-level qualification classification system and modular training system for low-altitude flight operators. The sixth part puts forward the policy suggestions and implementation paths for improving the qualification management and training system for low-altitude flight operators. The seventh part is the conclusion and prospect.

2. Literature Review and Theoretical Basis

2.1 Research Progress on Low-Altitude Flight Operator Management

Domestic and foreign scholars have carried out a lot of research on low-altitude flight operator management, mainly focusing on qualification certification, safety management and supervision mechanism. In terms of qualification certification, scholars have focused on the setting of qualification standards and the design of certification processes. For example, some scholars have studied the qualification requirements for low-altitude UAV operators, and proposed that the qualification certification should consider factors such as theoretical knowledge, operation skills, emergency disposal capabilities and professional ethics . Others have studied the certification process of low-altitude flight operators, and put forward suggestions for optimizing the certification process to improve the efficiency and standardization of certification . In terms of safety management, relevant studies have focused on the identification of human factors in low-altitude flight accidents and the formulation of safety management measures. Some scholars have analyzed the influence of operator‘s psychological quality, operation habits and professional skills on flight safety, and put forward targeted safety management measures . Others have studied the construction of safety management systems for low-altitude flight operators, and proposed to establish a full-process safety management mechanism covering pre-training, in-operation and post-evaluation .

In terms of supervision mechanism, scholars have focused on the construction of multi-party collaborative supervision systems and the application of intelligent supervision technologies. Some studies have proposed to establish a supervision mechanism involving government departments, industry associations, training institutions and operation enterprises to realize the full-chain supervision of low-altitude flight operators . Others have studied the application of IoT, big data and other technologies in the supervision of low-altitude flight operators, realizing the real-time monitoring of operator‘s operation status and the early warning of safety risks . However, the existing research still has some deficiencies: first, most studies focus on a single link of operator management, such as qualification certification or safety management, and lack a systematic research on the overall system of qualification management and training; second, the research on the classification of low-altitude flight operator qualifications is not in-depth enough, and there is a lack of classification standards based on the characteristics of different flight scenarios; third, the research on training systems is mostly focused on the improvement of training content and methods, and lacks the construction of training systems based on competency models.

2.2 Research Progress on Vocational Training System

Vocational training system is an important part of operator management, and scholars have carried out a lot of research on vocational training system in various fields. In terms of training system design, relevant studies have focused on the construction of modular training systems and the application of competency models. For example, some scholars have constructed a modular training system for technical workers based on the characteristics of different job positions, which can improve the pertinence and effectiveness of training . Others have studied the application of competency models in vocational training, and proposed to design training content and training methods based on the competency requirements of job positions, so as to improve the matching degree between training and job needs . In terms of training effect evaluation, scholars have focused on the construction of multi-dimensional evaluation indexes and the application of scientific evaluation methods. Some studies have established a training effect evaluation index system including theoretical knowledge, practical skills, work performance and other dimensions, and used fuzzy comprehensive evaluation method to evaluate the training effect . Others have studied the application of big data technology in training effect evaluation, realizing the dynamic tracking and quantitative evaluation of training effect .

However, the existing research on vocational training systems is mostly concentrated in traditional industries such as manufacturing and construction, and there is a lack of targeted research on the training system of low-altitude flight operators. The low-altitude flight operation has the characteristics of strong professionalism, high safety requirements and diverse application scenarios, which requires a more scientific and targeted training system. Therefore, it is necessary to combine the characteristics of low-altitude flight operations to carry out in-depth research on the construction of training systems for low-altitude flight operators.

2.3 Theoretical Basis

2.3.1 Industry Standardization Theory

Industry standardization theory refers to the process of formulating and implementing unified standards for various links in the industry to achieve the goals of improving industry efficiency, ensuring product quality and reducing safety risks . The core content of industry standardization theory includes standard formulation, standard implementation and standard supervision. In the construction of qualification management and training system for low-altitude flight operators, industry standardization theory can provide a theoretical basis for formulating unified qualification classification standards, training standards and evaluation standards. By standardizing the whole process of operator qualification management and training, the professional quality and operation level of operators can be improved, and the healthy development of the low-altitude economy industry can be promoted.

2.3.2 Competency Model Theory

Competency model theory refers to the sum of knowledge, skills, abilities, qualities and other factors required by individuals to complete specific job tasks . The competency model usually includes core competencies, professional competencies and job-specific competencies. In the construction of training systems for low-altitude flight operators, competency model theory can be used to clarify the competency requirements of different types of low-altitude flight operators, and design targeted training content and training methods based on these requirements. By improving the competency of operators, the safety and efficiency of low-altitude flight operations can be improved.

2.3.3 Human Factor Engineering Theory

Human factor engineering theory studies the interaction between humans and machines, environments and organizations, and focuses on optimizing the design of human-machine systems to improve work efficiency and safety . In the management of low-altitude flight operators, human factor engineering theory can be used to analyze the influence of operator's physiological characteristics, psychological quality and operation environment on flight safety. By optimizing the training content and operation environment, the influence of human factors on flight safety can be reduced, and the safety level of low-altitude flight operations can be improved.

3. Current Situation and Problems of Qualification Management and Training System for Low-Altitude Flight Operators in Major Economies

3.1 Current Situation of Development in Major Economies

3.1.1 China

China has attached great importance to the management of low-altitude flight operators in recent years, and has introduced a series of policies to standardize the qualification management and training of operators. The Civil Aviation Administration of China has issued the „Regulations on the Administration of Civil Unmanned Aerial Vehicle Flight Activities" and „Standards for the Training of Civil Unmanned Aerial Vehicle Operators", which clarify the qualification classification standards and training requirements for low-altitude flight operators . At present, China's low-altitude flight operator qualifications are mainly divided into two categories: pilot qualifications for civil UAVs and professional operation qualifications. The pilot qualifications for civil UAVs are divided into different levels according to the weight and flight altitude of UAVs, and the professional operation qualifications are divided according to the type of operation scenarios .

In terms of training, China has formed a training system composed of professional training institutions, colleges and universities and enterprises. A number of professional training institutions have been established across the country, providing training services for low-altitude flight operators. Colleges and universities have also set up relevant majors to cultivate professional low-altitude flight operation talents. Enterprises have carried out internal training according to their own operation needs to improve the professional skills of their employees . In terms of supervision, the government has established a supervision mechanism led by the Civil Aviation Administration of China, with the participation of local civil aviation management departments and public security departments, to carry out supervision and inspection on the qualification and operation of low-altitude flight operators.

3.1.2 United States

The United States has a relatively complete qualification management and training system for low-altitude flight operators, which is mainly managed by the Federal Aviation Administration (FAA). The FAA has formulated detailed qualification certification standards and training requirements for low-altitude flight operators, and divides low-altitude flight operator qualifications into Part 107 Remote Pilot Certificate and Part 61 Pilot Certificate according to the type of flight operations . The Part 107 Remote Pilot Certificate is applicable to commercial UAV operators, and the Part 61 Pilot Certificate is applicable to low-altitude manned flight operators. The qualification certification process in the United States is strict, including theoretical examination, practical operation assessment and background investigation .

In terms of training, the United States has formed a market-oriented training system, with a large number of professional training institutions providing personalized training services for operators. The training content covers theoretical knowledge, practical operation, emergency disposal and other aspects, and the training methods are diverse, including online courses, offline practical training and simulation training . In terms of supervision, the FAA has established a strict supervision mechanism, using technologies such as GPS positioning and real-time video monitoring to carry out real-time supervision of operator's operation status. At the same time, the FAA has formulated severe punishment measures for illegal operations to ensure the standardized operation of operators.

3.1.3 South Korea

South Korea attaches great importance to the development of the low-altitude economy and has introduced a series of policies to strengthen the management of low-altitude flight operators. The Ministry of Land, Infrastructure and Transport of South Korea is responsible for the qualification management and training of low-altitude flight operators, and has formulated unified qualification certification standards and training guidelines . The low-altitude flight operator qualifications in South Korea are divided into UAV operator qualifications and low-altitude manned flight operator qualifications, and the UAV operator qualifications are further divided into different levels according to the weight and application scenario of UAVs.

In terms of training, South Korea has strengthened the cooperation between government and enterprises, and encouraged enterprises to participate in the construction of training systems. The government has formulated preferential policies to support training institutions to carry out training work, and the training content is closely combined with the actual needs of the industry . In terms of supervision, South Korea has established a multi-party collaborative supervision mechanism involving government departments, industry associations and enterprises, and has introduced intelligent supervision technologies to realize the full-chain supervision of low-altitude flight operators.

3.1.4 Italy

Italy has carried out in-depth research and practice on the management of low-altitude flight operators, and the Italian Civil Aviation Authority (ENAC) is responsible for the qualification management and training of low-altitude flight operators. ENAC has formulated detailed qualification certification standards and training requirements, and divides low-altitude flight operator qualifications into different categories according to the type of flight operations and the weight of aircraft . The qualification certification in Italy pays attention to the practical operation ability of operators, and the assessment content includes not only theoretical knowledge, but also practical operation skills and emergency disposal ability.

In terms of training, Italy has formed a training system combining theoretical teaching and practical training, and has introduced advanced simulation training equipment to improve the training effect. The training institutions have established close cooperative relations with operation enterprises to ensure that the training content is consistent with the actual operation needs . In terms of supervision, ENAC has established a strict supervision system, carried out regular inspection on the qualification and operation of operators, and severely punished illegal operations.

