

Article

A System Dynamics Model of Multi-Airport Logistics System under the Impact of COVID-19: A Case of Jing-Jin-Ji Multi-Airport System in China

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Abstract: The development of a multi-airport logistics system (MLS) is closely linked to factors such as regional economy, international and domestic trade, competitive synergies between airports, and the impact of unforeseen events such as the COVID-19 outbreak. There are various causal relationships and feedback loops within the MLS, and it is always in a dynamic state of change, so it is ideal to use a system dynamics model to depict the MLS. Taking the Jing-Jin-Ji MLS as an example, a system dynamics model consisting of an economy subsystem, a trade subsystem, and an airport cluster subsystem is constructed, and the sustainable development of the MLS is studied by simulating three pandemic scenarios with different impact levels. At the same time, different policy simulations and sensitivity analyses are used to find effective strategies to enhance the sustainable development of the Jing-Jin-Ji MLS. The results can provide an effective method for forecasting air cargo volumes in the MLS under the COVID-19 pandemic and provide a basis for the relevant departments to formulate policies for the development of the MLS.

Keywords: multi-airport logistics; sustainability; system dynamics; COVID-19; Jing-Jin-Ji



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1. Introduction

Air logistics is the backbone of global supply chains. The cargo of air freight accounts for less than 1% of global trade by volume and more than 30% by value [1]. In particular, since the COVID-19 pandemic outbreak, air logistics has played an important role in combating the pandemic and ensuring the stability of the supply chain by virtue of its high speed and mobility. Therefore, a simulation study on the development of air logistics systems under the influence of the COVID-19 pandemic is important for planning the development strategy of airport logistics, boosting the growth of regional industries, and enhancing regional economy sustainable development.

It is important to note that the development of the multi-airport logistics system (MLS) is much more complex than that of the single-airport logistics system. Firstly, the MLS is not only affected by regional economy and social and policy contingencies such as the COVID-19 pandemic but also by the relationship between airports. Secondly, as multiple airports in the region share the same cargo hinterland, each airport must differentiate its positioning and develop in synergy to achieve sustainable development of regional air logistics. Thirdly, old airports may be retired, and new airports may come into operation in the multi-airport system, so we are unable to use traditional forecasting methods to predict the development trend of MLS. Therefore, it is very important to find an appropriate method to study the development trends and design policies for the MLS under the impact of the COVID-19 pandemic.

The multi-airport system in Beijing, Tianjin, and Hebei (the Jing-Jin-Ji) region is one of three world-class multi-airport systems in China and is responsible for around 10% of China's air cargo traffic. The Chinese government has been committed to promoting the integration and synergistic development of the Jing-Jin-Ji region and elevated it to the

level of a national strategy. In this policy background, the sustainability of the Jing-Jin-Ji MLS has become a hot topic of national concern and has received widespread attention. In September 2019, the commissioning of Beijing Daxing Airport and the shutdown of Beijing Nanyuan Airport brought big changes to the Jing-Jin-Ji MLS. Later, in December 2019, the COVID-19 pandemic created a huge impact on the development of the Jing-Jin-Ji MLS, and the impact is still ongoing. Therefore, the outlook for the Jing-Jin-Ji MLS remains uncertain.

On this basis, we adopt a system dynamics (SD) method to construct a system dynamics model of the Jing-Jin-Ji MLS, which consists of an economy subsystem, a trade subsystem, and an airport cluster subsystem. In the same time, we consider the impact of the COVID-19 pandemic on each system to study the effective means of enabling sustainable development of the MLS.

The remainder of this paper is structured as follows. Section 2 reviews the study of the air transport industry under the COVID-19 pandemic and the development forecast of MLS and the SD method. Section 3 introduces the MLS in the study area of Jing-Jin-Ji region in China. Section 4 describes the data, methodology, and the SD model employed in this study. Section 5 presents the empirical results and discussion. Finally, Section 6 summarises the findings and future policy implications.

2. Literature Review

2.1. Air Transport Industry under the Impact of the COVID-19 Pandemic

Since the outbreak of the COVID-19 pandemic, studies on the air transport industry development under the pandemic have gradually increased, but most have focused on the impact on the air passenger transport industry. Gelhausen et al. [2] conducted an empirical and model-based analysis of long-term global passenger and flight volume scenarios in a post-COVID-19 world and confirmed that the capacity crunch at the airport will continue for some time after the pandemic outbreak. Florido-Benitez [3] analysed the effects of COVID-19 on airlines, airports, and the destination of Andalusia, and found that the effects of the pandemic are devastating. Kitsou et al. [4] developed a forecasting model to estimate the international passenger traffic at the Hellenic airports from August to December 2021. Zhao et al. [5,6] used the input-output method to study the industrial correlation and economic contribution of air transport in China before and after the COVID-19 pandemic. There are also additional studies related to air passenger demand recovery in light of COVID-19 [7,8], the specific behaviours of air passengers, and policies of governments in response to the pandemic [9–11]. Studies related to the air logistics industry in the context of the COVID-19 pandemic include SWOT analysis of the air cargo industry [12], sustainable development strategies for the air cargo industry [13], assessment of the pandemic impact on the air cargo and logistics industry [14], optimisation of the imbalance in air cargo demand due to the pandemic [15], and trends in the shift from price to value in the air cargo market [16]. No relevant studies have been found on the development of the MLS in the context of the COVID-19 pandemic.

2.2. Development Forecast of MLS

The study of MLS originated in the research of multi-airport systems. A multi-airport system is a set of airports that serves the airline traffic of a metropolitan area [17], which is a hot topic of research in the field of air transport. In recent years, research on multi-airport systems has focused on the multi-airport passenger markets [18–22], the evolution of spatiotemporal dynamics [23,24], and the airspace management of multi-airport systems [25–28]. There is relatively limited literature on the multi-airport system from the perspective of logistics. Shen et al. (2016) proposed the concept of MLS and finding, through a case study, that the coordination of cargo development between multiple airports in an MLS is mainly through the experience that intelligences gain from their interactions with other intelligences and with their environment [29]. However, this study only presented a broad framework for analysing the MLS and does not provide quantitative forecasts of the

development of freight volumes in the context of competitive synergies between airports within a multi-airport system.

In fact, the development forecast of MLS requires predicting cargo throughput for the entire multi-airport logistics system and for each airport within the system. Current research methods for forecasting air cargo throughput fall into two main categories, which are economic models and time-series models [30]. Economic models refer to the establishment of multiple regression models to forecast airport cargo throughput based on various influencing factors. Wu and Man [31] analysed the coupling relationship between the influencing factors of regional air transport (per capita GDP, urbanisation rate, and population density) and established multiple linear regression equations to forecast airport throughput. Time series modelling refers to trend analysis and extrapolation based on historical data of airport air cargo flow. Li et al. [32] proposed an integrated method of secondary decomposition-ensemble (SDE) approach by applying optimised ARIMA and Elman neural network (ENN) to forecast trend and low-frequency components of air cargo and integrating the forecast values of each component. However, as airports in the MLS share the same regional cargo hinterland, there is competition and cooperation between them. In addition, the MLS is often subject to various contingencies, such as the decommissioning of old airports and the commissioning of new airports, as well as the impact of the COVID-19 pandemic, which make it impossible to forecast cargo throughput from historical data. Therefore, it is not appropriate to use either of these methods to predict the airport cargo volume in the MLS. We need to find a method that not only reflects the complex relationships within the MLS, but also simulates the development of the MLS under the influence of different levels of the COVID-19 pandemic and different policies.

