Scholar Publishing Group
Socio-Economic Statistics Research
https://doi.org/10.38007/SESR.2026.070108
ISSN 2790-2722 Vol. 7, Issue 1: 67-76

The Mechanisms of Synergistic Impact within the Low-Altitude Logistics Industry Chain in the Guangdong-Hong Kong-Macao Greater Bay Area

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Keywords: Low-altitude Logistics; Guangdong-Hong Kong-Macao Greater Bay Area; Industrial Chain Collaboration; Interpretive Structural Modelling (ISM); Drone Logistics

Abstract: Low-altitude logistics with emerging technologies like drones and eVTOL aircraft is a key enabler of the new quality productive forces in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA).However,issues with institutional variation in the GBA, complicated possibilities management and the variations in industrial actors make it the case horrible for this sector. This article uses the Interpretive Structural Modelling (ISM) framework for systematically analyzing the collaborative operational mechanisms. A list of 15 key influencing factors to the development of technologies were identified based on the expert scoring and Literature survey covering policy support to technological innovation. This research uses a hierarchical modeling approach to formulate an adjacency matrix and then a reachability matrix to plot the hierarchy of these factors. There is a 4-level structure: Root Environmental Drivers, Deep-level Technical Support, Organizational Transmission and Surface-level Coordination Outcomes. In addition, there are three main pathways for transmitting capabilities: Institutional Environment-Driven Pathway, Technological Capability Transmission Pathway and Market Demand and Social Feedback Pathway. This study offers some theoretical inspiration for decision makers and industry players in order to maximize synergy and sustainable development of the low altitude logistics industry chain in an integrated regional framework.

1. Introduction

The benefits of low altitude logistics enabled by new modes of transportation like drones and electric vertical take off & landing EVs (eVTOLs) are high efficiency, low cost and flexible delivery for specific use cases like on-demand delivery in urban areas, transport to remote areas, and emergency logistics. The Guangdong-Hong Kong-Macao Greater Bay Area is one of the most open and economically dynamic areas in China and has a complete manufacturing foundation and the most powerful technological innovation and a high concentration of urban structures, which is a favorable test bed for the development of low-altitude logistics. But because of the cross-regional (Guangdong, Hong Kong, Macao) institutional difference, the complexity of low-altitude logistics airspace resource management and the diversity of industry chain participants, the development of low-altitude logistics is still in the exploratory phase. Therefore, systematically studying the cooperative working mechanism of the low-altitude logistics industry chain in the Guangdong-Hong Kong-Macao Greater Bay Area is very important for promoting the "integration of the region" and developing new productive forces.

As drones are the primary tool for low-altitude logistics, scholars have focused on optimising their delivery operations. Ren Xinhui et al. (2023)[1] applied improved grid partitioning and the Voronoi polygon optimisation method to optimise the selection of drone landing points, ensuring balanced coverage of demand points. Zhang Qiquan et al. (2020)[2] addressed the operational challenges of logistics UAVs in complex low-altitude environments by constructing a multi-constraint path planning model that comprehensively considers airspace conditions, transport tasks and risk factors to optimise flight paths. Meanwhile, He et al. (2022)[3] proposed a route network planning method from the perspective of urban air delivery networks, enhancing the organisational efficiency of low-altitude routes and the allocation of airspace resources through city-level route structure design. Regarding collaborative delivery between drones and vehicles, Chen et al. (2021)[4] further optimised the collaborative delivery routes of ground vehicles and drones from the perspective of heterogeneous robotic systems, advancing vehicle-drone collaborative delivery from the optimisation of individual delivery tools to system-level resource allocation.

Regarding the design of collaborative mechanisms for low-altitude logistics, researchers have conducted studies on collaborative operation models and benefit-sharing mechanisms. Xie Hua et al. (2024) [5] utilised multi-objective mixed-integer programming and a greedy stochastic adaptive algorithm to optimise UAV flight sequences and airspace resource allocation, thereby achieving collaborative operations. Zhou et al. (2024)[6] employed multi-agent deep reinforcement learning to investigate collaborative decision-making in logistics delivery by low-altitude UAV formations. Luo et al. (2024)[7] utilised methods such as Shapley values and kernel functions to construct benefit-sharing models, promoting fair and reasonable benefit distribution among multiple stakeholders in low-altitude logistics to ensure collaborative cooperation.