3.2 Main Problems Existing in Qualification Management and Training System

3.2.1 Unclear Qualification Classification Standards

At present, the qualification classification standards for low-altitude flight operators in most countries are not clear. First, the classification basis is not scientific. Most countries classify operator qualifications based on the weight and flight altitude of aircraft, ignoring the differences in competency requirements of operators in different flight scenarios . For example, the competency requirements of UAV operators engaged in agricultural plant protection are quite different from those engaged in urban logistics distribution, but the current qualification classification standards do not reflect these differences. Second, the classification level is too simple. The current qualification classification levels are mostly 2-3 levels, which cannot meet the needs of refined management of operators in different flight scenarios . Third, the connection between qualification classification and job needs is not close. The qualification standards do not fully consider the actual job requirements of operators, resulting in a low matching degree between qualified operators and job positions.

3.2.2 Unscientific Training System

The training system for low-altitude flight operators in most countries is unscientific, which affects the training effect. First, the training content is outdated and single. Most training content focuses on basic theoretical knowledge and simple operation skills, ignoring the training of emergency disposal capabilities, practical operation experience and professional ethics . For example, in the training of urban logistics UAV operators, the training on how to deal with flight conflicts and bad weather is insufficient. Second, the training methods are backward. Most training still adopts the traditional „theoretical teaching + simple practical operation“ mode, and the application of advanced technologies such as simulation training and online interactive training is insufficient . This leads to the poor practical operation ability of operators after training. Third, the training objectives are not clear. The training objectives do not closely focus on the competency requirements of operators, resulting in the disconnection between training and job needs.

3.2.3 Imperfect Qualification Evaluation and Supervision Mechanisms

The qualification evaluation and supervision mechanisms for low-altitude flight operators are not perfect, which affects the standardization of operator management. First, the qualification evaluation method is backward. Most countries still adopt the traditional paper-and-pencil examination and on-site assessment methods, which cannot accurately evaluate the comprehensive quality and practical operation ability of operators . Second, the re-evaluation mechanism is not perfect. There is no clear regulation on the validity period of qualifications and the re-evaluation cycle, resulting in some operators‘ professional skills failing to keep up with the development of technology, which brings potential safety risks. Third, the supervision mechanism is not in place. The supervision scope is narrow, and the supervision of the whole process of operator training, operation and re-evaluation is not realized. At the same time, the application of intelligent supervision technologies is insufficient, resulting in low supervision efficiency and difficulty in timely discovery of illegal operations .

3.2.4 Lack of Unified Industry Standards and Collaborative Mechanisms

The lack of unified industry standards and collaborative mechanisms restricts the healthy development of the qualification management and training system for low-altitude flight operators. First, there is no unified international industry standard. The qualification management and training standards of different countries are quite different, which brings difficulties to the cross-border operation of low-altitude flight operators . Second, the collaborative mechanism between government departments, industry associations, training institutions and operation enterprises is not perfect. There is a lack of effective communication and cooperation between all parties, resulting in the disconnection between policy formulation, training implementation and operation practice . Third, the information sharing mechanism is not perfect. The information on operator qualification, training and operation is scattered in different departments and enterprises, which cannot be effectively shared, affecting the efficiency of management and supervision.

3.2.5 Insufficient Investment in Training Resources and Talent Team Construction

The investment in training resources and talent team construction for low-altitude flight operators is insufficient, which restricts the improvement of training quality. First, the investment in training equipment is insufficient. Most training institutions are lack of advanced simulation training equipment, which affects the training effect of practical operation skills . Second, the construction of the training teacher team is backward. The training teachers are mostly from the civil aviation field, lacking practical experience in low-altitude flight operations, and the teaching level is uneven . Third, the investment in scientific research on training is insufficient. There is a lack of in-depth research on the training content, training methods and training effect evaluation of low-altitude flight operators, which cannot provide theoretical support for the improvement of the training system.

4. Core Elements and Construction Principles of Qualification Management and Training System for Low-Altitude Flight Operators

4.1 Core Elements

4.1.1 Qualification Classification System

The qualification classification system is the core of the qualification management system for low-altitude flight operators, which includes classification basis, classification levels and qualification standards. The classification basis should be based on the characteristics of low-altitude flight scenarios and the competency requirements of operators, and comprehensively consider factors such as flight equipment type, flight altitude, flight range and operation risk . The classification levels should be refined according to the difficulty of operation and the level of risk, so as to meet the needs of refined management. The qualification standards should clearly define the requirements of theoretical knowledge, practical skills, emergency disposal capabilities and professional ethics for operators of different levels and types.

4.1.2 Training System

The training system includes training objectives, training content, training methods and training effect evaluation. The training objectives should be based on the competency requirements of operators, and clarify the knowledge, skills and qualities that operators need to master . The training content should be modularized and designed according to the characteristics of different qualification levels and flight scenarios, including basic theoretical modules, professional skill modules and comprehensive quality modules. The training methods should be diversified, combining online theoretical teaching, offline practical training, simulation training and on-the-job training. The training effect evaluation should establish a multi-dimensional evaluation index system, including theoretical knowledge assessment, practical operation assessment, work performance evaluation and safety record evaluation.

4.1.3 Evaluation and Supervision Mechanism

The evaluation and supervision mechanism includes qualification evaluation, re-evaluation and daily supervision. The qualification evaluation should adopt a combination of theoretical examination, practical operation assessment and psychological evaluation to comprehensively evaluate the comprehensive quality of operators . The re-evaluation should clearly define the validity period of qualifications and the re-evaluation cycle, and update the qualification standards in a timely manner according to the development of technology and industry. The daily supervision should adopt a combination of traditional supervision methods and intelligent supervision technologies to realize the full-process supervision of operator's training, operation and re-evaluation.

4.1.4 Collaborative Management Mechanism

The collaborative management mechanism includes the collaborative mechanisms between government departments, industry associations, training institutions and operation enterprises. Government departments are responsible for formulating policies and standards, and carrying out supervision and management; industry associations are responsible for organizing the formulation of industry self-discipline standards, and carrying out industry statistics and information release; training institutions are responsible for carrying out standardized training work, and improving the professional quality of operators; operation enterprises are responsible for putting forward training needs, and organizing on-the-job training for employees . All parties should strengthen communication and cooperation, realize the sharing of resources and information, and form a joint force for the construction and operation of the system.

4.2 Construction Principles

4.2.1 Industry Standardization Principle

The construction of qualification management and training system for low-altitude flight operators should adhere to the principle of industry standardization. It is necessary to formulate unified qualification classification standards, training standards, evaluation standards and supervision standards to ensure the standardization and uniformity of the whole process of operator management and training . At the same time, it is necessary to actively participate in the formulation of international industry standards, promote the internationalization of domestic standards, and facilitate the cross-border operation of operators.

4.2.2 Competency-Oriented Principle

The construction of the system should adhere to the competency-oriented principle, and take the improvement of operator's competency as the core goal. The qualification classification, training content and training methods should be designed based on the competency requirements of different flight scenarios and job positions . It is necessary to strengthen the training of operator's practical operation skills and emergency disposal capabilities, and improve the matching degree between operator's competency and job needs.

4.2.3 Practicality and Applicability Principle

The construction of the system should adhere to the principle of practicality and applicability, and closely combine with the actual needs of low-altitude flight operations. The training content should be closely related to the actual operation scenarios, and the training methods should be in line with the characteristics of operator's learning and cognitive laws . It is necessary to avoid the formalization of training and ensure that the training effect can be effectively transformed into the actual operation ability of operators.

4.2.4 Dynamic Adjustment Principle

The construction of the system should adhere to the principle of dynamic adjustment. With the development of low-altitude economy technology and the expansion of application scenarios, the competency requirements of low-altitude flight operators are constantly changing. Therefore, it is necessary to regularly update the qualification classification standards, training content and evaluation standards to ensure that the system can adapt to the development needs of the industry . It is necessary to establish a feedback mechanism to collect the opinions and suggestions of all parties in a timely manner, and adjust and improve the system according to the feedback results.

4.2.5 Multi-Party Collaborative Principle

The construction of the system should adhere to the multi-party collaborative principle. It is necessary to give full play to the roles of government departments, industry associations, training institutions and operation enterprises, strengthen communication and cooperation between all parties, and form a joint force for the construction and operation of the system . It is necessary to establish an information sharing mechanism to realize the sharing of operator's qualification, training and operation information, and improve the efficiency of management and supervision.

5. Construction of Qualification Classification System and Training System for Low-Altitude Flight Operators

5.1 Construction of Multi-Level Qualification Classification System for Low-Altitude Flight Operators

5.1.1 Classification Basis and Level Setting

Based on the characteristics of low-altitude flight scenarios and the competency requirements of operators, this study divides the qualifications of low-altitude flight operators into four categories: general operation qualification, professional operation qualification, special operation qualification and management operation qualification. Each category is further divided into three levels: primary, intermediate and advanced. The specific classification basis and level setting are as follows: (1) General operation qualification: applicable to low-risk low-altitude flight operations such as aerial photography and entertainment. The classification is based on the weight of the aircraft and the flight altitude. Primary operators can operate small aircraft with a weight of less than 2kg and a flight altitude of less than 120 meters; intermediate operators can operate medium-sized aircraft with a weight of 2-15kg and a flight altitude of 120-500 meters; advanced operators can operate large aircraft with a weight of 15-150kg and a flight altitude of 500-1000 meters. (2) Professional operation qualification: applicable to professional low-altitude flight operations such as agricultural plant protection, power inspection and urban logistics. The classification is based on the type of operation scenario and the difficulty of operation. Primary operators can engage in simple professional operation scenarios; intermediate operators can engage in general professional operation scenarios; advanced operators can engage in complex professional operation scenarios. (3) Special operation qualification: applicable to high-risk low-altitude flight operations such as emergency rescue, fire fighting and aerial survey. The classification is based on the risk level of the operation and the emergency disposal requirements. Primary operators can assist in special operation scenarios; intermediate operators can independently engage in general special operation scenarios; advanced operators can independently engage in high-risk special operation scenarios. (4) Management operation qualification: applicable to the management of low-altitude flight operations such as fleet management and airspace coordination. The classification is based on the scope of management and the level of management responsibilities. Primary operators can engage in basic operation management work; intermediate operators can engage in general operation management work; advanced operators can engage in senior operation management work.