2.3. System Dynamics Method

The SD method, originally developed by Forrester from MIT in the 1950–1960s, is a simulation method to study many complex systems through various feedback mechanisms. It has proven to be well suited to strategic policy analysis and as a support tool for decision-making in the transport field [33,34]. In recent years, the SD model has been increasingly used for different types of transport systems. In the field of road transport research, Tolujevs et al. [35] discussed possibilities to apply the SD method for the analysis of processes at road transport enterprises. Ghisolfi et al. [36] established an SD model to evaluate the impacts of overweight in road freight transportation and proved that the best vehicle loading policy depended on the relative importance of the economic and social costs involved. In the field of metro transport research, Gao et al. [37] and Peng et al. [38] proposed macroscopic passenger flow simulation models in metro stations based on the SD method. In the field of water transport and port management research, Fu et al. [39] put forward an SD model between the container port and the port backup service and proved the port backup service elements have positive effects on the development of the container port. In the field of air transport and airport management research, Suryani et al. [40] and Tascón and Díaz [41] applied the SD method to forecast air cargo demand and air traffic. Cui et al. [42] used Structure Equation Model and SD model to research the dynamic formation mechanism of airport competitiveness. He and Wang [43] adopted the SD method to analyse the change law of airport transport corridor systems under different economic growth modes. Yoon and Jeong studied the impact of different carbon reduction policies on the international aviation industry with an SD model. Peng [44] established an SD prediction model of airport environmental carrying capacity.

As the multi-airport system is a nonlinear complex system with dynamic changes and feedback mechanisms, the SD method is a very suitable research tool for studying multi-airport systems. Wang et al. [45] established an SD model for assessing the efficiency of the Jing-Jin-Ji MLS and found that the overall efficiency of the airport group had increased year by year. However, no relevant studies using the SD method to study the development of MLS have been found.

Based on the above analysis, it is clear that the SD method is very suitable for the study of MLS. The method can not only simulate the impact of unexpected events on the air logistics industry and the competition and cooperation between different airports in an MLS but also allows for providing reliable forecasts and generating scenarios to test alternative assumptions and decisions. Therefore, we constructed an SD model to study the outlook of the Jing-Jin-Ji MLS under the COVID-19 pandemic. By combining qualitative and quantitative methods, we incorporated various influencing factors into the analytical framework, set up different pandemic scenarios, and conducted policy simulation.

3. Study Area and System Structure

3.1. Study Area

3.1.1. Jing-Jin-Ji Region

The Jing-Jin-Ji region, which includes Beijing, Tianjin, and Hebei province, is China's Capital Economic Circle. It covers a geographical area of about 216,000 square kilometers, accounting for about 2.3% of China's land area. By the end of 2021, the Jing-Jin-Ji region's resident population was around 110 million, accounting for 7.8% of China's total population. The GDP of Jing-Jin-Ji region reached \$1493.9 billion, and foreign trade reached \$688.1 billion in 2021, accounting for 8.4% and 11.4% of China's total, respectively. The trends of GDP and foreign trade in the Jing-Jin-Ji region from 2011 to 2021 are shown in Figure 1.

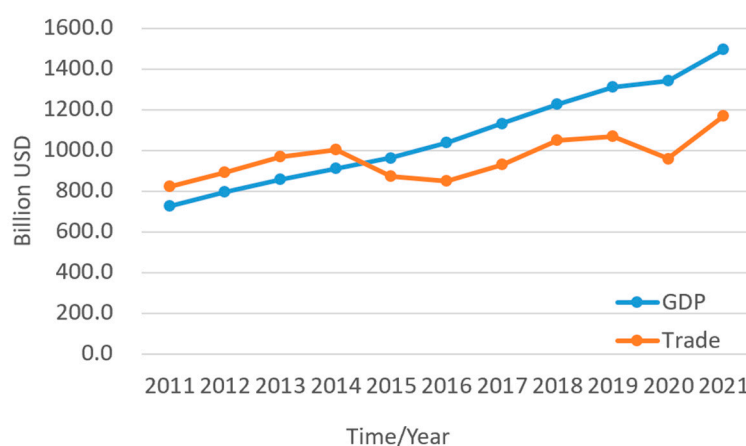


Figure 1. GDP and foreign trade of the Jing-Jin-Ji region from 2011 to 2021. Source: National Bureau of Statistics of China (<https://data.stats.gov.cn/easyquery.htm?cn=E0103>) (accessed on 7 october 2022).

3.1.2. MLS in Jing-Jin-Ji Region

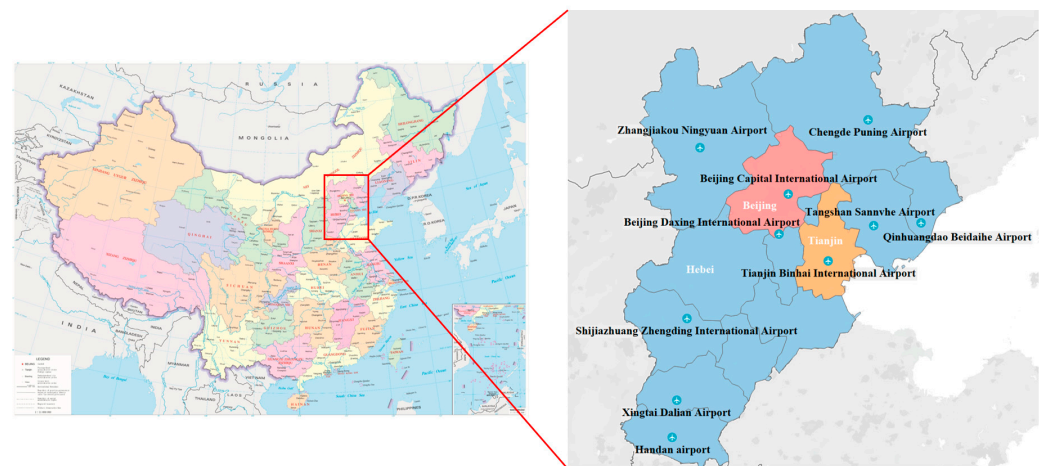
The multi-airport system in the Jing-Jin-Ji region mainly includes Beijing Capital International Airport, Beijing Daxing International Airport, Tianjin Binhai International Airport, Shijiazhuang Zhengding International Airport, and ten other small airports. The basic information of each airport is shown in Table 1, and the geographical distributions of each airport are shown in Figure 2.

The composition of air cargo traffic of the Jing-Jin-Ji MLS is shown in Figure 3. It can be found that the air cargo throughput of four major airports, Beijing Capital, Beijing Daxing, Tianjin Binhai, and Shijiazhuang Zhengding, account for more than 99%, so we focus on the air logistics development of these four airports. In addition, the air cargo throughput of Beijing Capital Airport accounts for nearly 77% in the Jing-Jin-Ji MLS. This situation has resulted in a significant imbalance in the MLS development, which is far from the goal of sustainability and transportation integration. Meanwhile, the COVID-19 pandemic has had a huge impact on the development of the Jing-Jin-Ji MLS. In 2020, the cargo throughput of the Jing-Jin-Ji MLS was 1.56 million tons, a significant drop of 30.9% from the previous year. In 2021, although it had grown to 1.82 million tons, it still has not recovered to the pre-pandemic level.

Table 1. Multi-airports system of Jing-Jin-Ji region.

