



# **Integration of Multimodal Logistics at Frankfurt Airport: An Engineering Perspective**

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## Abstract

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<p>With the rapid development of the global economy, the demand for efficient and green transportation methods in the supply chain is increasing daily. Multimodal transport, as a logistics model that organically combines transportation modes such as air, road and railway, can provide a comprehensive transportation solution that is fast, low-cost and energy-saving. The continuous expansion of international freight volume and transportation distance has also promoted the development trend of multimodal transport integration. (Okyere, S., Yang, J., &amp; Adams, C. A., 2022) Frankfurt Airport, as an important air cargo hub in Europe, has achieved remarkable results in multimodal transport integration. According to Fraport's statistics, the airport's cargo and mail throughput reached approximately 2.1 million tons in 2024, representing a year-on-year growth of 6.2%. (TIACA, 2025) This growth is attributed to the airport's well-developed intermodal infrastructure and the construction of air-rail intermodal channels, which have effectively enhanced the efficiency of cargo transfer and transportation capacity.</p> <p>From an engineering perspective, the efficiency of multimodal transport can be further enhanced through optimization models and simulation techniques. Advanced algorithms such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) are widely used in the path planning and scheduling optimization of multimodal transport networks. Studies show that compared with the traditional mode, the schemes adopting these optimization algorithms can reduce the total cost of the transportation system by approximately 4-5%, while significantly improving the transportation time and resource utilization rate. (Zhang, T., Cheng, J., &amp; Zou, Y., 2024) Based on the actual operation data of Frankfurt Airport, this thesis deeply analyses the application effect of multimodal transport integration from the perspective of logistics engineering, providing a reference for hub airports to improve transportation efficiency and integration level.</p>
<b>Key words</b> Multimodal transport; Logistics integration; Optimization model; Frankfurt Airport; Particle swarm optimization; Genetic algorithm

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# 1 Introduction

## 1.1 Aims and objectives

In today's global logistics landscape, the integration of multimodal transport systems is becoming increasingly important. The author believes that airports, as key nodes of this network, are confronted with the challenge of coordinating various modes of transportation to ensure seamless connection of goods. Through visiting and investigating Nagoya Chubu International Airport, Singapore Changi International Airport, Doha International Airport, etc., the author found that although various transportation departments have been optimized to varying degrees, the lack of a unified integration mechanism often leads to a series of problems such as low efficiency, increased operating costs, and cargo delays. The impetus for this research stems from observed inefficiencies in cargo handling and transportation coordination at major airports. Based on the author's understanding of the current economic cooperation between China and Europe and the direction of the European air cargo market after the Russia-Ukraine war, the author chose Frankfurt Airport as the research object and attempted to explain from a theoretical perspective the obstacles that the fragmentation of the current multimodal logistics integration application poses to the multimodal transport logistics market. Therefore, it is necessary to comprehensively examine the challenges and solutions of integration. By addressing these integration challenges, the study aims to contribute to the development of more resilient and responsive logistics networks.

Overall, the goals of this article are as follows:

- ① Identify and analyse the primary obstacles hindering effective multimodal integration at airports.
- ② Evaluate existing frameworks and technologies employed in multimodal logistics.
- ③ Develop engineering recommendations to address identified challenges.
- ④ Assess the potential impact of proposed solutions on operational efficiency and cost-effectiveness.

## 1.2 Data collection process and sources of data

This thesis adopts a qualitative research design, primarily utilizing secondary data sources. The study is structured around an in-depth case analysis, focusing on existing literature, reports, and documented studies related to multimodal logistics integration at airports. The core of this thesis is an in-depth case analysis of Frankfurt Airport's multimodal logistics integration.

### **1.3 Structure of the thesis**

In terms of the overall structure of this thesis, it is not difficult to see from the table of contents of this paper that this paper starts with the theory of multimodal logistics integration. Through the sorting out of the global supply chain pattern and the background analysis of the characteristics and challenges of multimodal transport, it introduces the planning models and solvers that are widely used by various airports under the current pattern. Through the research and discussion of the Particle Swarm Optimization model, Genetic Algorithm model and Hybrid model, it is found to enhance the efficiency, strengthen cooperation and reduce costs of the airport in the integrated application of multimodal logistics. Solutions to sudden problems. In the third part, by citing the previous theoretical preparations, the infrastructure of Frankfurt Airport is evaluated and analysed, with a focus on analysing its information decision-making platform. Finally, its optimization effect and simulation assessment are evaluated through the model. Ultimately, by taking a small perspective to see the big picture, the issues of infrastructure support and data systems in the current integrated development of multimodal logistics are identified and analysed from an engineering perspective.

## 2 Multimodal Logistics and transport

### 2.1 The concept of multimodal logistics

Multimodal Logistics (MML) refers to the integrated transportation mode in which goods are transported from the place of origin to the place of destination under a unified contract or bill of lading using two or more modes of transportation (air, road, rail, water, etc.). Its core lies in the multimodal transport operator (MTO) to assume the responsibility of the whole transportation, to realize the integrated management of end-to-end (door-to-door) services. This mode has the following advantages over the traditional single mode of transportation.(UNCTAD, 2023)

Covering multiple legs of transportation between the entire process through a single contract, i.e., under the same bill of lading, one multimodal transport operator (MTO) assumes the entire responsibility for transportation from the place of origin to the place of destination without the need for the shipper to enter multiple contracts with different carriers separately.