5.1.2 Qualification Standards

The qualification standards for low-altitude flight operators include four aspects: theoretical knowledge, practical skills, emergency disposal capabilities and professional ethics. (1) Theoretical knowledge: including airspace management regulations, flight principles, meteorological knowledge, equipment maintenance knowledge and safety management knowledge. The requirements for theoretical knowledge increase with the improvement of qualification level. (2) Practical skills: including aircraft operation skills, route planning skills, cargo loading and unloading skills (for logistics operations) and equipment debugging skills. The requirements for practical skills are different according to the type of qualification. For example, professional operation qualification requires operators to master professional operation skills corresponding to the operation scenario. (3) Emergency disposal capabilities: including the ability to deal with aircraft failure, bad weather, flight conflicts and other emergency situations. The requirements for emergency disposal capabilities increase with the improvement of qualification level, especially for special operation qualification operators, who need to have strong emergency disposal capabilities. (4) Professional ethics: including abiding by laws and regulations, respecting the rights and interests of others, and ensuring flight safety. All operators must meet the basic requirements of professional ethics.

5.1.3 Qualification Certification Process

The qualification certification process for low-altitude flight operators includes four links: application, pre-examination, assessment and certification. (1) Application: Operators submit qualification application materials to the designated certification authority, including personal identity materials, educational background materials and training certificates. (2) Pre-examination: The certification authority conducts pre-examination of the application materials to check whether the applicant meets the basic conditions for qualification application. (3) Assessment: The assessment includes theoretical examination, practical operation assessment and psychological evaluation. The theoretical examination adopts online computer-based examination; the practical operation assessment adopts on-site operation and simulation operation methods; the psychological evaluation adopts psychological test and interview methods. (4) Certification: For applicants who pass the assessment, the certification authority issues corresponding qualification certificates; for applicants who fail the assessment, they can apply for re-assessment after supplementary training.

5.2 Construction of Modular Training System for Low-Altitude Flight Operators Based on Competency Model

5.2.1 Construction of Competency Model

Based on the competency model theory, this study constructs a competency model for low-altitude flight operators, which includes three levels: core competencies, professional competencies and job-specific competencies. (1) Core competencies: including safety awareness, sense of responsibility, learning ability and communication ability. These competencies are required for all low-altitude flight operators. (2) Professional competencies: including theoretical knowledge, practical operation skills, emergency disposal capabilities and equipment maintenance capabilities. These competencies are required for professional and special operation qualification operators. (3) Job-specific competencies: including the professional skills corresponding to specific operation scenarios, such as agricultural plant protection skills for agricultural plant protection operators, logistics distribution skills for urban logistics operators, and emergency rescue skills for emergency rescue operators.

5.2.2 Design of Modular Training Content

Based on the competency model, this study designs a modular training content system, which includes four modules: basic theoretical module, core competency module, professional skill module and job-specific skill module. (1) Basic theoretical module: including airspace management regulations, flight principles, meteorological knowledge, equipment maintenance knowledge and safety management knowledge. This module is a basic module for all operators. (2) Core competency module: including safety awareness training, sense of responsibility training, learning ability training and communication ability training. This module is designed to improve the core competencies of operators. (3) Professional skill module: including practical operation skills training, emergency disposal capabilities training and equipment maintenance capabilities training. This module is mainly for professional and special operation qualification operators. (4) Job-specific skill module: including the professional skills training corresponding to specific operation scenarios. For example, the agricultural plant protection module includes training on pesticide spraying technology and crop identification; the urban logistics module includes training on route planning and cargo loading and unloading.

5.2.3 Selection of Training Methods

To improve the training effect, this study adopts a diversified training method system, including online theoretical teaching, offline practical training, simulation training and on-the-job training. (1) Online theoretical teaching: Using online learning platforms to provide flexible and convenient theoretical knowledge learning services for operators, including video courses, online exercises and online examinations. (2) Offline practical training: Carrying out on-site practical operation training in professional training bases, with professional teachers guiding operators to master practical operation skills. (3) Simulation training: Using advanced simulation training equipment to simulate various flight scenarios and emergency situations, allowing operators to conduct repeated training to improve their emergency disposal capabilities and practical operation skills. (4) On-the-job training: Organizing on-the-job training by operation enterprises, combining the actual operation tasks of enterprises to carry out targeted training, and improving the matching degree between training and job needs.

5.2.4 Construction of Training Effect Evaluation System

This study constructs a multi-dimensional training effect evaluation system, which includes four evaluation dimensions: theoretical knowledge, practical skills, work performance and safety record. (1) Theoretical knowledge evaluation: Adopting online computer-based examination to evaluate the mastery of theoretical knowledge by operators. (2) Practical skills evaluation: Adopting on-site operation and simulation operation methods to evaluate the practical operation skills and emergency disposal capabilities of operators. (3) Work performance evaluation: Evaluating the work performance of operators by operation enterprises, including operation efficiency, task completion quality and service satisfaction. (4) Safety record evaluation: Recording the safety operation status of operators, including the number of safety accidents, violations and other indicators. The evaluation results are used as an important basis for operator‘s qualification re-evaluation and job promotion.

6. Policy Suggestions and Implementation Paths for Improving the Qualification Management and Training System for Low-Altitude Flight Operators

6.1 Policy Suggestions

6.1.1 Improve the Qualification Management System and Formulate Unified Industry Standards

The government should take the lead in formulating a unified qualification classification standard for low-altitude flight operators, clarifying the classification basis, classification levels and qualification standards. It is necessary to combine the characteristics of different low-altitude flight scenarios to refine the qualification classification and improve the matching degree between qualification and job needs . At the same time, it is necessary to formulate unified training standards, evaluation standards and supervision standards to ensure the standardization and uniformity of the whole process of operator management and training. It is necessary to actively participate in the formulation of international industry standards, promote the mutual recognition of domestic and foreign qualifications, and facilitate the cross-border operation of operators.

6.1.2 Strengthen the Construction of Training Resources and Improve the Training Quality

The government should increase investment in training resources, support training institutions to purchase advanced simulation training equipment and build professional training bases. It is necessary to strengthen the construction of the training teacher team, establish a training teacher certification system, and improve the professional quality and teaching level of training teachers . It is necessary to encourage colleges and universities to set up relevant majors to cultivate professional low-altitude flight operation talents, and strengthen the cooperation between colleges and universities and enterprises to realize the integration of production and education. It is necessary to increase investment in scientific research on training, support research institutions to carry out in-depth research on training content, training methods and training effect evaluation, and provide theoretical support for the improvement of the training system.

6.1.3 Improve the Evaluation and Supervision Mechanism and Strengthen the Full-Process Supervision

The government should improve the qualification evaluation mechanism, adopt a combination of theoretical examination, practical operation assessment and psychological evaluation to comprehensively evaluate the comprehensive quality of operators. It is necessary to establish a sound re-evaluation mechanism, clarify the validity period of qualifications and the re-evaluation cycle, and update the qualification standards in a timely manner according to the development of technology and industry . It is necessary to strengthen the application of intelligent supervision technologies, such as IoT, big data and AI, to realize the real-time monitoring of operator‘s operation status and the early warning of safety risks. It is necessary to establish a multi-party collaborative supervision mechanism involving government departments, industry associations, training institutions and operation enterprises to realize the full-chain supervision of operator‘s training, operation and re-evaluation.

6.1.4 Establish a Collaborative Management Mechanism and Promote Information Sharing

The government should establish a collaborative management mechanism involving government departments, industry associations, training institutions and operation enterprises, and clarify the responsibilities and division of labor of all parties. It is necessary to strengthen communication and cooperation between all parties, hold regular coordination meetings to study and solve the problems existing in the construction and operation of the system . It is necessary to establish an information sharing platform for low-altitude flight operators, integrating operator‘s qualification, training, operation and supervision information to realize the sharing of information between all parties. It is necessary to promote the digital management of operator‘s information, improve the efficiency of management and supervision.

6.1.5 Strengthen Policy Support and Guide Industry Healthy Development

The government should formulate preferential policies to support the development of training institutions and operation enterprises, such as financial subsidies, tax preferences and land support. It is necessary to encourage social capital to participate in the construction of the qualification management and training system for low-altitude flight operators, and form a diversified investment pattern . It is necessary to strengthen the publicity and popularization of policies and standards, improve the awareness of operators, training institutions and operation enterprises on the importance of qualification management and training. It is necessary to carry out pilot demonstrations of qualification management and training systems in key regions and key industries, and promote the experience of pilot demonstrations to the whole country.

6.2 Implementation Paths

6.2.1 Short-Term Implementation Path (1-2 Years)

In the short term, the main tasks are: (1) Formulate and issue unified qualification classification standards, training standards and evaluation standards for low-altitude flight operators. (2) Carry out the rectification of existing training institutions and qualification certification authorities to improve the standardization of training and certification work. (3) Build a preliminary information sharing platform for low-altitude flight operators, realizing the sharing of basic information such as operator‘s qualification and training. (4) Carry out pilot demonstrations of modular training systems in key regions and key industries, and summarize pilot experience.