NO.	Airport	IATA Code / ICAO Code	Airport Level	Passenger Volume in 2021 (Ten Thousand Passengers)	Cargo Volume in 2021 (Ten Thousand Tons)
1	Beijing Capital International Airport	PEK/ZBAA	4F	3263.9	140.12
2	Beijing Daxing International Airport	PKX/ZBAD	4F	2505.1	18.59
3	Tianjin Binhai International Airport	TSN/ZBTJ	4E	1512.7	19.49
4	Shijiazhuang Zhengding International Airport	SJW/ZBSJ	4E	645.1	3.33
5	Handan Airport	HDG/ZBHD	4C	62.4	0.08
6	Tangshan Sannvhe Airport	TVS/ZBSN	4C	39.4	0.03
7	Qinhuangdao Beidaihe Airport	BPE/ZBDH	4C	21.8	0.01
8	Chengde Puning Airport	CDE/ZBCD	4C	29.5	0.01
9	Zhangjiakou Ningyuan Airport	ZQZ/ZBZJ	4C	46.5	0.004
10	Xingtai Dalian Airport *	XNT/ZBXT	4C	-	-
	Total			8126.4	181.7

* Xingtai Dalian Airport is undergoing renovation and expansion, and it is expected to be open in 2022.

**Figure 2.** Geographical distribution of Jing-Jin-Ji multi-airport system.**Figure 3.** Air cargo throughput of Jing-Jin-Ji MLS from 2011 to 2021. Source: Civil Aviation Administration of China (http://www.caac.gov.cn/XXGK/XXGK/index_172.html?fl=11) (accessed on 7 october 2022).

3.2. System Structure of MLS

In order to systematically study how to achieve the MLS sustainability, we divide the Jing-Jin-Ji MLS into three parts, which are the Jing-Jin-Ji economy subsystem, the Jing-Jin-Ji trade subsystem, and the Jing-Jin-Ji multi-airport subsystem. These three subsystems influence and interact with each other, forming a complex system with multiple feedbacks.

3.2.1. Jing-Jin-Ji Economy Subsystem

The regional economy is fundamental to the development of the Jing-Jin-Ji MLS. To simplify the model structure, we use the GDP of the Jing-Jin-Ji region to represent its economic development level and assume that the changes in the economy are mainly represented by the rate of economic growth as well as the rate of impediment to economic development. The economic growth rate is generally determined by several factors: the amount of investment in the region; the amount of labor; the quality of the workforce; the geographical environment; the utilisation of human, material, and financial resources; and the rate of impediment are adverse factors to economic development, such as the impact of the COVID-19 pandemic.

3.2.2. Jing-Jin-Ji Trade Subsystem

The Jing-Jin-Ji trade subsystem mainly consists of domestic trade and foreign trade. Domestic trade is influenced by the economic development of each region, and foreign trade is affected by trade structure, geographical conditions, resource distribution, and other factors. Meanwhile, we use the table function to simulate the change in foreign trade each year and use the SPSS method to fit the quantitative relationship between domestic trade and the economy.

3.2.3. Jing-Jin-Ji Multi-Airport Subsystem

The Jing-Jin-Ji multi-airport subsystem consists of air cargo production, airport cargo throughput, and airport cluster coordination. Air cargo production mainly consists of economy, trade, and investment in the air transport industry by the government and the civil aviation administration. The airport cargo throughput is determined by the cargo traffic and transit volume of each airport in the Jing-Jin-Ji MLS. Airport cluster coordination is a complex concept; it includes the synergy of each airport's logistics positioning, the synergy of each airport's air logistics service chain, and the synergy of each airport and the regional economy and society. To simplify the study, the airport cluster coordination is measured only in terms of the cargo business positioning of each airport and the proportional structure of cargo throughput. According to the positioning of Tianjin Binhai Airport as an international air logistics center, and its air cargo throughput ratio only accounts for 11% of the air cargo traffic in the Jing-Jin-Ji MLS, the cargo throughput of Tianjin Binhai Airport is used to evaluate the coordination of the airport cluster (the calculation formula is shown in Table 2). In addition, the impact of the COVID-19 pandemic can cause a large number of flight cancellations, and we use table functions to simulate the impact of flight cancellations on the Jing-Jin-Ji MLS.

Table 2. Auxiliary variable data.

Auxiliary	Formula	Units
Natural rate of economic growth ¹	$[(2011,0) - (2030,1)], (2011,0.09551), (2012,0.08201), (2013,0.06209), (2014,0.05583), (2015,0.07953), (2016,0.08929), (2017,0.08207), (2018,0.06985), (2019,0.01759), (2020,0.1287), (2021,0.07594), (2025,0.07702), (2030,0.07311))$	Dmnl
Growth in economic development	$\text{GDP of the Jing-Jin-Ji region} \times \text{Natural rate of economic growth} \times \text{Airport cluster coordination}$	Billion USD
Impediments to economic development	$\text{GDP of the Jing-Jin-Ji region} \times \text{The economic impact of COVID-19}$	Billion USD
Amount invested in transportation	$\text{GDP of the Jing-Jin-Ji region} \times \text{Proportion of investment in transportation}$	Billion USD
Amount invested in air transport	$\text{Amount invested in transportation} \times \text{Government civil aviation investment policy}$	Billion USD
Amount of investment conversion ²	$0.07 \times \text{Amount invested in air transport}$	Ten thousand tons
Added value of the primary industry	$\text{Share of primary industry} \times \text{GDP of the Jing-Jin-Ji region}$	Billion USD
Added value of the secondary industry	$\text{Share of secondary industry} \times \text{GDP of the Jing-Jin-Ji region}$	Billion USD
Added value of the tertiary industry	$\text{Share of tertiary industry} \times \text{GDP of the Jing-Jin-Ji region}$	Billion USD
Airport cargo throughput ²	$\text{Airport air cargo throughput ratio} \times \text{Multi-airport system air cargo throughput}$	Ten thousand tons
Freight loss obstruction	IF THEN ELSE (Regional loss of freight > 0, Regional loss of freight, 0)	Ten thousand tons
Airport cluster coordination	IF THEN ELSE ($0.3 \leq B \text{ Airport cargo throughput} / (A \text{ Airport cargo throughput} + C \text{ Airport cargo throughput} + D \text{ Airport cargo throughput} + E \text{ Airport cargo throughput})$): AND: $B \text{ Airport cargo throughput} / (A \text{ Airport cargo throughput} + C \text{ Airport cargo throughput} + D \text{ Airport cargo throughput} + E \text{ Airport cargo throughput}) \leq 1, 1.7, 1$)	Dmnl

¹ proposed by the authors based on National Bureau of Statistics of China. ² proposed by the authors based on Civil Aviation Administration of China.

4. Data and Methodology

4.1. Data Sources

The data used in this paper were mainly provided by the National Bureau of Statistics of China (<https://data.stats.gov.cn/staticreq.htm>, accessed on 29 July 2022), which includes information on GDP, industrial value added, the domestic and foreign trade of each city, etc. We collected the annual airport air cargo throughput through the annual production statistics bulletin of the Civil Aviation Administration of China (CAAC) and the annual statistical reports on the socio-economic development of each city.

4.2. System Dynamics Model Construction

4.2.1. Cause and Effect

According to the structure of the Jing-Jin-Ji MLS, the corresponding cause-and-effect loop diagram is established, as shown in Figure 4.