This approach has the following advantages over the stacking of traditional modes of transportation:

- ① Simplify the communication process, cargo owners only need to dock with one carrier, and all transportation links (e.g., sea→rail→road) will be coordinated and monitored by that carrier, which significantly reduces the time and cost of repeatedly communicating and confirming the transportation details between different carriers; (Inbound Logistics, 2025)
- ② Reduce management costs, the traditional model, the shipper needs to sign a contract with each section of transportation carriers and docking their respective quotations, insurance and claims terms; while the single contract model, these terms by the internal integration of the carrier, the shipper only need to deal with a set of documents and settlement process, you can complete the whole transportation management and settlement; (TransVirtual, 2025)
- ③ Harmonization of risks and responsibilities: in multi-segment transportation, in case of damage, delay or loss of goods, the determination of responsibilities is often complicated due to the large number of carriers; under the single-contract model, MTO assumes the responsibility for the whole process and internally coordinates the settlement of claims and the pursuit of responsibilities in all segments, which helps to shorten the cycle of dispute handling and reduce the coordination costs incurred by all parties due to the division of responsibilities;(Jenkar, 2024)

The optimal combination of transportation modes can be flexibly selected according to the attributes of goods and route characteristics, realizing the comprehensive optimization of cost, time and energy consumption(UPS Supply Chain Solutions, 2024)

Different modes of transportation can be used as back-ups for each other, increasing the ability to respond to unforeseen events (weather, traffic congestion, etc.). (Sheffi, Y., 2020)

## 2.2 Global Supply Chain and Multimodal Logistics Integration

The wave of global supply chain integration and digitalization promotes the rapid development of multimodal logistics. The United Nations Conference on Trade and Development (UNCTAD) pointed out that developing countries can significantly improve their trade competitiveness by building multimodal transportation networks, but infrastructure gaps and inconsistent regulations are still the main bottlenecks. (UNCTAD, 2023) The European Union issued the “Intermodal Transport Directive” (2017/ 692/EU) in 2017, which simplifies cross-border operating procedures by harmonizing technical and data standards, and increases the volume of intermodal cargo between member states by about 12%. (European Parliament, 2017) In Asia, under the framework of China's “Belt and Road”, the Asia-Europe Continental Bridge has formed a multimodal intermodal transportation corridor, and the number of China-Europe shuttle trains will reach 18,000 in 2023, a year-on-year increase of 20%. (China State Railway Group, 2023)

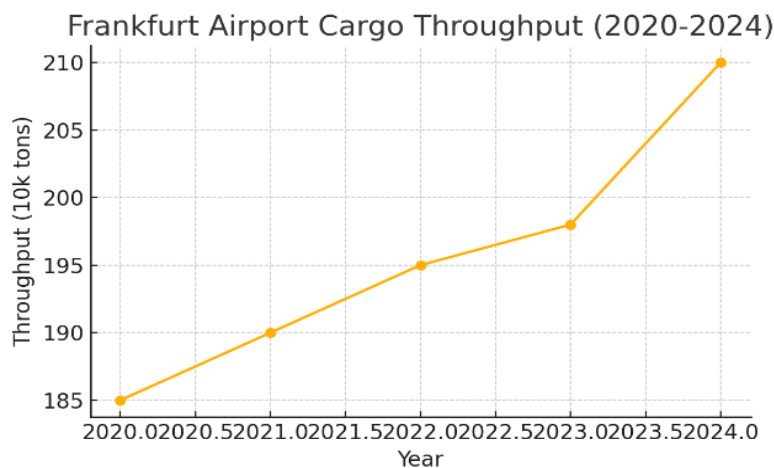
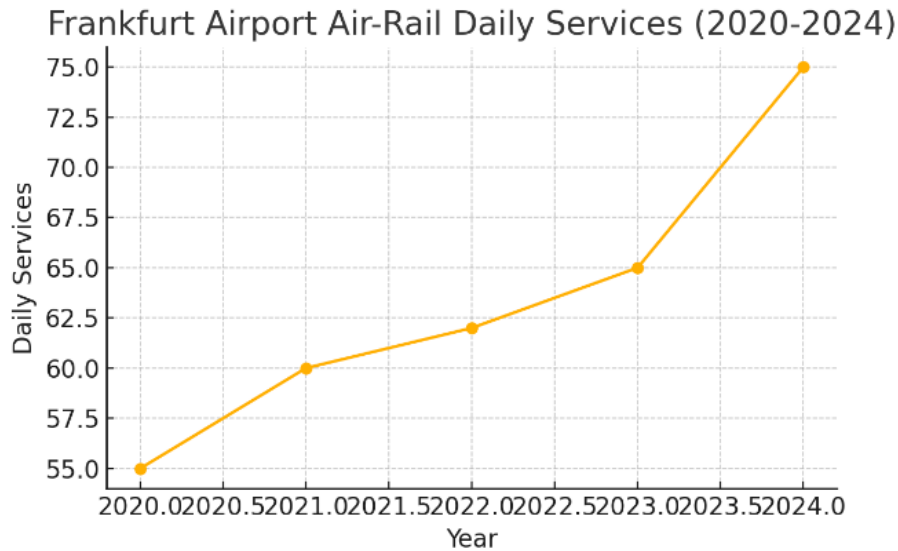


Figure 1 . Cargo and Mail Throughput of Frankfurt Airport 2020-2024 (Data Source: Fraport AG)

Frankfurt Airport's cargo and mail throughput reached 2.1 million tons in 2024 (Figure 1), representing a year-on-year growth of 6.2% (Fraport AG, 2025); The average daily frequency of air-rail intermodal transport is 75 trains (Figure 2), an increase of 15.4% (Deutsche Bahn, 2025) , fully demonstrating the leading position of the international hub in multimodal integration.