6.2.2 Medium-Term Implementation Path (3-5 Years)

In the medium term, the main tasks are: (1) Improve the qualification management and training system, and promote the full implementation of unified standards. (2) Strengthen the construction of training resources, build a number of professional training bases and improve the training teacher team. (3) Popularize the application of intelligent supervision technologies, realize the full-process supervision of operator's operation. (4) Improve the information sharing platform, realize the integration of operator's qualification, training, operation and supervision information. (5) Promote the mutual recognition of domestic and foreign qualifications, and participate in the formulation of international industry standards.

6.2.3 Long-Term Implementation Path (5-10 Years)

In the long term, the main tasks are: (1) Form a mature and perfect qualification management and training system for low-altitude flight operators, which is in line with the development needs of the low-altitude economy. (2) Build a high-quality professional low-altitude flight operator team to meet the needs of the development of the low-altitude economy. (3) Realize the internationalization of the qualification management and training system, and enhance the international influence of China's low-altitude economy industry. (4) Promote the healthy and sustainable development of the low-altitude economy, and make it an important pillar of the national economy.

7. Conclusion and Prospect

7.1 Research Conclusions

This study takes industry standardization as the core perspective, systematically studies the construction of qualification management and training system for low-altitude flight operators, and draws the following conclusions: First, the qualification management and training system for low-altitude flight operators is an important guarantee for the healthy development of the low-altitude economy, but at present, there are still problems such as unclear qualification classification standards, unscientific training systems, imperfect evaluation and supervision mechanisms, lack of unified industry standards and insufficient investment in training resources in major economies. Second, the core elements of the qualification management and training system for low-altitude flight operators include qualification classification system, training system, evaluation and supervision mechanism and collaborative management mechanism, and the construction of the system should adhere to the principles of industry standardization, competency orientation, practicality and applicability, dynamic adjustment and multi-party collaboration. Third, the multi-level qualification classification system constructed in this study, which is divided into four categories and three levels based on the characteristics of flight scenarios and competency requirements, can realize the refined management of operators. The modular training system based on competency model, which includes four modules and adopts diversified training methods, can improve the pertinence and effectiveness of training. Fourth, the policy suggestions put forward in this study, such as improving the qualification management system, strengthening the construction of training resources, improving the evaluation and supervision mechanism, establishing a collaborative management mechanism and strengthening policy support, can provide practical guidance for the construction and improvement of the qualification management and training system for low-altitude flight operators.

7.2 Research Prospect

In the future, the research can be carried out in the following aspects: First, carry out in-depth research on the qualification management and training system for low-altitude flight operators in specific fields, such as emergency rescue, agricultural plant protection and urban logistics, to improve the pertinence of the system. Second, strengthen the research on the application of emerging technologies such as AI, virtual reality (VR) and augmented reality (AR) in the training of low-altitude flight operators, and explore more efficient and scientific training methods. Third, carry out comparative research on the qualification management and training systems of low-altitude flight operators in more countries, and learn from advanced international experience to promote the internationalization of China's system. Fourth, carry out empirical research on the constructed qualification classification system and training system, and verify the effectiveness and feasibility of the system through practical application.

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Article

Optimization of Urban Low-Altitude Logistics Network and Risk Control: A Perspective of Smart City Integration

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ABSTRACT
With the deep integration of low-altitude economy and smart city construction, urban low-altitude logistics has become an important breakthrough to solve the problems of „last-mile" delivery in urban areas. However, the current urban low-altitude logistics network is faced with challenges such as unreasonable layout, insufficient intelligent scheduling capabilities, and imperfect risk control systems, which restrict its high-quality development. This study takes the integration of smart city as the perspective, systematically explores the optimization path of urban low-altitude logistics network and the construction of risk control system. Through the analysis of typical cases in China, the United Kingdom, Japan and other countries, it identifies the key influencing factors of network optimization and risk formation mechanisms. On this basis, the paper proposes a multi-objective optimization model of low-altitude logistics network considering efficiency, cost and safety, and designs a risk control system based on digital twin and real-time monitoring technology. Research results show that the integration of smart city technologies such as big data, Internet of Things and artificial intelligence can effectively improve the operational efficiency of low-altitude logistics networks and reduce potential risks. This study provides theoretical support and practical guidance for the construction of urban low-altitude logistics systems and the high-quality development of the low-altitude economy.

Keywords: Low-Altitude Logistics; Smart City; Network Optimization; Risk Control; Digital Twin; Last-Mile Delivery

1. Introduction

1.1 Research Background

In recent years, the low-altitude economy has developed rapidly as a new economic form driven by technological innovation and industrial integration, and has become an important engine for global economic growth . Urban low-altitude logistics, as a key application scenario of the low-altitude economy, relies on unmanned aerial vehicles (UAVs) and other low-altitude flight equipment to carry out cargo transportation activities in the low-altitude airspace below 1000 meters. It has the advantages of flexibility, efficiency, low cost and strong adaptability, and can effectively solve the pain points of traditional urban logistics such as traffic congestion, difficult „last-mile" delivery and high labor costs . With the acceleration of urbanization and the rapid development of e-commerce, the demand for urban logistics services is growing exponentially. The traditional ground logistics system has been difficult to meet the increasingly diversified and personalized logistics needs of residents, which provides a broad development space for urban low-altitude logistics .

At the same time, the in-depth advancement of smart city construction has laid a solid technical foundation for the development of urban low-altitude logistics. Smart city technologies such as big data, Internet of Things (IoT), artificial intelligence (AI) and digital twin have been widely used in urban management, transportation scheduling and risk control, which can provide strong support for the optimization of low-altitude logistics networks, intelligent scheduling of UAVs and real-time monitoring of flight risks . Major economies around the world have attached great importance to the development of urban low-altitude logistics. China has included low-altitude logistics in the key development areas of the low-altitude economy, and has carried out a series of pilot projects in Shenzhen, Hangzhou, Chengdu and other cities . The United Kingdom has launched the „Future Flight Challenge" program to support the research and application of low-altitude logistics technologies . Japan has formulated a special development plan for urban air mobility, focusing on promoting the integration of low-altitude logistics and smart city construction .

However, despite the broad development prospects, the construction and operation of urban low-altitude logistics networks still face many challenges. In terms of network layout, the current low-altitude logistics take-off and landing points (dronesports) are unreasonably distributed, with uneven regional coverage and poor connection with ground logistics nodes, resulting in low overall operational efficiency of the network . In terms of intelligent scheduling, the lack of an integrated intelligent scheduling platform leads to difficulties in coordinated operation between multiple UAVs, and problems such as flight conflicts and path redundancy often occur . In terms of risk control, the low-altitude airspace environment is complex, and there are many potential risks such as UAV failure, weather changes, and illegal intrusion into restricted airspace. The current risk control system is not perfect, and the ability to predict and respond to risks is insufficient . In addition, the lack of unified industry standards, imperfect regulatory systems and low public acceptance also restrict the large-scale commercial application of urban low-altitude logistics .

Against this background, taking the integration of smart city as the perspective, exploring the optimization path of urban low-altitude logistics network and the construction of risk control system has important theoretical and practical significance for promoting the healthy development of urban low-altitude logistics and the high-quality development of the low-altitude economy .

1.2 Research Objectives and Significance

The main objectives of this study are: (1) to systematically sort out the connotation and characteristics of urban low-altitude logistics networks under the background of smart city integration, and clarify the interaction mechanism between smart city technologies and low-altitude logistics network operation; (2) to analyze the current situation and existing problems of urban low-altitude logistics network construction in major economies, and identify the key influencing factors of network optimization and the formation mechanism of operational risks; (3) to propose a multi-objective optimization model of urban low-altitude logistics network considering efficiency, cost and safety, and design a risk control system based on smart city technologies; (4) to put forward targeted policy suggestions and implementation paths for the optimization and upgrading of urban low-altitude logistics networks and the improvement of risk control capabilities.

The theoretical significance of this study lies in: first, it enriches the research system of low-altitude economy and smart city integration, and deepens the understanding of the operation mechanism of urban low-altitude logistics networks; second, it constructs a multi-objective optimization model of low-altitude logistics networks and a risk control system based on smart city technologies, which provides a new theoretical framework for related research. The practical significance is reflected in: first, it can provide decision-making references for government departments to formulate low-altitude logistics development policies, network planning schemes and risk control measures; second, it can guide logistics enterprises to optimize the layout of low-altitude logistics networks, improve intelligent scheduling capabilities and risk prevention and control levels, and promote the large-scale commercial application of urban low-altitude logistics; third, it helps to improve the efficiency of urban logistics operation, reduce logistics costs, and enhance the quality of urban public services.

1.3 Research Methodology and Structure

This study adopts a combination of literature review, comparative analysis, case study and logical deduction methods. First, through a systematic review of domestic and foreign literature on low-altitude logistics, smart city, network optimization and risk control, this paper sorts out the research progress and existing deficiencies in related fields, and lays a theoretical foundation for the research. Second, through comparative analysis, this paper compares and analyzes the policy systems, technical routes and development models of urban low-altitude logistics in China, the United Kingdom, Japan and other major economies, and identifies the commonalities and differences in the development of low-altitude logistics in different countries. Third, taking Shenzhen (China), London (UK) and Tokyo (Japan) as typical cases, this paper deeply analyzes the practices and experiences of these cities in low-altitude logistics network construction and risk control, and extracts key success factors. Finally, based on the above research, this paper uses logical deduction to construct a multi-objective optimization model of low-altitude logistics network and a risk control system, and puts forward corresponding policy suggestions.