The model includes three loops:

Loop 1: GDP of the Jing-Jin-Ji region → Transportation investment → Air transport investment → Multi-airport system air cargo throughput → Airport cluster coordination → GDP of the Jing-Jin-Ji region

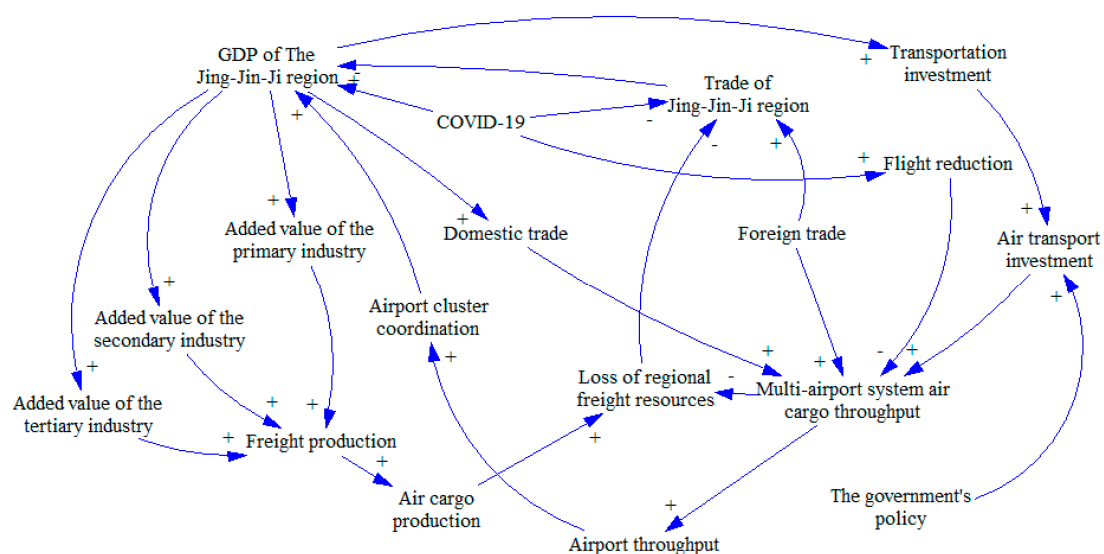


Figure 4. Causal loop diagram of Jing-Jin-Ji MLS. Notes: “+” represents the positive feedback characteristic of the loop; “-” represents the negative feedback characteristic of the loop.

Economic growth in the Jing-Jin-Ji region will lead to increased investment in transport. When the input volume of the whole transport system increases, the investment in air transport will also increase accordingly. These funds will be used to accelerate airport infrastructure development, increase cargo subsidies, and increase the proportion of regional cargo transported by air, thereby increasing airport throughput. The government can divert air cargo sources according to the functional positioning of each airport through policy regulation so that each airport can give full play to its function and improve the synergy of the MLS. In this way, it can promote the development of urban clusters and improve the sustainability of the Jing-Jin-Ji region. This loop mainly reflects the impact of changes in economic aspects on the airport cluster coordination and is a positive feedback reinforcement loop.

Loop 2: GDP of the Jing-Jin-Ji region → The added value of primary, secondary, and tertiary industries → Freight production → Air cargo production → Loss of regional freight resources → Trade of the Jing-Jin-Ji region → GDP of the Jing-Jin-Ji region

The economic development of the Jing-Jin-Ji region is closely related to regional industries, and the economic growth will inevitably increase the added value of the primary, secondary, and tertiary industries. The development of various industries will drive the development of their related logistics industry, resulting in greater demand for freight. However, since intra-regional air cargo supply resources are limited, it will result in a loss of air logistics volume and hinder the development of intra-regional trade, thus reducing economic development. This loop shows the relationship between various industries and multi-airport system air cargo throughput and is a weak loop with negative feedback.

Loop 3: GDP of the Jing-Jin-Ji region → Domestic trade → Multi-airport system air cargo throughput → Loss of air logistics volume → Trade of the Jing-Jin-Ji region → GDP of the Jing-Jin-Ji region

Economic growth in the Jing-Jin-Ji region will lead to higher domestic trade and promote increased trade volumes. Since trade requires the use of airports for transport and transit, it leads to an increase in airport throughput and a decrease in intra-regional freight loss. Therefore, it increases the level of trade and promotes the economic growth of the Jing-Jin-Ji region. This loop reflects the impact of the economy and trade on multi-airport system air cargo throughput and is a positive feedback reinforcement loop.

Within these three loops, there are also delayed relationships between variables, such as the throughput of each airport being affected by civil aviation authorities, airlines, and other sectors, which in turn has a delayed impact on the airport cluster coordination. Overall,

the causal loop diagram broadly reflects the feedback mechanism between the economy and trade within the Jing-Jin-Ji region, as well as the air cargo throughput in the MLS.

4.2.2. System Dynamics Flow Diagram Construction

To simplify the description, A, B, C, D, and E are used to represent different airports in the Jing-Jin-Ji MLS. A represents Beijing Capital International Airport; B represents Tianjin Binhai International Airport; C represents Shijiazhuang Zhengding International Airport; D represents Beijing Nanyuan Airport (now closed); and E represents Beijing Daxing International Airport. The system flow diagram is constructed accordingly, as shown in Figure 5.

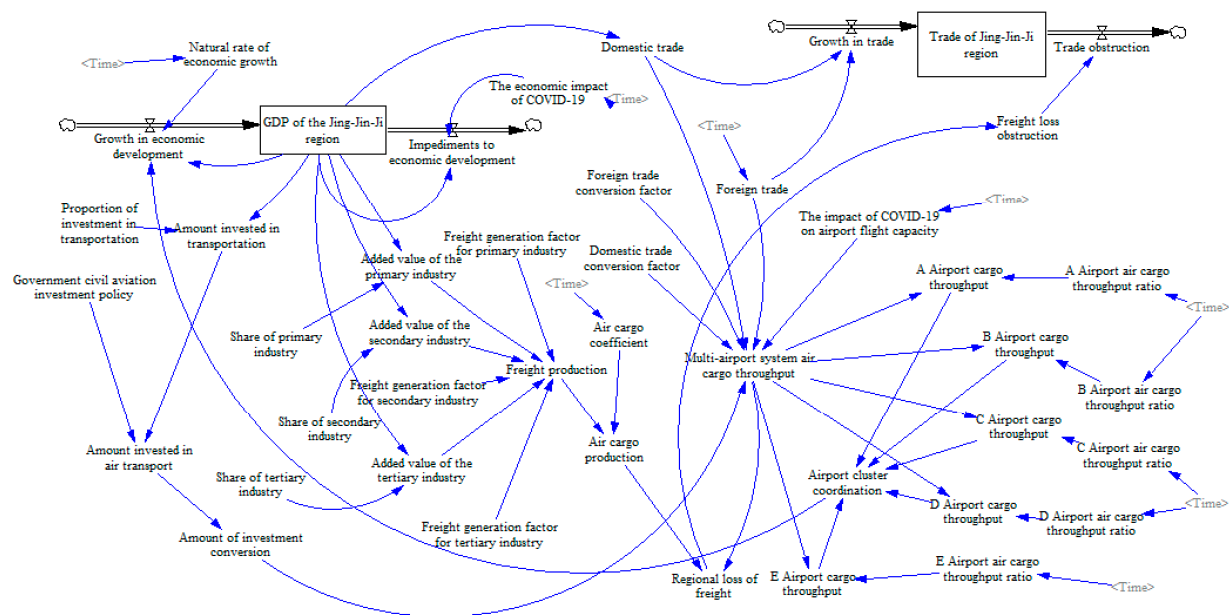


Figure 5. System flow diagram of Jing-Jin-Ji MLS.