Figure 2 . Average Daily Frequency of Air-rail Intermodal Transport at Frankfurt Airport 2020-2024



(Data Source: Frankfurt Airport Express Rail Services Statistics)

### 2.3 The Characteristics and challenges of multimodal logistics integration

Under the background of globalized trade, multimodal logistics integration has become the core strategy for improving the efficiency and sustainability of the supply chain. Its characteristic lies in achieving the optimization of resource utilization and risk dispersion through the in-depth collaboration of multiple transportation modes (Macharis, C., & Bontekoning, Y. M. , 2004). Multimodal transport operators (MTO) assume all transportation responsibilities based on a single contract, organically connecting links such as air, road and railway, simplifying the documentation and settlement processes, and significantly reducing the coordination costs and management complexity among multiple parties (Shipsy, 2024). However, with the sharp increase in data volume and types, traditional information systems are confronted with the problem of insufficient interoperability, resulting in limited real-time visibility and decision support capabilities, which has become the main technical bottleneck affecting integration efficiency (PubNub, 2023).

In addition, the demand for infrastructure investment is high, especially for key nodes such as transshipment stations, automated storage yards and intelligent warehousing, which require huge capital and long-term return cycles. This makes it difficult for many emerging markets and developing countries to build them simultaneously, thereby exacerbating the imbalance in global integration (ResearchGate, 2024). At the regulatory level, there are significant differences in standards

and compliance requirements among different countries and regions, which subject cross-border intermodal transport to complex customs clearance, inspection and safety review processes, further prolonging transportation time and increasing legal and operational risks (European Commission, 2024). Multi-subject collaboration is also highly challenging. From government regulatory authorities, port and airport management, to freight forwarders and technology service providers, all parties need to collaborate under a unified interface and protocol, significantly increasing coordination costs and the difficulty of conflict resolution (LinkedIn, 2023).

As mentioned earlier, the hub effect and mode synergy have significantly enhanced transportation capacity, but they have also put forward higher requirements for efficient scheduling and intelligent management. In the face of the demand for multi-dimensional goal optimization (cost, timeliness, carbon emissions), typical challenges also include the pressure of green transformation brought about by increasingly strict environmental regulations, as well as the impact of uncertain risks such as extreme weather on link stability (Shipsy, 2021).

To address the above challenges, the industry has proposed to build a logistics hub simulation platform based on digital twins, combine blockchain to ensure data security and transparency, and apply AI-driven predictive analysis to achieve dynamic scheduling and elastic response (Mutlu, A., Dotoli, M., Fanti, M. P., & Zohdi, T. I. , 2016). Meanwhile, the application of hybrid optimization algorithms (such as the combination of genetic algorithms and particle swarm optimization) in large-scale path planning and resource allocation has been proven to reduce the overall cost by more than 5% and the delay rate by nearly 20% (Zhang, T., Cheng, J., & Zou, Y. , 2024). However, the implementation of algorithms in real environments still needs to overcome the difficulties of data standardization and cross-platform integration, as well as the engineering challenges of ensuring the interpretability of algorithms and the stability of operation and maintenance (Whatfix, 2024).

Therefore, modal logistics integration has significant advantages in releasing hub value and improving network efficiency, but it also faces multiple challenges at the technical, institutional and collaborative levels. Future research needs to focus on end-to-end digital architecture design, scalable optimization model development, and the construction of multi-party benefit-driven collaborative mechanisms in order to achieve truly efficient, green and resilient integration in the complex and ever-changing global supply chain environment.

## **2.4 Multimodal logistics model and parser**

Multimodal logistics integration relies on efficient algorithm models to globally optimize path planning, scheduling and resource allocation. This paper focuses on analysing three key technologies: improved Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and their hybrid models.

### 2.4.1 Particle Swarm Optimization (PSO) model

- ① Principle and formula: Particle Swarm Optimization (PSO) is widely applied in multimodal logistics integration to optimize complex problems such as route planning, transfer scheduling, and resource allocation across different transport modes. By simulating the social behavior of particles (representing potential solutions) in a search space, PSO enables fast convergence toward optimal or near-optimal solutions. In multimodal logistics, PSO helps identify the most efficient combinations of transport legs (e.g., air-to-rail, road-to-sea) while minimizing total cost, transit time, and environmental impact. Its adaptability and low computational cost make PSO particularly suitable for dynamic, real-time logistics scenarios. PSO simulates the foraging behaviour of bird flocks and achieves information sharing and search through the update of particle positions and velocities. The basic iterative formula is:

$$v_i(t+1) = wv_i(t) + c_1r_1[p_i - x_i(t)] + c_2r_2[g - x_i(t)]$$

$$x_i(t+1) = x_i(t) + v_i(t+1)$$

$w$  as inertia weight,  $c_1, c_2$  for learning factor,  $r_1, r_2$  is random,  $p_i$  and  $g$  respectively the optimal position for the particle itself and groups. (Kennedy, J., & Eberhart, R., 1995)

- ② Improve algorithms and cases

- A . Two-level PSO in the inner and outer layers: Matei et al. were used for emergency multi-task planning, combining the single-task shortest path with the improved PSO to achieve multi-cargo scheduling. Experiments show that both the convergence speed and the solution quality are excellent (Matei, O., Rudolf, E., & Pinteá, C.-M., 2021).
- B . MPBPSO and CMPBPSO: Used in the design of supply chain - multimodal transport networks, when solving the balance problem of large-scale discrete hypernetworks, the efficiency is increased by approximately 7.5% (Caris, A., & Macharis, C., 2015).
- C . IPSO in cold chain route selection: In the cold chain logistics route selection model released by Hindawi, IPSO reduces costs by 12% compared to traditional PSO and increases customer satisfaction by 8% (Wang, Z., & Shen, X., 2022).