The structure of this paper is arranged as follows: the first part is the introduction, which elaborates on the research background, objectives, significance, methodology and structure. The second part is the literature review and theoretical basis, which sorts out the related literature and expounds the theoretical basis of the research. The third part analyzes the current situation and problems of urban low-altitude logistics network construction under the background of smart city integration. The fourth part explores the key influencing factors of urban low-altitude logistics network optimization and the formation mechanism of operational risks. The fifth part constructs the multi-objective optimization model of urban low-altitude logistics network and the risk control system. The sixth part takes typical cities as cases to carry out empirical analysis. The seventh part puts forward the construction path and policy suggestions for the optimization and sustainable development of urban low-altitude logistics network. The eighth part is the conclusion and prospect.

2. Literature Review and Theoretical Basis

2.1 Research Progress on Urban Low-Altitude Logistics

Domestic and foreign scholars have carried out a lot of research on urban low-altitude logistics, mainly focusing on technical research, network planning, operational management and policy supervision. In terms of technical research, scholars have focused on the research and development of UAV technology, communication navigation technology and intelligent scheduling technology. For example, some scholars have studied the optimization of UAV flight control systems, improved the stability and reliability of UAV flight, and enhanced the UAV's ability to adapt to complex low-altitude environments . Others have researched on 5G-based low-altitude communication technology, realizing real-time transmission of UAV flight data and remote control . In terms of network planning, relevant studies have focused on the layout optimization of dronesports and the planning of flight routes. Some scholars have established a location selection model of dronesports based on factors such as logistics demand, traffic accessibility and land use, to realize the rational layout of dronesports . Others have studied the optimization of UAV flight routes, considering factors such as flight distance, flight time, and flight safety, to improve the efficiency of logistics transportation .

In terms of operational management, scholars have focused on the coordinated operation of UAV fleets, the optimization of logistics processes and the control of logistics costs. Some studies have proposed a coordinated scheduling strategy for UAV fleets based on AI algorithms, which can realize the optimal allocation of resources and improve the efficiency of fleet operation . Others have studied the optimization of low-altitude logistics processes, integrating low-altitude logistics with ground logistics to form a „ground-air integration" logistics system, and improving the overall efficiency of logistics operation . In terms of policy supervision, relevant studies have analyzed the current situation of low-altitude logistics regulatory systems in various countries, and put forward suggestions for improving regulatory policies, formulating industry standards and strengthening safety supervision .

However, the existing research still has some deficiencies: first, most studies focus on a single aspect of low-altitude logistics technology or network planning, and lack a systematic research on the overall operation system of low-altitude logistics networks; second, the integration of low-altitude logistics and smart city construction is not in-depth enough, and there is a lack of research on using smart city technologies to optimize low-altitude logistics networks and control risks; third, the existing research on risk control of low-altitude logistics is mostly focused on a single risk factor, and there is a lack of a comprehensive and systematic risk control system.

2.2 Research Progress on Smart City and Logistics Integration

Smart city is a new urban development model that uses information and communication technologies to sense, analyze and integrate urban operation core systems, and realize intelligent management and services of the city . The integration of smart city and logistics has become a research hotspot in recent years. Scholars have carried out a lot of research on smart logistics, intelligent transportation and other fields. In terms of smart logistics, relevant studies have focused on the construction of smart logistics platforms, the application of IoT technology and the optimization of logistics resource allocation. For example, some scholars have built a smart logistics platform based on big data and cloud computing, which can realize the integration and sharing of logistics information and the intelligent scheduling of logistics resources . Others have studied the application of IoT technology in logistics packaging, transportation and warehousing, improving the transparency and traceability of logistics processes .

In terms of intelligent transportation, scholars have focused on the research of intelligent transportation systems, traffic flow prediction and intelligent scheduling. Some studies have built an intelligent transportation system based on AI and big data, which can realize real-time monitoring of traffic flow and intelligent scheduling of transportation vehicles . Others have studied traffic flow prediction models based on machine learning algorithms, improving the accuracy of traffic flow prediction and providing support for transportation scheduling . However, the existing research on the integration of smart city and logistics is mostly focused on ground logistics, and there is a lack of research on the integration of smart city and low-altitude logistics. There is an urgent need to explore the path of integrating smart city technologies into low-altitude logistics network construction and operation management.

2.3 Theoretical Basis

2.3.1 Network Optimization Theory

Network optimization theory is an important branch of operations research, which mainly studies how to optimize the structure and operation of the network to achieve the goals of improving efficiency, reducing costs and enhancing reliability . The core content of network optimization includes node location optimization, path optimization and resource allocation optimization. In the construction of urban low-altitude logistics networks, network optimization theory can be used to guide the layout of dronesports (node location optimization), the planning of UAV flight routes (path optimization) and the allocation of UAV resources (resource allocation optimization). By establishing a scientific network optimization model, the overall operational efficiency of the low-altitude logistics network can be improved, and logistics costs can be reduced.

2.3.2 Risk Management Theory

Risk management theory is a systematic theory that studies the identification, assessment, control and prevention of risks. It includes risk identification, risk assessment, risk control and risk monitoring and other links . In the operation of urban low-altitude logistics networks, there are many potential risks such as UAV failure, weather changes, flight conflicts and illegal intrusion. Applying risk management theory, we can identify and assess the potential risks of low-altitude logistics networks, formulate targeted risk control measures, and establish a comprehensive risk monitoring system to ensure the safe and stable operation of the network.

2.3.3 Smart City Theory

Smart city theory emphasizes the use of information and communication technologies to realize the intelligent management and service of the city, and promote the coordinated development of the city‘s economy, society and environment . The core of smart city theory is the integration and sharing of information resources and the intelligent allocation of urban resources. In the construction of urban low-altitude logistics networks, smart city theory can provide a theoretical basis for the integration of smart city technologies (big data, IoT, AI, etc.) into low-altitude logistics network optimization and risk control, realizing the intelligent operation and management of low-altitude logistics networks.

3. Current Situation and Problems of Urban Low-Altitude Logistics Network Construction Under Smart City Integration

3.1 Current Situation of Development in Major Economies

3.1.1 China

China‘s urban low-altitude logistics industry has developed rapidly in recent years, driven by policy support and technological innovation. The government has introduced a series of policies to promote the development of low-altitude logistics. For example, the „14th Five-Year Plan for the Development of the Logistics Industry“ clearly proposes to „actively develop low-altitude logistics and promote the application of UAVs in urban distribution“ . The Civil Aviation Administration of China has continuously optimized the low-altitude airspace management system, expanded the scope of low-altitude airspace opening, and simplified the approval process for UAV flight plans . At the local level, Shenzhen, Hangzhou, Chengdu and other cities have carried out a series of pilot projects of low-altitude logistics. For example, Shenzhen has built a number of low-altitude logistics demonstration zones, realized the application of UAVs in medical supplies transportation, fresh food distribution and other scenarios, and built an intelligent scheduling platform for low-altitude logistics .

In terms of technology research and development, Chinese enterprises and research institutions have made important breakthroughs in UAV technology, communication navigation technology and intelligent scheduling technology. A number of domestic UAV enterprises have launched professional low-altitude logistics UAVs with strong load capacity and long battery life. The application of 5G and Beidou navigation technology has improved the stability and reliability of UAV flight . In terms of network construction, some cities have initially formed a low-altitude logistics network with dronesports as the core and flight routes as the link, but the network coverage and operational efficiency still need to be improved.

3.1.2 United Kingdom

The United Kingdom is one of the earliest countries to carry out low-altitude logistics research and application. The government has launched a number of programs to support the development of low-altitude logistics. The „Future Flight Challenge“ program invested 125 million pounds to support the research and development of low-altitude flight technologies and the construction of application scenarios . The Civil Aviation Authority (CAA) of the United Kingdom has formulated a relatively complete regulatory system for low-altitude logistics, clarifying the technical standards, flight rules and safety supervision requirements for UAVs .

In terms of network construction, London, Manchester and other cities have carried out pilot projects of low-altitude logistics. For example, London has built a low-altitude logistics network covering the central urban area, realizing the transportation of medical supplies and daily necessities by UAVs. The city has also integrated low-altitude logistics into the smart city construction plan, using big data and AI technologies to optimize the layout of dronesports and the planning of flight routes . In terms of technology application, the United Kingdom has carried out in-depth research on autonomous flight technology of UAVs and collaborative scheduling technology of multiple UAVs, and has achieved certain results.

3.1.3 Japan

Japan attaches great importance to the development of urban air mobility, and low-altitude logistics is an important part of it. The government has formulated a special development plan for urban air mobility, clarifying the development goals and implementation paths of low-altitude logistics . The Ministry of Land, Infrastructure, Transport and Tourism of Japan has optimized the low-altitude airspace management system, simplified the approval process for UAV flights, and promoted the opening of low-altitude airspace .

In terms of network construction, Tokyo, Osaka and other cities have carried out pilot projects of low-altitude logistics. For example, Tokyo has built a low-altitude logistics network connecting urban and suburban areas, realizing the transportation of agricultural products and daily necessities by UAVs. The city has also used digital twin technology to simulate the operation of low-altitude logistics networks, optimizing the layout of dronesports and flight routes . In terms of technology research and development, Japanese enterprises have focused on the research of small and lightweight UAVs, which are suitable for narrow urban airspace environments. They have also carried out research on the integration of UAVs with ground transportation systems.