4.2.3. Model Parameters Determination

We use the data collection method, mathematical modelling method, and reference literature method to estimate the parameters related to the Jing-Jin-Ji MLS. Specifically, econometrics models were used to analyse and simulate the data of Beijing, Tianjin, and Hebei for each year. The auxiliary variables, constants, and data sources in the model are shown in Tables 2–4.

Table 3. Constant data.

Constant *	Value	Units
Proportion of investment in transportation	0.057	Dmnl
Government civil aviation investment policy	0.024	Dmnl
Share of primary industry	0.054	Dmnl
Share of secondary industry	0.327	Dmnl
Share of tertiary industry	0.619	Dmnl
Freight generation factor for primary industry	136.3	Dmnl
Freight generation factor for secondary industry	623.2	Dmnl
Freight generation factor for tertiary industry	−7.6	Dmnl
Domestic trade conversion factor	0.115617	Dmnl
Foreign trade conversion factor	0.046005	Dmnl

* This part of the data was obtained from the SPSS analysis.

Table 4. Data source.

Data	Source	Data	Source
Natural rate of economic growth	National Bureau of Statistics of China	Share of secondary industry	National Bureau of Statistics of China
Amount of investment conversion	Civil Aviation Administration of China	Share of tertiary industry	National Bureau of Statistics of China
Airport cargo throughput	Civil Aviation Administration of China	Freight generation factor for primary industry	SPSS analysis
The impact of COVID-19 on airport flight capacity	Civil Aviation Administration of China	Freight generation factor for secondary industry	SPSS analysis
Proportion of investment in transportation	Ministry of Transport of the People's Republic of China	Freight generation factor for tertiary industry	SPSS analysis
Government civil aviation investment policy	Civil Aviation Administration of China	Domestic trade conversion factor	SPSS analysis
Share of primary industry	National Bureau of Statistics of China	Foreign trade conversion factor	SPSS analysis

In this paper, growth and impediments to economic development are used to describe the degree of change in the GDP of the Jing-Jin-Ji region, and GDP is considered a cumulative variable over time. For this reason, we set GDP as a level variable and express it by using the integral formula by referring to the literature [46]. The total GDP of the Jing-Jin-Ji region in 2011 was set as the initial GDP, and the natural economic growth rate was predicted according to the actual annual growth rate as well as SPSS analysis. SPSS analysis was performed on the GDP, domestic trade, the added value of the three industries, and multi-airport system air cargo throughput to derive the following equations.

$$\text{Domestic trade} = 108.501 + 0.294 \times \text{GDP of the Jing-Jin-Ji region} \quad (1)$$

$$\begin{aligned} \text{Freight production} = & 136.3 \times \text{Added value of the primary industry} + 623.2 \times \\ & \text{Added value of the tertiary industry} - 7.6 \times \text{Added value of the secondary} \\ & \text{industry} + 83,784 \end{aligned} \quad (2)$$

$$\begin{aligned} \text{Multi-airport system air cargo throughput} = & 140.762 + 0.115617 \times \text{Domestic} \\ & \text{trade} + 0.046005 \times \text{foreign trade} \end{aligned} \quad (3)$$

4.3. Model Test

The model checking tools Check Model and Units check, which are in the Vensim software, are used to check the feasibility of the model. The results of testing several major variables in the model are shown in Table 5.

Table 5. Comparison of simulated value with actual value.

Time/Year	Multi-Airport System Air Cargo Throughput/Ten Thousand Tons			Domestic Trade/Billion USD		
	Actual Value	Value of Simulation	Error Value	Actual Value	Value of Simulation	Error Value
2015	218.8	213.8	−2.29%	397	391.4	−1.41%
2016	225.1	214.4	−4.75%	426.6	413.9	−2.98%
2017	236.2	220.6	−6.60%	454	441.1	−2.84%
2018	240.4	228.9	−4.78%	474.9	468.4	−1.37%
2019	225.8	232	2.75%	500.3	493.6	−1.34%
2020	155.9	154.5	−0.90%	465.2	500.3	7.98%
2021	181.5	183.5	1.10%	498.4	531.6	6.66%

As shown in Table 5, the multi-airport system air cargo throughput and domestic trade from 2015 to 2021 have an error of no more than 10% from the actual values. Therefore, it can be seen that this model fits well with the actual situation and can accurately predict the actual development of the Jing-Jin-Ji MLS in the short term.

5. Simulation Results and Discussions

5.1. Simulation of Different Pandemic Scenarios

In this paper, the impact of the COVID-19 pandemic is divided into three levels to simulate the future development of the Jing-Jin-Ji MLS under different impacts of the pandemic [47]. According to the severity of the spread of the pandemic, different regions will implement different prevention and control policies to control personnel, transportation, and flight volume. The pandemic impact levels were set according to the criteria of each region's prevention and control policy for the outbreak. COVID-19 caused a 4.9% decrease in the economic development of the Jing-Jin-Ji region in 2020 compared to 2019, a scenario designated as a level 2 impact of COVID-19. This is also used as a benchmark to set the level 1 impact and level 3 impact of COVID-19. The level 1 impact of COVID-19 is a low-risk regional management model, the pandemic would be 50% less of a hindrance to the economy, at 2.45%, and the level 3 impact of COVID-19 is a high-risk regional management model, the pandemic would be 100% more of a hindrance to the economy, at 9.8%.

Meanwhile, to ensure the accuracy of the forecast, we adjusted the model based on the realistic conditions. Due to the continued impact of various mutant strains of COVID-19, such as Delta and Omicron, the cargo throughput of Chinese airports all declined to varying degrees in the first half of 2022. We readjusted our model to better fit this trend. In addition, Zhao (2022) predicted the overall development of COVID-19 would end around 2024 [48], so we re-simulated the trend of airport cargo throughput around 2024 to make the model prediction results closer to the situation. The impact of different pandemic levels on air cargo throughput in the Jing-Jin-Ji MLS simulated according to the SD model is shown in Figure 6.

As shown in Figure 6, the system dynamics model shows the development of the Jing-Jin-Ji MLS shows different changes under the influence of different pandemic levels. In 2022, there is a high probability that air cargo throughput in the Jing-Jin-Ji MLS will be reduced due to the emergence of various mutant strains of the pandemic. From 2022 to 2024, the pandemic consistently affects air cargo throughputs to varying degrees. Assuming the pandemic ends after 2024, air cargo throughput in the Jing-Jin-Ji MLS will grow steadily after 2024. According to the first level impact of the pandemic, the air cargo throughput of the Jing-Jin-Ji MLS will return to pre-pandemic levels in 2023, and the growth rate will gradually accelerate in the subsequent years. According to the second level impact of the pandemic, the air cargo volume of the Jing-Jin-Ji MLS will recover to the pre-pandemic level around 2024. According to the third level impact of the pandemic, the air cargo throughput Jing-Jin-Ji MLS will recover around 2026, and the long-term impact of the pandemic will make it more difficult for the air logistics industry to recover.