The low-altitude economy and the logistics sector mutually reinforce and develop in tandem; the coupling relationship between the two has attracted widespread attention from scholars. Huang et al. (2024)[8] the new challenges and development pathways facing the logistics industry within the context of the low-altitude economy. Yang and Xu (2026)[9] investigated the underlying logic by which the low-altitude economy drives the logistics industry towards intelligent and unmanned development. Zhang et al. (2023)[10] explored logistics drone technology, including drone scheduling optimisation, route planning and intelligent decision-making.

In summary, existing research has yielded substantial results in areas such as the optimisation of drone delivery, the design of coordination mechanisms, and the coupling relationship with the low-altitude economy. However, the following shortcomings remain: Firstly, research has largely focused on individual technologies or specific stages, lacking a systematic analysis of the overall coordinated operation of the low-altitude logistics industry chain. Secondly, research on coordination mechanisms against the backdrop of institutional differences within the Guangdong-Hong Kong-Macao Greater Bay Area remains relatively weak.

This study will employ the Interpretive Structural Modelling (ISM) framework to conduct a systematic analysis of the structural relationships, transmission mechanisms and hierarchical pathways among the factors influencing industrial chain synergy within the Guangdong-Hong Kong-Macao Greater Bay Area's low-altitude logistics sector. It aims to address the following key questions: which factors are root drivers, which act as mediating factors, and which are surface-level direct influences; and how these factors collectively impact the level of industrial chain synergy.

2. Steps for Constructing the ISM Model

2.1 Determination of the influencing factor set

Fifteen key influencing factors were selected as the subjects for the ISM model analysis. The coding of these factors is shown in Table 1, and the factor set S is constructed as follows:

$$S = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}\}$$

Table 1. Coding of influencing factors

Code	Variable Name	Code	Variable Name
S_1	Aircraft R&D and manufacturing capability	S_2	Level of information sharing & digital platforms
S_3	Completeness of low-altitude infrastructure	S_4	Flight safety control technology
S_5	Degree of technical standardization	S_6	Level of industrial chain collaboration
S_7	Resource integration and allocation capability	S_8	Rationality of benefit distribution
S_9	Collaborative governance capability	S_{10}	Inter-subject trust level
S_{11}	Policy support intensity	S_{12}	Institutional synergy of Guangdong-Hong Kong-Macao
S_{13}	Degree of airspace openness	S_{14}	Market demand scale
S_{15}	Social acceptance		

2.2 Construction of the adjacency matrix

The ISM model first requires identifying the direct relationships among the influencing factors. This paper adopts the expert judgment method, inviting experts in the fields of low-altitude economy, regional governance, and logistics systems to conduct pairwise comparisons of the relationships between the factors. If factor S_i has a direct influence on factor S_j, it is assigned a value of 1; otherwise, it is assigned 0. That is:

$$a_{ij} = \begin{cases} 1, S_i \rightarrow S_j \\ 0, S_i \nrightarrow S_j \end{cases}$$

Thus, a 15×15 adjacency matrix A is formed:

$$A = [a_{ij}]_{15\times 15}$$

Based on the expert scoring method and the logic of the low-altitude logistics industry chain, pairwise relationships among the 15 factors were determined. Accordingly, the adjacency matrix A is constructed, where the diagonal elements are all 0, indicating that a factor does not directly act upon itself; rows represent the "influencing factors" and columns represent the "influenced factors".

$$A=\begin{bmatrix}
0&0&0&1&0&1&1&0&0&0&0&0&0&0&0\\
0&0&0&0&1&0&1&0&1&1&0&0&0&0&0\\
0&1&0&0&0&1&1&0&0&0&0&0&0&0&0\\
0&0&0&0&1&0&0&0&1&0&0&0&0&0&1\\
0&1&0&0&0&1&1&0&1&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
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0&0&1&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&1&1&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&1&0&0&0&0
\end{bmatrix}$$

2.3 Addition of the Identity Matrix

After constructing the adjacency matrix *A*, an identity matrix *I* is introduced to the adjacency matrix. This ensures that the ISM model can capture both the “direct relationships” and “reflexive relationships” among the factors, thereby constructing the initial reachability matrix *B*.