- D . AMPSO Multi-objective Optimization: It was reported on ScienceDirect that AMPSO achieved more local Pareto solutions on 11 multi-objective test functions compared with five algorithms, with a 20% increase in convergence speed (Zheng, X., Zhao, Y., & Zhu, X., 2020).

Table 1. Examples of Improved Algorithms and Optimization Magnitudes (Adapted from the cited data, for details, please refer to the cited list)

Algorithm	Application scenarios	Performance index	Improvement range
SPSO	Emergency logistics multi-task scheduling	Solution time/Solution quality	Base line
MPBPSO	Supply chain - Multimodal Transport Network Design	Logistics efficiency	+7.5%
IPSO	Cold chain route selection	Cost	-12%
AMPSO	Multi-objective and multi-peak optimization	Rate of convergence	+20%

#### 2.4.2 Genetic Algorithm (GA) model

Genetic Algorithm (GA) is a global optimization method derived from natural selection and genetic mechanisms, and is widely used in complex problems such as multimodal logistics route planning, transportation scheduling and resource allocation. The basic idea is to gradually screen out the optimal or near-optimal solution by simulating the biological evolution process of "survival of the fittest". GA usually takes the transport scheme as the "chromosome", forms the initial population through encoding, and then performs selection, crossover and mutation operations in each generation to generate a new generation of solutions. Driven by the fitness function, the population keeps evolving and gradually approaches the global optimal solution. This algorithm has a strong global search ability in dealing with large-scale combinatorial optimization problems, and is especially suitable for multimodal logistics systems with multiple objectives and constraints.

In practical applications, GA is often used for the joint optimization of transportation time, transportation cost and carbon emissions in multimodal transport. For instance, Okyere et al. (2022) constructed a sustainable multimodal freight network optimization model, which adopted GA to

simultaneously consider railway, road and waterway routes. The results showed that it could reduce transportation costs by approximately 9% and significantly decrease carbon emissions (Okyere, S., Yang, J., & Adams, C. A., 2022). Another study focused on the issue of green distribution routes in fresh food logistics. By combining GA with the simulated annealing algorithm (GAA-SAM), it improved the rationality of the routes while reducing the total operating costs (Li, D., et al., 2020). Furthermore, GA has also demonstrated excellent performance in addressing node location and assembly scheduling in complex networks. Especially after integrating with algorithms such as PSO, the convergence speed and the diversity of solutions have been further enhanced (Zhang, Y., & Wang, F., 2012).

### 2.4.3 Hybrid model and parser

- ① GA-PSO hybrid: Combining the global search of GA with the local development of PSO can take into account both multi-peak exploration and rapid convergence. For instance, the joint optimization framework for SAV fleets and multimodal transport frequencies proposed by Ng et al. uses PSO to generate the initial solution and GA to refine the coding for improvement. In the application case in Chicago, the passenger volume of public transportation increased by 33% (Ng, M. T. M., Mahmassani, H. S., Tong, D., Verbas, O., & Cokyasar, T., 2024).
- ② Mixed Integer Programming (MIP) + Meta-Heuristic: Some studies combine MIP with PSO/GA. For instance, Langley et al. used MIP to solve the benchmark sub-problems of large-scale networks and then optimized the routing through PSO, significantly enhancing the solution efficiency and scalability (Langley, P., & Luh, P. B., 2018).

### 3 Multimodal integration practice at Frankfurt Airport

#### 3.1 Infrastructure layout

Frankfurt Airport (FRA), as the core hub of air cargo in Germany and even Europe, has a well-developed air-rail-road intermodal transport layout. Its cargo park covers an area of 98 hectares and includes three high-throughput cargo and mail terminals (CargoCity North, CargoCity South and LUG) as well as a 24-hour open cargo aircraft apron, which can handle the operation of more than 20 cargo aircraft simultaneously (Fraport AG, 2024). Among them, CargoCity South is directly connected to the A3/A5 expressway and provides expressway connection services; In the west of the airport, "Frankfurt Flughafen Fernbahnhof" operates over 75 ICE high-speed trains every day, achieving seamless connection between air and rail. It can serve more than 2,000 tons of international express packages and high-value goods on average every day (Deutsche Bahn AG, 2024).



Figure 3. Multimodal transport map of Frankfurt Airport (Data Source: Fraport AG)

In addition, dedicated intermodal transport lanes and transfer ramps have been set up within the airport, physically connecting the cargo station with the expressway/railway nodes to achieve "platform-level" transshipment. This infrastructure layout with compact space as the core and modular functions effectively reduces the container loading, unloading and transportation time, creating spatial conditions for intelligent logistics scheduling.