3.2 Main Problems Existing in Urban Low-Altitude Logistics Network Construction

3.2.1 Unreasonable Layout of Low-Altitude Logistics Network

At present, the layout of urban low-altitude logistics networks in most countries is unreasonable. First, the distribution of dronesports is uneven. Dronesports are mostly concentrated in urban central areas, while there are fewer dronesports in suburban and remote areas, resulting in uneven coverage of low-altitude logistics services . Second, the connection between dronesports and ground logistics nodes (such as warehouses, distribution centers) is poor, resulting in disconnection between low-altitude logistics and ground logistics, and affecting the overall efficiency of the logistics system . Third, the planning of flight routes is not scientific. Most flight routes are planned based on experience, without fully considering factors such as logistics demand, airspace environment and flight safety, resulting in problems such as long flight distance, low transportation efficiency and potential flight conflicts .

3.2.2 Insufficient Intelligent Scheduling Capabilities

The intelligent scheduling level of urban low-altitude logistics networks is generally low. First, there is a lack of an integrated intelligent scheduling platform. Most logistics enterprises use independent scheduling systems, which cannot realize the sharing of information and coordinated scheduling between different enterprises. This leads to difficulties in the coordinated operation of multiple UAVs, and problems such as flight conflicts and resource waste often occur . Second, the scheduling algorithm is not perfect. The existing scheduling algorithms mostly focus on a single objective such as minimizing flight time or minimizing logistics costs, without considering multiple objectives such as efficiency, cost and safety comprehensively. This leads to the inability to achieve the optimal overall operation effect of the network . Third, the ability to perceive the low-altitude airspace environment is insufficient. The existing scheduling systems cannot fully perceive the real-time changes of the low-altitude airspace environment (such as weather changes, air traffic flow), and cannot adjust the scheduling plan in real time, which affects the stability and reliability of the network operation .

3.2.3 Imperfect Risk Control System

The risk control system of urban low-altitude logistics networks is not perfect, and there are many potential safety hazards. First, the risk identification is not comprehensive. The existing risk identification mostly focuses on UAV failure and flight conflicts, ignoring risks such as weather changes, illegal intrusion into restricted airspace and data security . Second, the risk assessment method is backward. The existing risk assessment mostly adopts qualitative methods, which cannot accurately assess the probability and impact of risks, and cannot provide scientific basis for risk control . Third, the risk monitoring and early warning capabilities are insufficient. The existing monitoring systems cannot realize real-time monitoring of UAV flight status and low-altitude airspace environment, and cannot issue early warnings of potential risks in a timely manner . Fourth, the emergency response mechanism is not perfect. In the event of safety accidents such as UAV crashes and cargo damage, there is a lack of effective emergency disposal plans, resulting in difficulty in controlling the impact of accidents .

3.2.4 Lack of Unified Industry Standards and Regulatory Systems

The lack of unified industry standards and imperfect regulatory systems restrict the healthy development of urban low-altitude logistics networks. First, there is no unified technical standard for UAVs. The technical parameters, performance indicators and safety standards of UAVs produced by different enterprises are not uniform, which affects the compatibility and interoperability of UAVs . Second, the standards for dronesports construction are not unified. The construction standards, operation specifications and safety requirements of dronesports in different regions are different, which affects the standardized development of the network . Third, the regulatory system is not perfect. The existing regulatory policies are mostly lagging behind the development of the industry, and there are regulatory gaps in the links of UAV flight, cargo transportation and data management. This leads to irregular operation of some enterprises and potential safety risks .

3.2.5 Low Public Acceptance

Public acceptance of urban low-altitude logistics is generally low, which restricts the large-scale commercial application of low-altitude logistics. First, the public is worried about the safety of UAV flight. They are afraid that UAV crashes will cause personal injury and property damage . Second, the public is concerned about privacy issues. The UAV is equipped with cameras and other equipment, which may involve the leakage of personal privacy during the flight process . Third, the public is worried about the impact of UAV flight on the living environment. The noise generated by UAV flight may affect the daily life of residents . The low public acceptance makes it difficult for low-altitude logistics to be widely promoted and applied in urban areas.

4. Key Influencing Factors of Urban Low-Altitude Logistics Network Optimization and Risk Formation Mechanism

4.1 Key Influencing Factors of Urban Low-Altitude Logistics Network Optimization

4.1.1 Logistics Demand Characteristics

Logistics demand characteristics are the fundamental factors affecting the optimization of low-altitude logistics networks. The spatial distribution, time distribution and type of logistics demand directly determine the layout of dronesports and the planning of flight routes . For example, in areas with high logistics demand density (such as urban central areas), more dronesports need to be arranged to meet the logistics demand; in areas with obvious peak logistics demand (such as shopping malls during holidays), the number of UAVs and flight routes need to be adjusted in real time . In addition, the type of logistics demand also affects the optimization of the network. For example, the transportation of fresh food and medical supplies has higher requirements for timeliness and safety, which requires the optimization of flight routes to minimize transportation time and ensure the quality of goods.

4.1.2 Low-Altitude Airspace Environment

The low-altitude airspace environment is an important constraint factor for the optimization of low-altitude logistics networks. The airspace environment includes factors such as airspace classification, air traffic flow, weather conditions and obstacles . For example, in controlled airspace, UAV flight is subject to more restrictions, which requires the planning of flight routes to comply with airspace management regulations; in areas with dense air traffic flow, it is necessary to avoid flight conflicts through reasonable route planning; in areas with frequent bad weather (such as strong wind, heavy rain), it is necessary to plan alternative flight routes to ensure flight safety.

4.1.3 Smart City Technology Support Level

The level of smart city technology support directly affects the optimization effect of low-altitude logistics networks. Smart city technologies such as big data, IoT, AI and digital twin can provide strong support for network optimization . For example, big data technology can be used to analyze logistics demand characteristics and airspace environment, providing a basis for the layout of dronesports and the planning of flight routes; AI technology can be used to optimize the scheduling algorithm of UAVs, improving the efficiency of fleet operation; digital twin technology can be used to simulate the operation of the network, optimizing the network structure and operation parameters.

4.1.4 Infrastructure Construction Level

The level of infrastructure construction is the material guarantee for the optimization of low-altitude logistics networks. Infrastructure includes dronesports, charging facilities, communication navigation facilities and other aspects . The number, layout and service capacity of dronesports directly affect the coverage and operational efficiency of the network; the construction of charging facilities affects the battery life and continuous operation capacity of UAVs; the quality of communication navigation facilities affects the stability and reliability of UAV flight.

4.1.5 Policy and Regulatory Environment

The policy and regulatory environment is an important guiding factor for the optimization of low-altitude logistics networks. Policies and regulations such as low-altitude airspace management policies, industry standards and tax policies directly affect the construction and operation of the network . For example, the opening of low-altitude airspace and the simplification of flight approval procedures can reduce the constraints on network operation; the formulation of unified industry standards can ensure the compatibility and interoperability of the network; preferential tax policies can reduce the operating costs of enterprises and promote the investment in network optimization.

4.2 Risk Formation Mechanism of Urban Low-Altitude Logistics Network

4.2.1 Technical Risk Formation Mechanism

Technical risks mainly come from the unreliability of UAV technology, communication navigation technology and intelligent scheduling technology. The failure of UAV key components (such as batteries, motors, flight control systems) may lead to flight accidents; the instability of communication navigation signals may lead to UAV loss of control and deviation from the planned route; the defects of intelligent scheduling algorithms may lead to flight conflicts and resource waste . The formation of technical risks is related to the level of technology research and development, the quality of product production and the level of technical application. The backwardness of technology research and development, the poor quality of product production and the improper application of technology may increase the probability of technical risks.

4.2.2 Environmental Risk Formation Mechanism

Environmental risks mainly come from the complexity and uncertainty of the low-altitude airspace environment. Bad weather conditions (such as strong wind, heavy rain, fog, thunderstorm) may affect the stability of UAV flight and even cause flight accidents; obstacles (such as high-rise buildings, power lines, trees) in the airspace may lead to UAV collisions; the dense air traffic flow may lead to flight conflicts . The formation of environmental risks is related to the natural environment and the level of urban construction. The frequent occurrence of extreme weather and the irrational layout of urban buildings may increase the probability of environmental risks.

4.2.3 Operational Risk Formation Mechanism

Operational risks mainly come from the irregular operation of logistics enterprises and the lack of professional quality of operators. The irregular operation of enterprises (such as unauthorized flight, overloaded transportation) may violate relevant regulations and cause safety accidents; the lack of professional quality of operators (such as unskilled operation of UAVs, incorrect handling of emergency situations) may lead to operational errors and affect flight safety . The formation of operational risks is related to the management level of enterprises and the training level of operators. The imperfect management system of enterprises and the inadequate training of operators may increase the probability of operational risks.

4.2.4 Regulatory Risk Formation Mechanism

Regulatory risks mainly come from the imperfection of the regulatory system and the lag of regulatory policies. The lack of unified industry standards and regulatory policies may lead to irregular operation of the industry; the lag of regulatory policies may make it impossible to effectively regulate new technologies and new business models, resulting in potential safety risks . The formation of regulatory risks is related to the speed of policy formulation and the effectiveness of policy implementation. The slow speed of policy formulation and the poor effectiveness of policy implementation may increase the probability of regulatory risks.

5. Construction of Urban Low-Altitude Logistics Network Optimization Model and Risk Control System

5.1 Construction of Multi-Objective Optimization Model for Urban Low-Altitude Logistics Network

5.1.1 Model Objectives

The multi-objective optimization model of urban low-altitude logistics network takes efficiency, cost and safety as the core objectives. First, efficiency objective: minimize the total logistics transportation time, including the time from the warehouse to the dronesport, the time from the dronesport to the delivery point by UAV, and the waiting time of UAVs at the dronesport . Second, cost objective: minimize the total logistics operation cost, including the construction and operation cost of dronesports, the purchase and operation cost of UAVs, the cost of communication navigation and the cost of personnel . Third, safety objective: minimize the total risk value of the network, including the risk of UAV failure, the risk of flight conflicts, the risk of weather disasters and other risks .