Therefore, mathematically, the identity matrix *I* is added to the adjacency matrix A to obtain the initial reachability matrix:

$$\mathrm{B}=\mathrm{A}+\mathrm{I}$$

Here, the diagonal elements of the identity matrix *I* are all 1, while the rest are 0, representing the reachability of each factor to itself. In the reachability matrix *B*, if there is a direct influence from factor S_i to S_j, then $\mathrm{b}_{\mathrm{ij}}=1$; if there is no direct relationship but i = j, then $\mathrm{b}_{\mathrm{ii}}=1$, indicating that the reflexive relationship holds; for all other cases, the value is 0.

2.4 Calculating the Reachability Matrix via Boolean Matrix Multiplication

To further identify indirect relationships between factors, matrix *B* must be subjected to Boolean power operations, i.e.:

$$\mathrm{M}=(\mathrm{A}+\mathrm{I})^{\mathrm{k}}(\mathrm{k}\geq\mathrm{n}-1)$$

Here, n denotes the number of factors (in this study, n = 15). Therefore, theoretically, when $\mathrm{k}\ \geq\ 14$, the matrix will tend towards a stable state, satisfying:

$$\mathrm{B}^{\mathrm{k}}=\mathrm{B}^{\mathrm{k}+1}$$

The matrix obtained at this stage is the final reachability matrix *M*. This matrix not only reflects the direct influence relationships between factors but also reveals multi-level transmission relationships formed through intermediate nodes, thereby providing a comprehensive relational foundation for subsequent hierarchical classification and structural interpretation.

$$M = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

2.5 Reachable Sets and Hierarchical Classification

For any factor S_i, the reachable set denotes the set of all factors that can be reached from factor S_i via the reachability matrix *M*. The reachable set is defined as:

$$\mathrm{R}(\mathrm{S_i}) = \{\mathrm{S_j} | \mathrm{m_{ij}} = 1\}$$

The antecedent set denotes the set of all preceding factors that can influence factor S_i. The antecedent set is defined as:

$$\mathrm{A}(\mathrm{S_i}) = \{\mathrm{S_j} | \mathrm{m_{ji}} = 1\}$$

The intersection is defined as:

$$\mathrm{C}(\mathrm{S_i}) = \mathrm{R}(\mathrm{S_i}) \cap \mathrm{A}(\mathrm{S_i})$$

When the condition $R(S_i)$=$C(S_i)$ is satisfied, the factor is classified into the current highest level.

3. Analysis of the hierarchical structure of influencing factors

Through iterative calculations using the reachability matrix and hierarchical classification, the 15 influencing factors can be categorised into four levels, as shown in Figure 1. The factors influencing industrial chain synergy in low-altitude logistics within the Guangdong-Hong Kong-Macao Greater Bay Area form a hierarchical structure driven by the underlying environment, supported by deep-level technology, transmitted through the intermediate organisational layer, and resulting in surface-level synergy. From a structural perspective, variables at the foundational level determine the institutional boundaries and development scope of industrial chain synergy; variables at the technological level constitute the capability foundation for low-altitude logistics operations; variables at the organisational level serve to translate technological capabilities into collaborative performance; whilst variables at the surface level directly reflect the ultimate outcomes of industrial chain synergy.