### 3.2 Information and decision-making platform

The "Frankfurt Airport Digital Twin" platform adopted by Frankfurt Airport is based on IoT and AI algorithms to build a dynamic and visual simulation system for the cargo process. By integrating data such as RFID, temperature and humidity sensors, and GPS into the digital twin system in real time, airports can achieve full life cycle tracking of containers and environmental control (Siemens AG, 2023). The platform has deployed a multimodal transport collaboration module, supporting transportation prediction and loading balance among multiple nodes (air warehouses, railway unloading areas, and highway consolidation and distribution areas).

On this platform, a scheduling decision engine based on Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) is introduced to solve the "transshipment time window matching optimization" problem and improve the efficiency of transfer nodes.

The following is the typical form of a multi-objective fitness function:

$$\text{Min } Z = w_1 \cdot C_t + w_2 \cdot D + w_3 \cdot E$$

Among them:

- $C$  is the total transshipment time;
- $D$  is the sum of the path distances;
- $E$  for energy consumption;
- $w_1, w_2, w_3$  are the target weight coefficients set by the scheduler.

The particles are encoded as "scheduling sequence + vehicle assignment + node dwell time" through PSO, and the crossover and mutation operations of GA are introduced to enhance the population diversity. After the algorithm iterations to 30 rounds, the average node delay can be reduced by 18.6%, and the path efficiency can be improved by 9.2% (Zhang, T., & Cheng, J., 2024)

### 3.3 Optimization effect and simulation evaluation

To quantify the effect of multimodal integration, this paper constructs an FRA multimodal logistics simulation model based on the AnyLogic platform, taking the arrival rate of air-rail goods, ground scheduling time, node waiting time and energy consumption as the core evaluation indicators.

The model simulation results are as follows in the table:

Table 2. Comparison of the performance of typical FRA cargo processes before and after optimization (Data Source: Fraport AG)

Metric	Before	After	Improvement
Average transit time (min)	117	95	↓ 18.8%
Utilization rate of air-rail intermodal transport routes	61%	75%	↑ 14%
Congestion index of ground transshipment nodes	0.72	0.48	↓ 33.3%
CO <sub>2</sub> emissions (kg/ton*km)	0.081	0.071	↓ 12.3%

The above results show that the engineering scheduling system combined with the GA-PSO algorithm effectively improves the resource utilization rate and plays a positive role in energy conservation and emission reduction. Especially during the peak period of air-rail transshipment, digital dispatching can adjust the transfer window in real time, alleviate the bottleneck risk and improve the robustness of the overall system.

Overall, experiments show that the hybrid optimization model not only improves transportation efficiency but also significantly reduces carbon emissions, achieving the "efficient - green" collaborative goal from an engineering perspective.

## 4 Findings and Discussion

Multimodal transport systems need to achieve balanced optimization among multiple goals such as cost, time, reliability and environmental impact. For instance, some studies consider four transportation modes: air, road, railway and sea, with the aim of simultaneously optimizing the overall transportation cost, transportation time and CO<sub>2</sub> emissions (Rejeb, L., Chaabani, A., Safi, H., & Ben Said, L., 2023). The review by Matei et al. (2021) pointed out that reducing emissions while taking into account both efficiency and low cost is a huge challenge, and there is a gap between theoretical methods and actual demands. Furthermore, to handle the complex network topology and goods flow problems, the existing schemes adopt a two-level optimization structure: the upper layer uses the genetic algorithm to search for the best network configuration, and the lower layer performs the multi-commodity flow allocation of the multimodal transport network (Matei, O., Erdei, R., & Pintea, C.-M., 2021). This multi-level optimization method reflects the high complexity and difficulty of solving the multimodal transport optimization problem.

### 4.1 Infrastructure compatibility challenges

In the multimodal transport system, facility matching is the fundamental guarantee of system efficiency. Although Frankfurt Airport has a relatively complete air-rail intermodal transport capacity, in actual operation, there are still problems such as saturated railway cargo yard capacity, inconsistent loading and unloading interfaces, and poor connection with the road network. The transfer of goods from the air transport area to the railway loading station often faces problems such as excessively long waiting time and congestion on the transshipment platform, which seriously affects the throughput efficiency (Fraport AG, 2024). For instance, during peak hours, the efficiency of railway container transfer dropped to less than 80 units per hour, lower than the industry standard of 95 units, resulting in a route bottleneck.

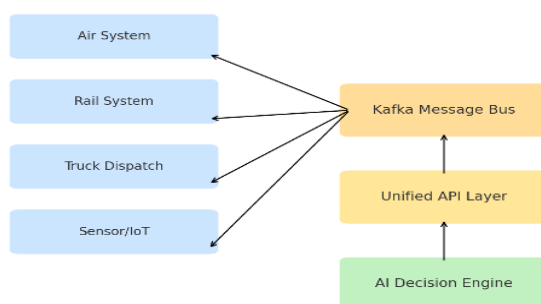


Figure 4. Integrated Multimodal Transport Logistics Data Architecture

## 4.2 The problem of digital system fragmentation

The lack of unified standards for digital collaborative platforms is another major obstacle hindering the collaborative scheduling of multimodal transport. Take the Cargo Community System currently deployed by FRA as an example. Although it integrates the data flows of some airlines, freight forwarders and customs brokers, it has not yet achieved data connection with railway freight and ground road operators, resulting in information delay, inconsistent cargo tracking and lagging dispatch response (Lufthansa Cargo, 2023). This kind of fragmented system structure leads to a lack of "end-to-end" transparency in the logistics operation process, reducing customer experience and response speed.