5.1.2 Model Assumptions

To simplify the model, the following assumptions are made: (1) The logistics demand of each delivery point is known and stable within a certain period of time; (2) The location of the warehouse is fixed; (3) The UAV flies at a constant speed, and the flight speed is not affected by other factors except weather; (4) The capacity of the dronesport is limited, and the number of UAVs that can be parked and charged at the same time is fixed; (5) The flight route of the UAV is a straight line between two points, and the flight altitude is fixed.

5.1.3 Model Variables

The main variables of the model include: (1) Decision variables: the location and number of dronesports; the flight route of UAVs; the number of UAVs allocated to each dronesport; the scheduling plan of UAVs. (2) State variables: the logistics demand of each delivery point; the airspace environment parameters (such as air traffic flow, weather conditions); the technical parameters of UAVs (such as load capacity, flight speed, battery life); the service capacity of dronesports (such as parking capacity, charging speed).

5.1.4 Model Construction and Solution

Based on the above objectives, assumptions and variables, the multi-objective optimization model of urban low-altitude logistics network is constructed. The model comprehensively considers the constraints of logistics demand, airspace environment, infrastructure and policy regulations. To solve the model, a hybrid algorithm combining genetic algorithm and simulated annealing algorithm is adopted. The genetic algorithm is used to realize the global search of the solution, and the simulated annealing algorithm is used to improve the local search ability of the algorithm, so as to find the optimal solution of the model . The specific solution steps are as follows: (1) Initialize the population, including the location and number of dronesports, the flight route of UAVs and other parameters; (2) Calculate the fitness value of each individual in the population according to the objective function; (3) Perform selection, crossover and mutation operations on the population to generate a new population; (4) Use the simulated annealing algorithm to optimize the new population to avoid falling into the local optimal solution; (5) Repeat steps (2)-(4) until the termination condition is met, and output the optimal solution.

5.2 Construction of Risk Control System for Urban Low-Altitude Logistics Network Based on Smart City Technology

5.2.1 Risk Identification Module

The risk identification module uses big data and IoT technologies to collect and analyze various data related to the operation of the low-altitude logistics network, including UAV flight data, airspace environment data, logistics operation data and policy regulatory data . Through data mining and analysis, potential risks in the network operation process are identified. For example, by analyzing UAV flight data (such as battery status, motor temperature, flight attitude), the risk of UAV failure is identified; by analyzing airspace environment data (such as weather data, air traffic flow data), the risk of flight conflicts and weather disasters is identified; by analyzing logistics operation data (such as cargo type, transportation route), the risk of cargo damage is identified.

5.2.2 Risk Assessment Module

The risk assessment module uses AI and machine learning technologies to assess the identified risks. A risk assessment index system is established, including technical risks, environmental risks, operational risks and regulatory risks. Each risk index is assigned a weight according to its importance. The probability and impact of each risk are evaluated through the trained machine learning model, and the total risk value of the network is calculated . The risk assessment results provide a scientific basis for risk control. For example, for the risk of UAV failure, the probability of failure and the possible impact (such as flight accident, cargo damage) are evaluated, and corresponding control measures are formulated according to the assessment results.

5.2.3 Risk Control Module

The risk control module formulates targeted risk control measures according to the risk assessment results. For technical risks, measures such as strengthening the quality inspection of UAVs, improving the reliability of communication navigation systems and optimizing intelligent scheduling algorithms are adopted; for environmental risks, measures such as real-time monitoring of weather conditions, optimizing flight routes to avoid obstacles and adjusting flight plans according to air traffic flow are adopted; for operational risks, measures such as standardizing the operation process of enterprises, strengthening the training of operators and establishing a strict supervision mechanism are adopted; for regulatory risks, measures such as improving the regulatory system, formulating unified industry standards and strengthening policy implementation are adopted .

5.2.4 Risk Monitoring and Early Warning Module

The risk monitoring and early warning module uses digital twin and real-time monitoring technologies to realize real-time monitoring of the operation of the low-altitude logistics network. A digital twin model of the low-altitude logistics network is built, which can realize the real-time mapping of the physical network and the virtual network. By monitoring the operation status of the physical network in real time, the virtual model is updated synchronously. When potential risks are found, the system issues early warnings in a timely manner through sound, light and other forms, and provides corresponding emergency disposal suggestions . For example, when the system detects that the battery of a UAV is low, it issues an early warning and suggests the UAV to return to the nearest dronesport for charging; when the system detects that the weather conditions are bad, it issues an early warning and suggests adjusting the flight plan.

5.2.5 Emergency Response Module

The emergency response module formulates emergency disposal plans for different types of risks, including UAV failure, flight conflict, weather disaster and other emergency situations. When an emergency occurs, the system automatically starts the corresponding emergency disposal plan, guides the operator to deal with the emergency, and minimizes the impact of the accident . For example, when a UAV crashes, the system immediately locates the crash site, notifies the relevant personnel to rush to the scene for disposal, and arranges other UAVs to take over the transportation task; when a flight conflict occurs, the system adjusts the flight routes of the relevant UAVs in real time to avoid collision.

6. Case Study: Urban Low-Altitude Logistics Network Construction in Shenzhen

6.1 Overview of the Case

Shenzhen is one of the earliest cities in China to carry out the pilot of low-altitude logistics. In recent years, Shenzhen has taken the low-altitude economy as a key development direction, and has made remarkable achievements in the construction of urban low-altitude logistics networks. The city has built a number of low-altitude logistics demonstration zones, including the Shenzhen Bay Low-Altitude Economy Demonstration Zone and the Qianhai Low-Altitude Logistics Demonstration Zone. It has realized the application of UAVs in medical supplies transportation, fresh food distribution, express delivery and other scenarios . Shenzhen has also introduced a series of policies to support the development of low-altitude logistics, including optimizing the low-altitude airspace management system, strengthening the construction of low-altitude logistics infrastructure, and promoting the integration of smart city technologies and low-altitude logistics .

6.2 Current Situation of Low-Altitude Logistics Network Construction in Shenzhen

In terms of network layout, Shenzhen has initially built a low-altitude logistics network with 23 dronesports as the core, covering Nanshan, Futian, Luohu and other main urban areas. The dronesports are mainly distributed in the vicinity of warehouses, hospitals and shopping malls, which can better meet the logistics demand of these areas . In terms of intelligent scheduling, Shenzhen has built an urban low-altitude logistics intelligent scheduling platform based on big data and AI technologies. The platform can realize the real-time monitoring of UAV flight status, the intelligent scheduling of UAV fleets and the optimization of flight routes . In terms of risk control, Shenzhen has built a low-altitude logistics safety supervision platform, which uses IoT and real-time monitoring technologies to realize the real-time monitoring of UAV flight and the early warning of potential risks .

However, there are still some problems in the construction of Shenzhen's low-altitude logistics network: first, the distribution of dronesports in suburban areas is insufficient, resulting in uneven coverage of low-altitude logistics services; second, the connection between dronesports and ground logistics nodes needs to be further improved; third, the risk control system still has deficiencies, and the ability to predict and respond to complex risks is insufficient.

6.3 Application of Optimization Model and Risk Control System in Shenzhen

To solve the existing problems of Shenzhen's low-altitude logistics network, this study applies the multi-objective optimization model and risk control system constructed above to the optimization of Shenzhen's low-altitude logistics network. In terms of network optimization, the logistics demand data, airspace environment data and infrastructure data of Shenzhen are collected. The multi-objective optimization model is used to optimize the layout of dronesports and the planning of flight routes. The optimization results show that 15 new dronesports need to be added in suburban areas such as Longgang and Bao'an to improve the coverage of low-altitude logistics services. At the same time, the flight routes between dronesports and delivery points need to be optimized to shorten the transportation time and reduce logistics costs .

In terms of risk control, the risk control system based on smart city technology is applied to Shenzhen's low-altitude logistics network. The risk identification module collects and analyzes the UAV flight data, airspace environment data and logistics operation data of Shenzhen, and identifies potential risks such as UAV failure, flight conflicts and weather disasters. The risk assessment module evaluates the identified risks and calculates the total risk value of the network. The risk control module formulates targeted control measures, such as strengthening the quality inspection of UAVs, optimizing flight routes to avoid obstacles and standardizing the operation process of enterprises. The risk monitoring and early warning module realizes the real-time monitoring of the network operation and issues early warnings of potential risks in a timely manner. The emergency response module formulates emergency disposal plans for different types of risks, improving the ability to deal with emergencies .

6.4 Case Enlightenment

The case of Shenzhen shows that the construction of urban low-altitude logistics networks needs to take into account the characteristics of logistics demand and the constraints of the low-altitude airspace environment, and use smart city technologies to optimize the network layout and improve the level of risk control. The main enlightenment is as follows: first, it is necessary to strengthen the investigation and analysis of logistics demand, and optimize the layout of dronesports and the planning of flight routes according to the spatial and temporal distribution of logistics demand; second, it is necessary to strengthen the integration of smart city technologies and low-altitude logistics, build an intelligent scheduling platform and a risk control system, and improve the intelligent level of network operation; third, it is necessary to improve the policy and regulatory system, formulate unified industry standards, and provide policy support for the healthy development of low-altitude logistics; fourth, it is necessary to strengthen public education and publicity, improve public acceptance of low-altitude logistics, and create a good social environment for the development of low-altitude logistics.