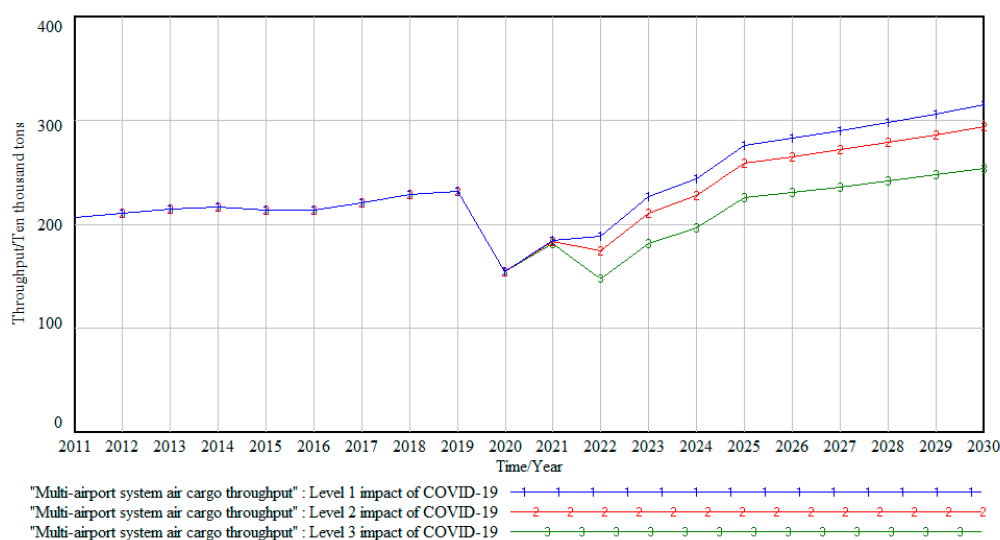


Figure 6. Impact of different pandemic levels on air cargo throughput of Jing-Jin-Ji MLS.

5.2. Policy Simulation Analysis

5.2.1. Policy 1: Increase the Proportion of Investment in the Air Logistics Industry

The investment in the field of the air logistics industry in the Jing-Jin-Ji region is relatively small, accounting for only 2.4% of the total investment in the transport industry. Therefore, the amount of investment in the air logistics industry can be increased. If the government investment policy of the air logistics industry is adjusted to 5%, 10%, and 20%, the simulation results are obtained, as shown in Figure 7.

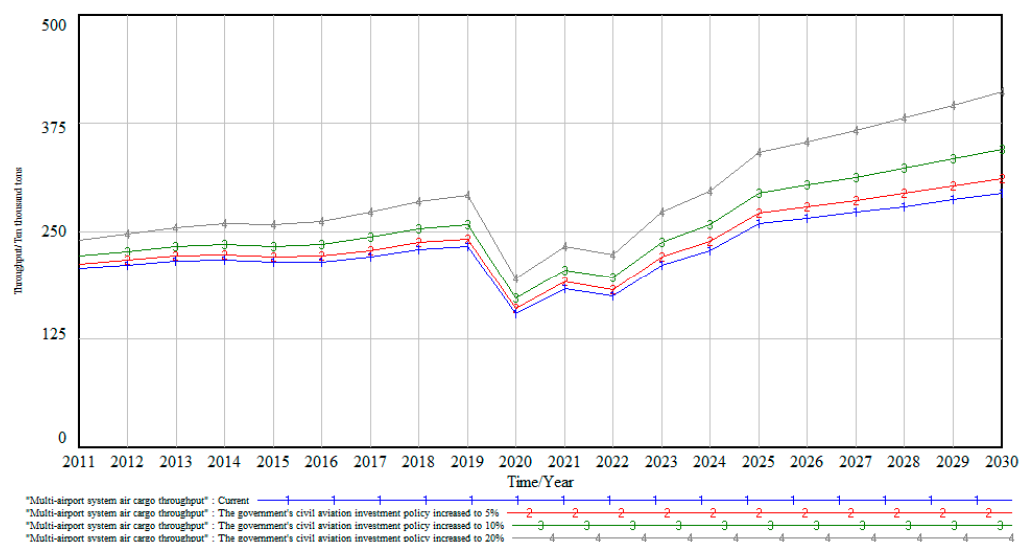


Figure 7. The impact of government investment policy on air cargo throughput of Jing-Jin-Ji MLS.

As shown in Figure 7, the cargo throughput of the Jing-Jin-Ji MLS will increase significantly after increasing the coefficient of government investment in the air logistics industry. If the air logistics investment policy increases to 5%, 10%, and 20%, the air cargo throughput of the Jing-Jin-Ji MLS will reach 3.11 million tons, 3.45 million tons, and 4.11 million tons, respectively, in 2030, which is 1.06 times, 1.17 times, and 1.4 times the throughput that can be achieved according to the current investment ratio. It shows that government investment in the air logistics industry can boost the growth of the Jing-Jin-Ji MLS.

5.2.2. Policy 2: Adjustment of Regional Industrial Structure

Due to the different functional positioning, economic development, and other conditions of Beijing, Tianjin, and Hebei in the Jing-Jin-Ji region, there is a great disparity in the air logistics resources between the three cities. The proportion of high-tech industries in Tianjin and Hebei is relatively weak, and there are fewer goods suitable for air transport, so the air cargo throughput of Tianjin Binhai Airport and Shijiazhuang Zhengding Airport is relatively small. Therefore, the proportion of air cargo in the trade process can be increased through the adjustment and upgrading of the industrial structure so that the conversion factor of domestic and foreign trade can be improved, which in turn will enhance the air cargo throughput of the Jing-Jin-Ji MLS. In the current "dual circulation" development context, the industrial structure upgrade has different impacts on domestic and foreign trade if the impact of foreign trade is only half of the domestic trade when the domestic trade conversion factor is increased by 10%, 30%, and 50% and the foreign trade conversion factor is increased by 5%, 15%, and 25%; the simulation results are shown in Figure 8.

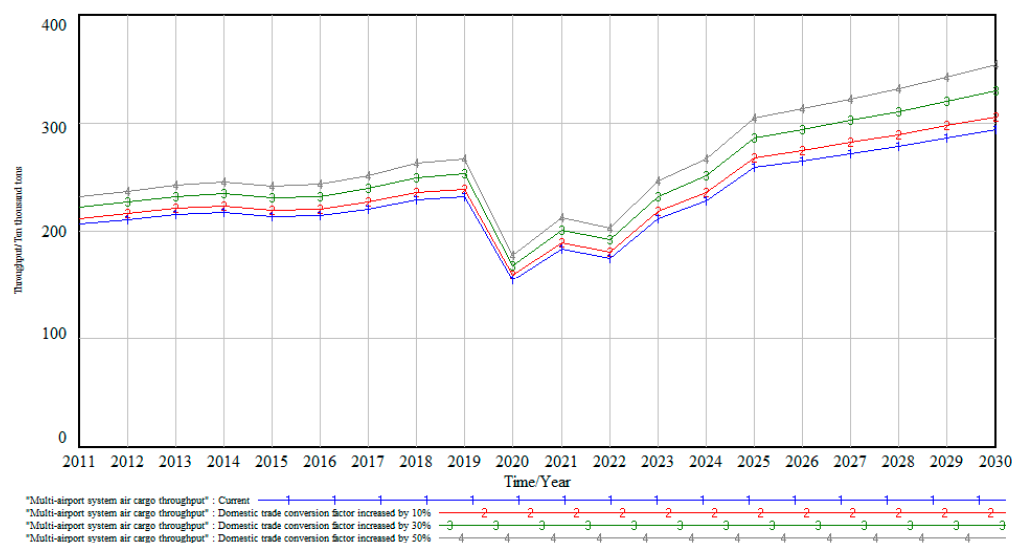


Figure 8. The influence of regional industrial structure adjustment on air cargo throughput of Jing-Jin-Ji MLS.