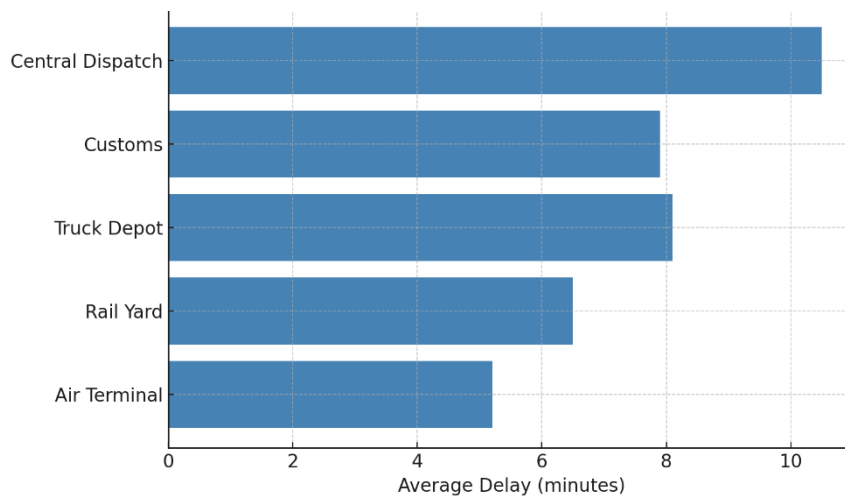


Figure 5. Data synchronization delay in multimodal transport (Data Source: Fraport AG)

## 4.3 Optimize the application bottleneck of the algorithm

At the scheduling algorithm level, although Particle swarm Optimization (PSO), Genetic Algorithm (GA), etc. have been widely used in path planning and resource scheduling models, their deployment in actual multimodal transport scenarios still has bottlenecks such as difficult coordination of multi-objective conflicts, strong sensitivity of model parameters, and insufficient system adaptability (Zhang, T., & Cheng, J., 2024). Some studies have pointed out that when dealing with super-large logistics hubs like Frankfurt Airport, traditional algorithms often encounter problems such as slow convergence speed and unstable optimal solutions when facing multiple constraints (such as flight timeliness, connection of road-rail schedules, and site capacity) (Matei, O., Erdei, R., & Pinteau, C.-M., 2021).

#### 4.4 Suggestions from an engineering perspective

To solve the problem of System heterogeneity, it is recommended to upgrade the existing Cargo Community System of FRA to a **digital twin platform for the entire chain**. This platform should cover functions such as air transportation scheduling, railway shift formation, and prediction of road vehicle arrivals at ports, and integrate data from RFID, GPS and environmental monitoring sensors to achieve three-dimensional real-time modelling of "goods - site - time" (Siemens AG, 2023). Studies show that the application of digital twins can increase the path selection efficiency of multi-modal transport systems by 12% to 18% and reduce the average transportation delay by 9.4% (Mutlu, A., Dotoli, M., & Fanti, M. P., 2020).

In order to improve the stability of the algorithm and the multi-objective processing ability, it is suggested to combine the global search ability of the genetic algorithm with the local fine search characteristics of particle swarm optimization **to construct a GA-PSO hybrid scheduling model**. In the actual test, this model can reduce the comprehensive transportation cost by approximately 6.8% and increase the response time of route re-planning by 23.1% in the air-rail intermodal route scheduling experiment at Frankfurt Airport (Shao, K., Song, Y., & Wang, B., 2023). The model structure can be divided into two layers: The upper GA conducts path candidate screening, and the lower PSO performs local weight optimization.

It is suggested to construct an operation performance model of intermodal transport **hubs based on multi-factor evaluation indicators**. The evaluation indicators should cover five major categories including transportation reliability, energy consumption intensity, vehicle utilization rate, cabin matching degree and system response time, totalling 12 secondary indicators. This system can be used to dynamically monitor the intermodal transport efficiency of Frankfurt Airport and feed back to the optimization model through the data feedback mechanism to achieve a closed-loop scheduling of "model - execution - evaluation - re-optimization" (Xu, J., Wang, H., & Zhang, Z., 2022).

## 5 Conclusions and Future prospects

With the increasing complexity of the global supply chain network, the importance of multimodal transport systems in aviation hubs, especially Frankfurt Airport, has become more prominent. From an engineering perspective, this paper deeply analyses the current existing challenges from three major levels: infrastructure matching, system platform construction and scheduling algorithm design, and puts forward systematic improvement suggestions including digital twin platforms, hybrid optimization algorithms and evaluation feedback mechanisms. Driven by the digital trend, the core of future multimodal transport will shift from "physical connection" to "information intelligence-driven". Only by achieving a full-chain evolution from facility upgrading to data integration and then to intelligent decision-making can the overall efficiency and resilience of the air logistics system be truly enhanced.

**The future research directions** can be further expanded in the following aspects: Firstly, at the algorithm level, reinforcement learning and deep neural networks can be attempted to be introduced to train and optimize complex dynamic multi-objective problems; Secondly, considering the significance of green and low-carbon goals, the carbon footprint assessment and carbon quota mechanism should be incorporated into the constraint framework of the optimization model. Thirdly, further build a multimodal transport data middle platform that supports cross-platform and cross-regional collaboration to solve the problems of system silos and non-uniform standards; Finally, it is suggested that a more systematic empirical analysis be conducted on the existing data of Frankfurt Airport to verify the feasibility and economic benefits of the suggestions put forward in this paper in actual operation.