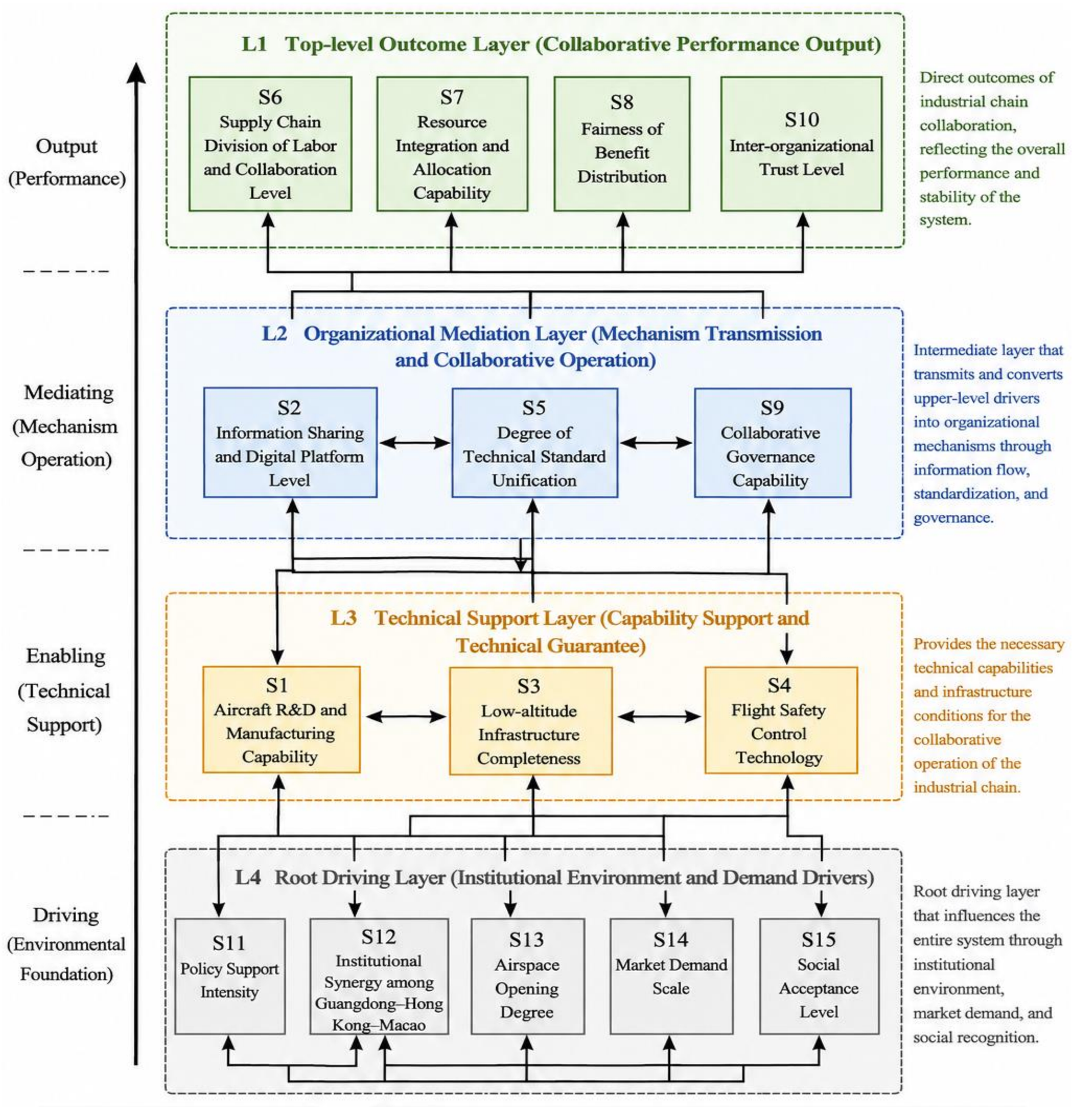

Figure 1: ISM diagram of factors influencing synergy within the low-altitude logistics industry chain in the Guangdong-Hong Kong-Macao Greater Bay Area