As shown in Figure 8, with the upgrading of the industrial structure of the Jing-Jin-Ji region and the resulting increase in the conversion coefficient of domestic and foreign trade, it can be found that the air cargo throughput of the Jing-Jin-Ji MLS has been significantly improved. When the domestic trade conversion factor is increased to 10%, 30%, and 50% and the foreign trade conversion factor is increased by 5%, 15%, and 25%, the air cargo throughput of the Jing-Jin-Ji MLS will reach 3.06 million tons, 3.3 million tons, and 3.54 million tons, respectively, in 2030, which is an increase of 119 thousand tons, 357 thousand tons, and 595 thousand tons compared with before the industrial structure was adjusted. Therefore, the adjustment of the industrial structure in the Jing-Jin-Ji region has a positive impact on the sustainability of the Jing-Jin-Ji MLS.

5.2.3. Policy 3: Promote Synergistic Development of MLS

In terms of the cargo throughput composition of the Jing-Jin-Ji MLS, the current cargo throughput ratio of major airports is seriously disproportionate. In 2021, the structure ratio of cargo throughput of the four major airports of Jing-Jin-Ji MLS (Beijing Capital, Beijing Daxing, Tianjin Binhai, and Shijiazhuang Zhengding) was 77:10:11:2, which is a serious imbalance in development. The air cargo flow in the Jing-Jin-Ji region is still overly concentrated in the Beijing Capital Airport, Daxing International Airport has not yet reached its full potential, Tianjin Binhai Airport has seen limited air cargo growth, and Shijiazhuang Zhengding Airport has a serious waste of facilities and equipment resources. Therefore, to realise the coordinated development of the Jing-Jin-Ji MLS, the cargo throughput structure needs to be adjusted according to the positioning of each airport. According to the positioning of multiple airports in the Jing-Jin-Ji region, Beijing Daxing Airport is positioned as an international first-class air transport hub, and Tianjin Binhai Airport is positioned as an international air logistics centre in China. If the CAAC and the local governments can effectively divert the air cargo flow to Beijing Daxing Airport and Tianjin Binhai Airport by introducing appropriate policies, it will not only enhance the synergy of air cargo in the Jing-Jin-Ji region but also enable the Jing-Jin-Ji MLS as a whole to achieve an increase in air cargo volume. When the ratio of cargo throughput of the MLS reaches 30:40:25:5 and 30:40:25:5, the simulation results are shown in Figure 9.

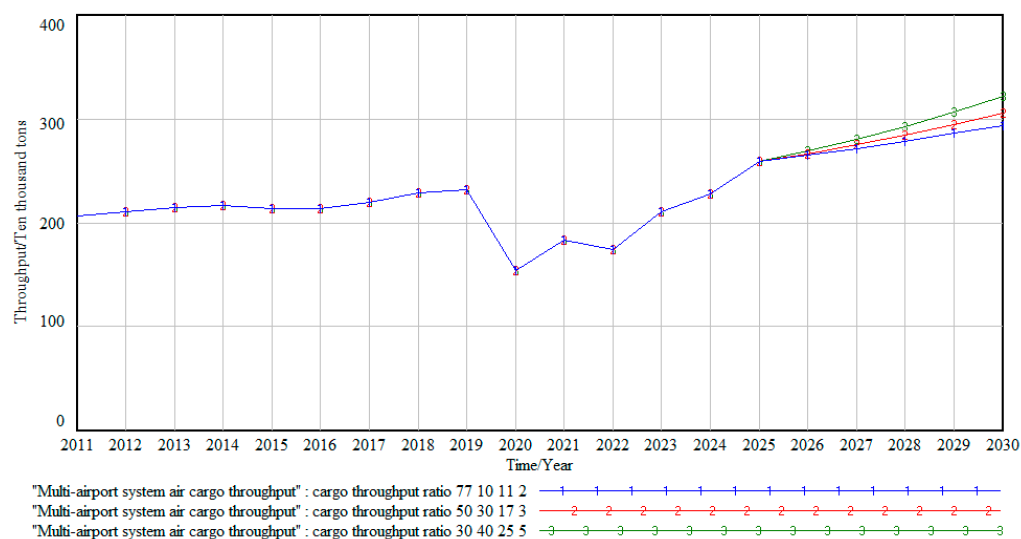


Figure 9. Effects of airport cluster coordination on air cargo throughput of the Jing-Jin-Ji MLS.

As shown in Figure 9, if the air cargo flow in the Jing-Jin-Ji region is redistributed among the airports through policy guidance, the overall air cargo throughput of the Jing-Jin-Ji MLS is increased to a certain extent. When the cargo throughput ratio of the MLS reaches 50:30:17:3, the cargo throughput of the Jing-Jin-Ji MLS is expected to reach 3.05 million tons in 2030, an increase of 114 thousand tons compared to the time when the policy was not adjusted. When the cargo throughput ratio of the MLS reaches 30:40:25:5, the cargo throughput is expected to reach 3.22 million tons in 2030, an increase of 283 thousand tons compared to the time when the policy was not adjusted. Moreover, as time goes on, the effect of the increased cargo throughput of the Jing-Jin-Ji MLS will become increasingly evident.

5.3. Sensitivity Analysis

To determine the degree of influence of key variables in the SD model on air cargo throughput, we performed a sensitivity analysis. Since the SD model includes the economic subsystem and trade subsystem, we chose the two key variables, namely growth in economic development and foreign trade, to observe the change in air cargo throughput. In this paper, four scenarios are designed: +10% growth in economic development, -10% growth in economic development, +10% foreign trade, and -10% foreign trade. The results of the sensitivity analysis are shown in Figure 10.

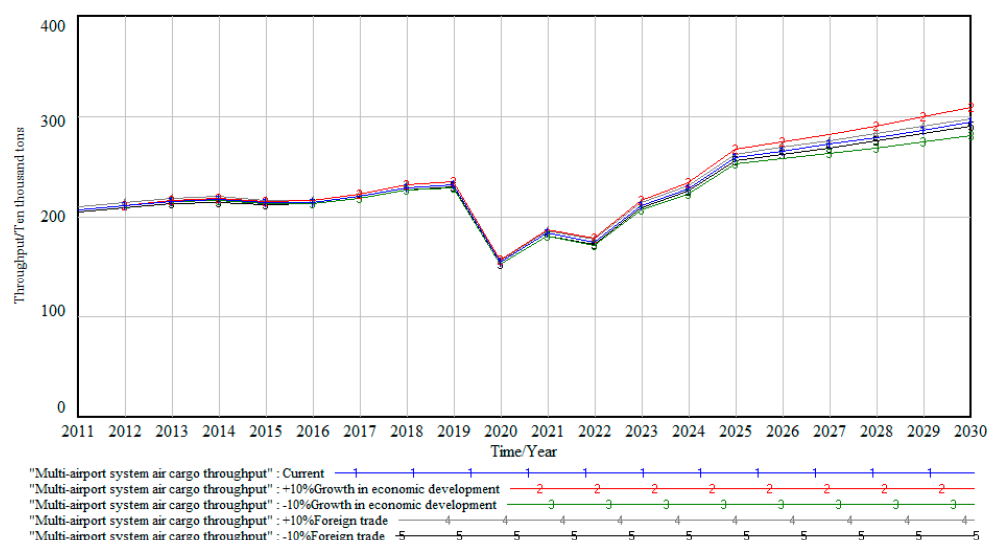


Figure 10. Sensitivity analysis results.