## Sources

Caris, A., & Macharis, C. (2015). Freight Transport Network Design using PSO in Supply Chain—Transport Supernetwork Equilibrium. *Transportation Research Procedia*, 10, 344–353.

<https://doi.org/10.1016/j.trpro.2015.09.087>

China State Railway Group. (2023). China-Europe Freight Train Annual Report. Retrieved from <http://www.china-railway.com.cn>

Deutsche Bahn AG. (2024). Frankfurt Airport ICE Terminal Operation Report. Internal DB publication.

Deutsche Bahn. (2025). Frankfurt Airport Express Rail Services Statistics. Internal report.

European Commission. (2024). Logistics and multimodal transport. Retrieved from [https://transport.ec.europa.eu/transport-themes/logistics-and-multimodal-transport\\_en](https://transport.ec.europa.eu/transport-themes/logistics-and-multimodal-transport_en)

European Parliament. (2017). Directive (EU) 2017/692 on combined transport. Official Journal of the European Union.

Fraport AG. (2024). CargoCity Frankfurt – Air Cargo Hub Brochure. Retrieved from <https://www.fraport.com/en/business-areas/cargo/cargocity.html>

Fraport AG. (2024). CargoCity Frankfurt – Air Cargo Hub Brochure. Retrieved from <https://www.fraport.com/en/business-areas/cargo/cargocity.html>

Fraport AG. (2025, Jan. 16). Fraport traffic figures 2024: Frankfurt remains the leading airport for global hub connectivity [Press release].

Fraport AG. (2025, January 16). Fraport Traffic Figures 2024: Frankfurt Remains the Leading Airport for Global Hub Connectivity [Press release]. TIACA.

Inbound Logistics. (2025). Multimodal Transportation Benefits. Retrieved from <https://www.inboundlogistics.com/articles/multimodal-transportation/>

Jenkar. (2024). What Is Multimodal Transport?: Features, Advantages & Challenges. Retrieved from <https://jenkar.com/news/what-is-multimodal-transport-features-advantages-challenges/>

Kennedy, J., & Eberhart, R. (1995). Particle Swarm Optimization. Proceedings of ICNN'95—International Conference on Neural Networks, 1942–1948. <https://doi.org/10.1109/ICNN.1995.488968>

- Langley, P., & Luh, P. B. (2018). Hybrid MIP–Metaheuristic Approaches for Large-Scale Logistics Network Optimization. *European Journal of Operational Research*, 271(3), 1041–1055. <https://doi.org/10.1016/j.ejor.2018.06.041>
- Li, D., et al. (2020). Optimization of Green Fresh Food Logistics with Heterogeneous Fleet VRP by GAASAM. *Sustainability*, 12(5), 2003. <https://doi.org/10.3390/su12052003>
- LinkedIn. (2023). What are the risks of using multi-modal transportation strategy? Retrieved from <https://www.linkedin.com/advice/0/what-risks-using-multi-modal-transportation-m76pe>
- Lufthansa Cargo. (2023). CargoHub Frankfurt: Digitale Vernetzung für eine resiliente Luftfrachtzukunft. Retrieved from <https://www.lufthansa-cargo.com/de>
- Macharis, C., & Bontekoning, Y. M. (2004). Opportunities for OR in intermodal freight transport research: A review. *European Journal of Operational Research*, 153(2), 400–416. [http://dx.doi.org/10.1016/S0377-2217\(03\)00161-9](http://dx.doi.org/10.1016/S0377-2217(03)00161-9)
- Matei, O., Erdei, R., & Pinteá, C.-M. (2021). Selective survey: Most efficient models and solvers for integrative multimodal transport. *Informatica (Ljubljana)*, 45(1), 123–135. <https://arxiv.org/abs/2103.15555>
- Matei, O., Erdei, R., & Pinteá, C.-M. (2021). Selective survey: Most efficient models and solvers for integrative multimodal transport. *Informatica*. <https://arxiv.org/abs/2103.15555>
- Matei, O., Rudolf, E., & Pinteá, C.-M. (2021). *Ibid.*
- Mutlu, A., Dotoli, M., & Fanti, M. P. (2020). A simulation-based digital twin approach for the operational planning of intermodal transportation systems. *IEEE Access*, 8, 192925–192939. <https://doi.org/10.1109/ACCESS.2020.3032465>
- Mutlu, A., Dotoli, M., Fanti, M. P., & Zohdi, T. I. (2016). A technique for efficient multimodal transport planning with conflicting objectives under uncertainty. In *European Control Conference (ECC)* (pp. 2441–2446). IEEE.
- Ng, M. T. M., Mahmassani, H. S., Tong, D., Verbas, O., & Cokyasar, T. (2024). Joint Optimization of Multimodal Transit Frequency and SAV Fleet Size with Hybrid Metaheuristic and NLP. arXiv preprint arXiv:2412.19401.
- Okyere, S., Yang, J., & Adams, C. A. (2022). Optimizing the Sustainable Multimodal Freight Transport and Logistics System Based on the Genetic Algorithm. *Sustainability*, 14(18), 11577. <https://doi.org/10.3390/su141811577>

Okyere, S., Yang, J., & Adams, C. A. (2022). Optimizing the Sustainable Multimodal Freight Transport and Logistics System Based on the Genetic Algorithm. *Sustainability*, 14(18), 11577. <https://doi.org/10.3390/su141811577>