3.1 Fourth Layer: Root Environmental Drivers

Policy support (S_{11}), institutional coordination within the Guangdong-Hong Kong-Macao Greater Bay Area (S_{12}), the degree of airspace openness (S_{13}), the scale of market demand (S_{14}) and social acceptance (S_{15}) constitute the root drivers for the coordinated operation of the entire low-altitude logistics industry chain. Judging by the results of the reachability matrix, the factors in this layer exert a broad range of direct or indirect influence on factors in all other layers, whilst themselves being subject to few reverse constraints from other variables, exhibiting a distinct “high-drive, low-dependence” characteristic. Among these, institutional synergy (S_{12}) and degree of airspace openness (S_{13}) demonstrate stronger cross-layer transmission capabilities within the path structure, serving as crucial bridge variables connecting the policy system and the technology system.

3.2 Third Layer: Deep-level Technical Support Layer

Aircraft R&D and manufacturing capabilities (S_1), the completeness of low-altitude infrastructure (S_3), and flight safety control technologies (S_4) constitute the physical foundation and capability support layer for the collaborative operation of the industrial chain. These factors determine whether the low-altitude logistics industrial chain “can operate” and define the “boundaries of its operational capability”, forming the capability foundation layer for synergy. From the perspective of path relationships in the reachability matrix, factors at the environmental layer influence variables at the technological layer through institutional provision and market traction. For example, policy support and airspace opening jointly promote the improvement of infrastructure, whilst institutional coordination influences the development direction of safety control technologies through standardisation mechanisms. Factors at this layer also exert a significant forward-looking supportive effect on variables at the organisational layer, serving as a key intermediate foundation linking the macro-environment with micro-coordination.

3.3 Second Layer: Organisational Transmission Layer

Level of information sharing and digital platforms (S_2), degree of technical standardisation (S_5) and co-governance capacity (S_9) constitute the core intermediary structure for multi-stakeholder collaborative operations within the industrial chain. As evident from the path relationships in the reachability matrix, factors in this layer exhibit a typical “bridging” characteristic: on the one hand, they receive capability outputs from the technology layer, transforming infrastructure and safety technologies into an operational system of information and rules; on the other hand, they influence surface-level collaborative behaviours such as resource integration, interest distribution and trust mechanisms. Among these, the digital platform (S_2) exhibits strong characteristics of a central node across multiple pathways, serving as a key hub variable connecting technology and organisational coordination.

3.4 First Layer: Surface-Level Coordination Outcomes

Level of division of labour and collaboration within the industrial chain (S_6), resource integration and allocation capacity (S_7), reasonableness of interest distribution (S_8), and level of trust between entities (S_{10}) directly determine the performance of the industrial chain’s coordinated operation, constituting the direct manifest variables of the low-altitude logistics industrial chain’s coordinated operation. From the perspective of the matrix structure, the factors at this level are primarily influenced by the combined effects of variables from the intermediary and underlying layers; their changes directly reflect the level of synergy efficiency and stability within the industrial chain. Among these, the level of trust (S_{10}) exhibits distinct outcome aggregation characteristics under the influence of multiple pathways, serving as the ultimate manifestation of the system’s collaborative stability.

4. Pathways of the ISM Hierarchical Structure Model

Based on the hierarchical structure and taking into account the path accessibility relationships between factors in the reachability matrix M, three pathways for the coordinated operation of the low-altitude logistics industry chain in the Guangdong-Hong Kong-Macao Greater Bay Area have been identified.

4.1 Institutional Environment-Driven Pathway

Starting from the intensity of policy support (S_{11}), the institutional coordination among Guangdong, Hong Kong and Macao (S_{12}), and the degree of airspace openness (S_{13}), the impact is transmitted upwards through the technical standards system and governance structure, ultimately influencing the collaborative performance of the industrial chain. Specifically, the institutional environment first influences the completeness of low-altitude infrastructure (S_3) by regulating airspace resource allocation and approval mechanisms; this subsequently affects aircraft operational capabilities and safety control technologies (S_1, S_4); and is then transmitted to the organisational level via standardisation mechanisms (S_5) and collaborative governance mechanisms (S_9), ultimately influencing the level of division of labour and collaboration as well as resource integration capabilities (S_6, S_7). This pathway indicates that, within the specific institutional context of the Guangdong-Hong Kong-Macao Greater Bay Area, institutional synergy constitutes a prerequisite for the realisation of cross-regional coordination within the low-altitude logistics industrial chain.