As shown in Figure 10, both the growth in economic development and foreign trade have a significant effect on the Jing-Jin-Ji MLS. Meanwhile, the two variables have different degrees of influence on air cargo throughput. For example, in 2030, a 10% increase in economic development growth would result in a cargo throughput of 3.09 million tons for the Jing-Jin-Ji MLS, an increase of 150,000 tons compared to the unadjusted figure; a 10% reduction in economic development growth would result in cargo throughput of 2.809 million tons for the Jing-Jin-Ji MLS, a reduction of 131,000 tons compared to the unadjusted figure; the overall change in the cargo throughput of the Jing-Jin-Ji MLS is around 5.1%. When the foreign trade increases by 10%, the cargo throughput of the Jing-Jin-Ji MLS will reach 2.977 million tons, an increase of 37,000 tons compared to the unadjusted level. When the foreign trade is reduced by 10%, the cargo throughput of the Jing-Jin-Ji MLS will reach 2.904 million tons, a reduction of 36,000 tons compared with the unadjusted level. The overall change in the cargo throughput of the Jing-Jin-Ji MLS is around 1.2%.

The above analysis shows that, compared with foreign trade, growth in economic development has a greater degree of influence on the air cargo throughput of the Jing-Jin-Ji MLS. This is related to the higher proportion of domestic trade cargo in the Jing-Jin-Ji region, which also indicates that the degree of export orientation of the Jing-Jin-Ji region has yet to be improved. In general, the current cargo throughput of the Jing-Jin-Ji MLS is more sensitive to changes in the amount of economic development growth, and the improvement of economic aspects is more important for the improvement of air cargo throughput. Therefore, to maintain the sustainable development of the Jing-Jin-Ji MLS, we should pay more attention to the economic development of the whole region and propose more effective measures and suggestions for economic development.

6. Conclusions and Policy Implications

6.1. Conclusions

Affected by the COVID-19 pandemic, the global air transport industry is facing severe challenges. As one of the three major multi-airport systems in China, the Jing-Jin-Ji MLS has also suffered a serious impact. Based on the principle of system dynamics, this study constructs an SD model of the Jing-Jin-Ji MLS considering the impact of the COVID-19 pandemic and carries out simulation analysis by setting up different pandemic impact scenarios and policy interventions.

The analysis of MLS shows that the cargo sources in the hinterland of multi-airport systems are cross-shared, and the development of their air cargo industry has a complex relationship between competition and synergy, so it is more appropriate to forecast the development of the regional air cargo industry from the perspective of multi-airport systems. Unlike traditional forecasting models or econometric models that require time-consuming historical data and cannot reflect the influencing factors such as unexpected events and policy changes, the SD approach can integrate more practical situations and better consider the development of the air cargo industry in important situations such as the COVID-19 pandemic and policy directions.

The SD model of the Jing-Jin-Ji MLS constructed in this paper can fit the historical data with high accuracy and within a 10% error. The model simulates that under different levels of pandemic scenarios, the air cargo throughput of Jing-Jin-Ji MLS will recover to the pre-pandemic level in 2023, 2024, and 2026, respectively. The model's analysis of policy simulation can meet the development trend of air cargo in the Jing-Jin-Ji MLS under different policy conditions. Increasing the government civil aviation investment to 5%, 10%, and 20% will increase the air cargo throughput by 1.06 times, 1.17 times, and 1.4 times, respectively; adjusting the regional industrial structure to increase the domestic trade conversion factor by 10%, 30%, and 50% and the foreign trade conversion factor by 5%, 15%, and 25% will increase the air cargo throughput by 119 thousand tons, 357 thousand tons, and 595 thousand tons; the air cargo throughput of the Jing-Jin-Ji region will increase by 114 thousand tons and 283 thousand tons when the ratio of air cargo flow distribution is guided by policies to 50:30:17:3 and 30:40:25:5.

We also carried out a sensitivity analysis of the SD model. It shows that the current cargo throughput of the Jing-Jin-Ji MLS is more sensitive to changes in the growth in economic development relative to foreign trade. This is related to the higher proportion of domestic trade cargo in the air freight, which also indicates that the degree of outward orientation of the Jing-Jin-Ji region has yet to be improved.

6.2. Policy Implications

The results show that the COVID-19 pandemic has formed a major obstacle to the development of the Jing-Jin-Ji MLS. In view of the rapid and wide spread of virulent strains, such as Delta and Omicron, in order to ensure the rapid recovery and subsequent development of the Jing-Jin-Ji MLS, certain measures need to be taken based on the results of the policy simulations, which are recommended as follows.

1. Improve the work of air freight services under the pandemic and flexibly adjust capacity to meet market demand. With the rapid and wide spread of virulent strains such as Delta and Omicron, air transport is the front line to block the import of pandemics. Further explore the air logistics market by simplifying the approval of cargo route flights as much as possible, liberalising the cargo flight schedule during airport peak hours, encouraging the “freighters”. At the same time, reduce the market access threshold, support airlines to flexibly adjust their capacity and effectively match market demand, and improve freight accessibility and convenience under the impact of the COVID-19 pandemic.

2. Increase support for the air logistics industry and implement a number of preferential policies. The development of the air logistics industry is inseparable from the support of the state and the government. Especially under the influence of the COVID-19 pandemic, it will be difficult to recover quickly only by itself. According to the simulation model built in this paper, it can be found that increasing the government's financial and material support for the air logistics industry will effectively reduce the freight loss of the Jing-Jin-Ji MLS and make the regional air cargo volume increase significantly. Therefore, the government should further strengthen the support for the Jing-Jin-Ji MLS, and solve difficulties for air logistics enterprises by reducing aviation business charges and ground service charges, setting up a special fund for air logistics development, increasing relevant subsidies for cargo routes and air logistics enterprises, reducing various tax burdens of air logistics enterprises, and optimising administrative approval process and other government services so as to promote the sustainable and healthy development of the Jing-Jin-Ji MLS under the COVID-19 pandemic.

3. Attract agglomeration development of aviation-preferred industries and promote regional industrial structure upgrading. The development of MLS is closely related to the development of the regional economy and industrial structure. According to the simulation results in this paper, adjusting the industrial structure can accelerate the sustainable development of the MLS. Therefore, the government should start by developing the regional economy and adjusting the industrial structure, guiding different types of aviation-preferred industries to gather in the airport area according to the industrial development positioning of each place, and forming an aviation logistics ecosystem so as to promote the upgrading of the regional industrial structure and make the airport area a booster for promoting the dual domestic and international circulation and achieving high-quality regional development under the COVID-19 pandemic.

4. Guide the distribution of goods sources effectively and promote the coordinated development of the MLS. One of the core problems that currently restrict the development of the Jing-Jin-Ji MLS is the serious uneven distribution of cargo flow and the low degree of synergistic development. Although the commissioning of Daxing International Airport has played a role in relieving the cargo source of the Beijing Capital airport, there are still a lot of idle and wasted facilities and resources in Tianjin Binhai Airport and Shijiazhuang Zhengding Airport. Through the analysis of the model causality diagram and the simulation model, it can be seen that the redistribution of air cargo flow between the four airports can not only improve the coordination degree of the MLS but also improve

the overall cargo volume of the region to a certain extent. Therefore, it is necessary to further clarify the functional positioning of each airport in the MLS and give full play to their respective comparative advantages so that all airports can enjoy the benefits of the coordinated development of the MLS and achieve the sustainable and healthy development under the normalisation of COVID-19 prevention and control.

The SD model of the Jing-Jin-Ji MLS constructed in this paper not only truly reflects the competitive and synergistic relationship between different airports but also provides an effective method to study the air logistics development situation in the MLS under the COVID-19 pandemic. However, due to the many factors involved in the development of the MLS and the complex interrelationships among airports, there are still some shortcomings in the model. In the future, the selection of parameters and the relationship between variables in the SD model will continue to be improved to further enhance the accuracy and applicability of the model.

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