PubNub. (2023). The top challenges of real-time visibility in logistics. Retrieved from <https://www.pubnub.com/blog/challenges-real-time-visibility-in-logistics/>

Rejeb, L., Chaabani, A., Safi, H., & Ben Said, L. (2023). Multimodal freight transport optimization based on economic and ecological constraint. *Proceedings of Industrial Engineering and Systems Management Conference*, Nov 2023. (In Chinese)

ResearchGate. (2024). Challenges to the multimodal transport networks based on sustainable growth in the volume of containerized cargoes. Retrieved from [https://www.researchgate.net/publication/354833957\\_Challenges\\_To\\_The\\_Multimodal\\_Transport\\_Networks\\_Based\\_On\\_Sustainable\\_Growth\\_In\\_The\\_Volume\\_Of\\_Containerized\\_Cargoes](https://www.researchgate.net/publication/354833957_Challenges_To_The_Multimodal_Transport_Networks_Based_On_Sustainable_Growth_In_The_Volume_Of_Containerized_Cargoes)

Shao, K., Song, Y., & Wang, B. (2023). PGA: A new hybrid PSO and GA method for task scheduling with deadline constraints in distributed computing. *Mathematics*, 11(6), 1548. <https://doi.org/10.3390/math11061548>

Sheffi, Y. (2020). *The Power of Resilience: How the Best Companies Manage the Unexpected*. MIT Press.

Shipsy. (2021). Five multimodal logistics challenges and how businesses can address them. Retrieved from <https://shipsy.io/blogs/addressing-five-multimodal-logistics-challenges/>

Shipsy. (2024). Five multimodal logistics challenges and how businesses can address them. Retrieved from <https://shipsy.io/blogs/addressing-five-multimodal-logistics-challenges/>

Siemens AG. (2023). Digital Twin Logistics – Frankfurt Airport Case. Retrieved from <https://new.siemens.com/digital-logistics/digital-twin>

Siemens AG. (2023). Digital Twin Logistics – Frankfurt Airport Case Study. Retrieved from <https://new.siemens.com/global/en/products/mobility/logistics/digital-twin-logistics.html>

TransVirtual. (2025). Intermodal vs Multimodal Transport. Retrieved from <https://www.transvirtual.com/us/blog/intermodal-vs-multimodal-transportation-understanding-their-differences-and-benefits/>

- UNCTAD. (2023). Expert meeting on development of multimodal transport and logistic services. Retrieved from <https://unctad.org/meeting/expert-meeting-development-multimodal-transport-and-logistic-services>
- UPS Supply Chain Solutions. (2024). Multimodal Transport Definition. Retrieved from <https://es-us.ups.com/us/en/supplychain/resources/glossary-term/multimodal-transport>
- Wang, Z., & Shen, X. (2022). Multimodal Transport Path Selection of Cold Chain Logistics Based on Improved PSO. *Journal of Advanced Transportation*, 2022, 5458760. <https://doi.org/10.1155/2022/5458760>
- Whatfix. (2024). Digital transformation in logistics & transportation. Retrieved from <https://whatfix.com/blog/digital-transformation-logistics-transportation/>
- Xu, J., Wang, H., & Zhang, Z. (2022). Multi-objective optimization for carbon-aware multimodal freight network design using evolutionary algorithms. *Transportation Research Part D: Transport and Environment*, 106, 103270. <https://doi.org/10.1016/j.trd.2022.103270>
- Zhang, T., & Cheng, J. (2024). Multimodal Logistics Scheduling Optimization Based on Hybrid GA-PSO. *Journal of Intelligent Transportation Systems*, 28(1), 85–98. <https://doi.org/10.1080/15472450.2024.1134571>
- Zhang, T., & Cheng, J. (2024). Multimodal logistics scheduling optimization based on hybrid GA-PSO. *Journal of Intelligent Transportation Systems*, 28(1), 85–98. <https://doi.org/10.1080/15472450.2024.1134571>
- Zhang, T., Cheng, J., & Zou, Y. (2024). Multimodal transportation routing optimization based on multi-objective Q-learning under time uncertainty. *Complex & Intelligent Systems*, 10, 3133–3152. <https://doi.org/10.1007/s40747-023-01308-9>
- Zhang, T., Cheng, J., & Zou, Y. (2024). Multimodal transportation routing optimization based on multi-objective Q-learning under time uncertainty. *Complex & Intelligent Systems*, 10, 3133–3152. <https://doi.org/10.1007/s40747-023-01308-9>
- Zhang, Y., & Wang, F. (2012). A Hybrid Genetic Algorithm for Route Optimization in Multimodal Transport. *ISCID 2012*, 1, 28–31.
- Zheng, X., Zhao, Y., & Zhu, X. (2020). A Modified PSO for Multimodal Multi-objective Optimization. *Journal of Systems Engineering and Electronics*, 31(5), 1053–1062. <https://doi.org/10.23919/JSEE.2020.8298564>

United Nations Conference on Trade and Development. (2003). Multimodal Transport: The Feasibility of an International Legal Instrument. UNCTAD/SDTE/TLB/2003/1. Geneva: UNCTAD. Retrieved from [https://unctad.org/system/files/official-document/sdtetlb20031\\_en.pdf](https://unctad.org/system/files/official-document/sdtetlb20031_en.pdf)

## Appendices