4.2 Pathway of Technological Capability Transmission

Taking aircraft R&D and manufacturing capabilities (S_1), the level of low-altitude infrastructure development (S_3), and flight safety control technologies (S_4) as the core starting points, this pathway facilitates organisational-level transformation through information platforms and standardisation systems, thereby further influencing collaborative performance. Specifically, this manifests as follows: technical capabilities first integrate data flows through information-sharing and digital platforms (S_2), then achieve rule compatibility through the unification of technical standards (S_5), and finally, through collaborative governance capabilities (S_9), are transformed into multi-stakeholder collaborative behaviour, thereby enhancing the efficiency of resource allocation and the level of interest coordination. This pathway indicates that technical factors do not directly determine collaborative outcomes, but rather exert an indirect influence through organisational mechanisms.

4.3 Market Demand and Social Feedback Pathway

This pathway begins with the scale of market demand (S_{14}) and the degree of social acceptance (S_{15}), and indirectly influences the evolution of technology and organisational structures by affecting the level of policy support (S_{11}) and the degree of airspace openness (S_{13}). Specifically, growth in market demand increases the willingness to provide policy support, whilst social acceptance influences the institutional tolerance for low-altitude logistics operations. Together, these factors contribute to the optimisation of the institutional environment and further influence the expansion rate and spatial scope of the entire industrial chain’s collaborative system.

5. Conclusion

The low altitude logistics industry chain is a systematic issue of coordinated development of multiple factors such as multiple stakeholders, cross regional jurisdictions and interdisciplinary technologies. Through the ISM model, this study systematically explores the synergistic relationships among the industry chains of the low-level logistics in the Greater Bay Area of Guangdong, Hong Kong and Macao in detail. The research relies on the key factors' reachability and hierarchy to build a four-layer structure: the underlying layer, the environmental layer, the collaborative layer, and the result layer, which shall help explain the mechanism of the underlying factors influencing surface factors and how the surface collaborative factors influence results. The study concludes that the synergy mechanism acts within a framework defined by being uncovered by the environment, leveraged by technology, spread by organization and achieved in results.

The study's conclusions are that the synergies operate with a“driven by environment, supported by technology, transmitted by organization and manifested in outcomes” structure. Factors like policy support, institutional coordination and airspace openness, in particular, act as “root drivers” with strong driving power. They help to define the boundaries of development by affecting the deep level technical support layer (infrastructure and safety technology) and the organizational transmission layer (digital platform and standardization). In addition, technological capabilities are also not determinate, but become operational efficiency via organizational processes, which include cooperation in the form of information sharing and co-governance. Three distinct pathways are identified to explain the transmission of synergy:

(1) The Institutional Environment-Driven Pathway: Emphasizes on the underpinning expectation of cross-regional institutional synergy with a view to facilitating infrastructure connectivity and security management.

(2) The Technological Capability Transmission Pathway: This illustrates a mechanism of how the technical resources are translated to collaborative behavior, in this instance to standardization and also by way of digital platforms.

(3) The Market Demand and Social Feedback Pathway: Makes market scale and social acceptance an indirect influence on the institutional level and the technological evolution.

Funding

2026 Research Project of the China Society of Logistics and the China Federation of Logistics & Purchasing: Research on the Collaborative Mechanism and Optimization Path of the Low-Altitude Logistics Industry Chain in the Guangdong–Hong Kong–Macao Greater Bay Area(No.2026CSLKT3-194); 2024 Teaching Team Development Project of Zhuhai College of Science and Technology: Intelligent Logistics Teaching Team; The 2025 Zhuhai College of Science and Technology Quality Project: Virtual Teaching and Research Office (No. ZLGC20251101); Industry Education Integrated Program (No. ZLGC20250101).

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