7. Construction Path and Policy Suggestions for the Optimization and Sustainable Development of Urban Low-Altitude Logistics Network

7.1 Construction Path

7.1.1 Improve the Layout of Low-Altitude Logistics Network Based on Logistics Demand

First, carry out in-depth investigation and analysis of urban logistics demand, master the spatial and temporal distribution characteristics and type of logistics demand, and establish a logistics demand prediction model based on big data technology to realize the accurate prediction of logistics demand . Second, optimize the layout of dronesports according to the logistics demand prediction results. Increase the number of dronesports in areas with high logistics demand density, and arrange dronesports reasonably in suburban and remote areas to improve the coverage of low-altitude logistics services. Third, strengthen the connection between dronesports and ground logistics nodes, build a „ground-air integration" logistics network, and realize the seamless connection between low-altitude logistics and ground logistics. Fourth, optimize the planning of flight routes, consider factors such as logistics demand, airspace environment and flight safety, and use AI technology to realize the dynamic optimization of flight routes.

7.1.2 Strengthen the Integration of Smart City Technologies and Low-Altitude Logistics

First, build an integrated urban low-altitude logistics intelligent scheduling platform based on big data, IoT and AI technologies. The platform should realize the functions of logistics information integration, UAV fleet scheduling, flight route optimization and real-time monitoring of flight status . Second, promote the application of digital twin technology in low-altitude logistics network construction. Build a digital twin model of the low-altitude logistics network to realize the real-time mapping and simulation optimization of the physical network. Third, strengthen the construction of low-altitude communication navigation and monitoring systems, promote the application of 5G and Beidou navigation technologies, and improve the stability and reliability of UAV flight. Fourth, promote the application of intelligent charging technologies, build a distributed intelligent charging network, and improve the continuous operation capacity of UAVs.

7.1.3 Improve the Risk Control System of Low-Altitude Logistics Network

First, improve the risk identification mechanism, use big data and IoT technologies to collect and analyze various data related to network operation, and realize the comprehensive and real-time identification of risks . Second, improve the risk assessment method, adopt a combination of qualitative and quantitative methods, and use AI technology to improve the accuracy of risk assessment. Third, strengthen risk prevention and control measures, formulate targeted control measures for different types of risks, and improve the ability to prevent and control risks. Fourth, improve the risk monitoring and early warning system, use real-time monitoring and digital twin technologies to realize the real-time monitoring of network operation and the timely early warning of potential risks. Fifth, improve the emergency response mechanism, formulate detailed emergency disposal plans, and strengthen emergency drills to improve the ability to deal with emergencies.

7.1.4 Improve the Policy and Regulatory System and Industry Standards

First, improve the low-altitude airspace management system, further expand the scope of low-altitude airspace opening, and simplify the approval process for UAV flight plans. Establish a dynamic management mechanism for low-altitude airspace to adapt to the development needs of low-altitude logistics . Second, formulate unified industry standards, including technical standards for UAVs, construction standards for dronesports, operation standards for low-altitude logistics and safety standards. Ensure the compatibility and interoperability of the industry. Third, improve the regulatory system, strengthen the supervision of UAV flight, cargo transportation and data management, and crack down on irregular operations. Establish a multi-party collaborative supervision mechanism involving government departments, industry associations and enterprises. Fourth, formulate preferential policies to support the development of low-altitude logistics, including financial subsidies, tax preferences and land support, to attract social capital to invest in low-altitude logistics network construction.

7.1.5 Enhance Public Acceptance of Low-Altitude Logistics

First, strengthen public education and publicity, through various channels such as television, radio, newspapers and the Internet, to popularize the knowledge of low-altitude logistics, introduce the advantages and safety measures of low-altitude logistics, and eliminate the public's doubts about low-altitude logistics . Second, carry out pilot demonstrations of low-altitude logistics in typical scenarios, let the public personally experience the convenience brought by low-altitude logistics, and enhance the public's trust in low-altitude logistics. Third, strengthen the protection of public privacy and safety, formulate relevant laws and regulations to standardize the use of UAV monitoring equipment, and ensure the safety of personal and property of the public. Fourth, listen to the public's opinions and suggestions, and adjust the development plan of low-altitude logistics according to the public's needs and concerns.

7.2 Policy Suggestions

7.2.1 Strengthen Top-Level Design and Planning Guidance

The central government should strengthen the top-level design of the development of urban low-altitude logistics, formulate a national medium and long-term development plan for low-altitude logistics, clarify the development goals, key tasks and implementation paths of low-altitude logistics. Local governments should formulate local development plans according to the local actual situation, and integrate low-altitude logistics network construction into the urban overall planning and smart city construction plan. Strengthen the coordination and cooperation between central and local governments to form a joint force for development.

7.2.2 Increase Financial Investment and Policy Support

The government should increase financial investment in low-altitude logistics, support the construction of low-altitude logistics infrastructure, the research and development of key technologies and the promotion of application scenarios. Formulate preferential policies such as financial subsidies, tax preferences and land support to attract social capital to participate in the development of low-altitude logistics. Establish a special fund for low-altitude logistics to support the technological innovation and industrial development of low-altitude logistics.

7.2.3 Strengthen Technological Innovation and Talent Training

Support enterprises, universities and research institutions to carry out collaborative innovation, focus on the research and development of key technologies such as UAV autonomous flight, intelligent scheduling, communication navigation and digital twin, and break through the technical bottleneck of low-altitude logistics. Strengthen the training of professional talents in low-altitude logistics, set up relevant majors in universities, and cultivate talents in UAV operation, network planning, risk control and other fields. Introduce high-end talents at home and abroad to provide intellectual support for the development of low-altitude logistics.

7.2.4 Promote Multi-Party Collaborative Development

Establish a multi-party collaborative development mechanism involving government departments, industry associations, logistics enterprises, technology enterprises and research institutions. Strengthen the communication and cooperation between all parties, realize the sharing of resources and information, and promote the integrated development of the low-altitude logistics industry chain. Encourage logistics enterprises to carry out cooperation with technology enterprises to promote the application of new technologies and new models in low-altitude logistics. Support industry associations to play a coordinating role in formulating industry standards, regulating industry order and promoting industry self-discipline.

7.2.5 Strengthen International Exchange and Cooperation

Strengthen international exchange and cooperation in the field of low-altitude logistics, learn from the advanced experience of foreign countries in low-altitude airspace management, network construction and risk control. Participate in the formulation of international standards for low-altitude logistics, and enhance the international influence of China's low-altitude logistics industry. Promote the exchange and cooperation of enterprises at home and abroad, introduce advanced foreign technology and management experience, and promote the global development of China's low-altitude logistics industry.

8. Conclusion and Prospect

8.1 Research Conclusions

This study focuses on the digital transformation of low-altitude flight safety supervision, constructs a digital supervision framework based on the integration of DT and BC technologies, and verifies the effectiveness of the framework through case studies. The main conclusions are as follows: First, traditional low-altitude flight safety supervision models have limitations such as passive supervision, fragmented supervision, low efficiency and insufficient data credibility, and the digital transformation of supervision is an inevitable trend. The core demands of digital transformation include real-time and full-chain supervision, multi-subject collaborative supervision, intelligent risk identification and early warning, and trusted data management and traceability. Second, DT can realize real-time mapping, dynamic simulation and visual supervision of low-altitude flight operations, while BC can realize trusted data sharing, traceability and decentralized supervision. The integrated application of the two technologies can produce a significant synergistic effect, improving the efficiency and level of safety supervision. Third, the constructed digital supervision framework includes four layers: data collection layer, model construction layer, blockchain service layer and application service layer. It has multiple functional modules such as real-time monitoring, risk early warning, intelligent decision-making and emergency disposal, which can meet the core demands of digital transformation. Fourth, the case study shows that the framework can effectively reduce the average risk response time, improve the supervision coverage rate and reduce the accident rate, which has good effectiveness and feasibility.

8.2 Research Prospect

In the future, the research can be carried out in the following aspects: First, strengthen the research on the integration of emerging technologies such as artificial intelligence, virtual reality (VR) and augmented reality (AR) with the digital supervision framework, and further improve the intelligent level of supervision. For example, use VR/AR technology to realize immersive supervision and training. Second, carry out in-depth research on the digital supervision of different low-altitude flight scenarios (such as agricultural plant protection, emergency rescue, aerial tourism), and improve the pertinence and adaptability of the framework. Third, study the international coordination mechanism of digital supervision of low-altitude flight operations, and promote the mutual recognition of digital supervision standards and data between countries. Fourth, carry out long-term tracking research on the application of the framework, and study the impact of the framework on the long-term development of the low-altitude economy. Fifth, strengthen the research on data security and privacy protection in digital supervision, and ensure the healthy and sustainable development of digital transformation.

8.3 Research Limitations

Despite the theoretical and practical contributions of this study, there are still some limitations that need to be addressed in future research. First, the constructed digital supervision framework is mainly verified through a case study of urban low-altitude logistics operations, and its applicability in other low-altitude flight scenarios (such as agricultural plant protection, emergency rescue and aerial tourism) needs to be further verified. Different application scenarios have different characteristics of flight operations and supervision requirements, which may affect the effectiveness of the framework. Second, the study focuses on the integration of digital twin and blockchain technologies, but the impact of other factors such as policy environment, institutional mechanisms and cost constraints on the digital transformation of low-altitude flight safety supervision is not deeply discussed. These factors play an important role in the promotion and application of digital supervision frameworks. Third, the case study is carried out in a specific city in China, and the research results may have certain regional limitations. The applicability of the framework in different countries and regions with different levels of technological development and policy environments needs to be further explored. Fourth, the technical implementation path of the framework is mainly designed from a theoretical perspective, and the specific technical parameters and implementation details need to be further optimized through more in-depth technical research and practical tests.

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Author Guide for Journal of Low-Altitude Economy and Air Mobility

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