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Research Article

Supply Chain Resilience of Mineral Resources Industry in China

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Improving the supply chain resilience of the mineral resources industry is crucial for ensuring national economic security in China. Based on the supply and demand data of China's mineral resources industry from 2002 to 2018, this study adopts system dynamics model to simulate the supply chain resilience of the mineral resources industry, the mining industry, and the smelting and processing industry under the scenario of steady economic development and the scenario of supply chain crisis. From the simulation results, the reserves of the mineral resources industry and the smelting and processing industry under the two scenarios are nearly the same, indicating that they are weakly affected by the foreign market, and both have strong resilience. The mining industry has a high dependence on imports and a lack of supply chain resilience. Under the condition of steady economic development, the output of the mining industry needs to develop at a low speed to reduce production capacity. More attention should be paid to the high level of import dependence and insufficient supply chain resilience of the mining industry. In the stable international trade situation, reserves of important minerals should be increased to alleviate the resource shortage during the supply chain crisis.

1. Introduction

The mineral resources industry provides basic material and energy security for human beings, and supports the prosperity and development of the world economy and society. China is a major producer and consumer of mineral resources in the world, and has an important influence on the world mining market. In the long run, China's demand for mineral resources will remain at a high level. However, in recent years, factors such as the continuous recurrence of the COVID-19, the slowdown of global economic growth and geopolitical conflicts have increased the uncertainty of the development of the global mineral resources industry, and the supply of China's mineral resources industry has also been affected. Therefore, it is particularly important to improve the supply chain resilience and ensure the timely supply of mineral resources [1].

Reserve is a basic strategy for building supply chain resilience, which can solve the unexpected events of supply interruption or surge in demand [2]. Mineral resources reserves can cope with economic, political, and natural emergencies, ensure steady economic development, and prevent the interruption of mineral resources supply. China also pays more and more attention to mineral resources reserve. In the mineral resources planning, China has formulated the mineral resources reserve system in detail, which lays a good foundation for improving the supply chain resilience of the mineral resources industry. However, it is rarely considered in the relevant literature to study the supply chain resilience of mineral resources industry through the change of reserves. We should further study the supply chain resilience on the basis of establishing a model to analyze mineral resources reserves.

Based on the availability of data and the comprehensiveness of the analysis, the data of the mineral resources industry from 2002 to 2018 are used, and a system dynamics model (SD: system dynamics) is employed to simulate the interrelationship of import, supply, and reserve of mineral resources industry, mining industry, and smelting and processing industry.

The following are the two main contributions of this study: (1) In terms of research content, on the basis of the simulation of reserves, the supply chain resilience of mineral resources industry, mining industry, and smelting and processing industry is compared and analyzed, so that the analysis of supply chain resilience of the mineral resources industry is more comprehensive. (2) In terms of research perspective, the mineral resource reserves are closely related to supply chain resilience. Through the simulation of the reserve scale, the analysis of the supply chain resilience can better serve the management of the mineral resource industry supply chain.

2. Survey on Related Work

The mineral resources industry is an industrial system consisting of economic activities related to the mineral resources mining, smelting, and processing. The supply chain resilience of the mineral resources industry refers to the ability of the downstream industry to recover its original state when the upstream suppliers face emergencies in the mineral resources industry.

Recent research that focused on supply chain resilience and mineral resource reserves are as follows:

First is research on supply chain resilience, which is often associated with supply chain risk management [3] and supply inventory management [4]. The research contents mainly include: the measurement of supply chain resilience [5], the scale of supply chain resilience [6], and more results focus on the analysis of driving factors of supply chain resilience [7, 8]. The research on certain industrial supply chain resilience has mainly focused on improving the resilience of the industrial supply chain [9] and the analysis of influencing factors [10]. There are few research results on the supply chain resilience of the mineral resources industry. The main results in this area include the mineral economic implications related to the supply chain and the supply chain resilience [11], and an assessment model for oil and gas supply chain resilience [12]. In studies on the supply chain resilience of the mineral resources industry, more emphasis has been placed on improving the resilience under various risks.

Second is research on mineral resource reserves. The US and Japan were the first to establish mineral resource reserves [13]. The research content of mineral resources reserve mainly covers the mineral resource reserve management [14] and the reserve scale [15]. Calculations of the reserve scale of mineral resources focus on different kinds of ores. The optimal reserves of oil and gas [16] and copper ore [17] are calculated through the actual reserves and the demand for mineral products.

The list of classifications of the literature is addressed in Table 1, which are extracted based on supply chain resilience and mineral resource reserves. In general, research results on supply chain resilience, supply chain resilience of mineral resources industry, and mineral resources reserves are abundant, but there are not enough results to further analyze supply chain resilience through the scale of mineral resources reserves. The existing studies tend to analyze the reserves and supply chain resilience of a certain type of minerals and rarely focus on the overall and the industrial heterogeneity of mineral resources industry. By simulating the supply chain resilience of mineral resources industry, mining industry, and smelting and processing industry, the results can provide a scientific basis for the sustainable development of China's mineral resources industry, and also provide a more accurate basis for the formulation of supply and reserve policies of mineral resources industry.

3. Problem Description

Mineral resources reserves can reduce the possibility of interruption of mineral resources supply chain, but large-scale reserves cannot be equated with strong supply chain resilience. In order to solve this problem, we use system dynamics model to establish supply, demand, and reserve system, and explore the supply chain resilience of mineral resources industry by analyzing reserves.

3.1. System Analysis and Data Sources. The supply chain resilience of China's mineral resources industry is studied using system dynamics (SD) model. The supply chain and demand chain of mineral resources industry are closely related to mineral resources reserves, so it is necessary to construct three subsystems to simulate the relationship among them, focusing on imports, supply, and reserves, and then analyzing the supply chain resilience. From a macro perspective, the supply of the mineral resources industry includes imports and domestic supply. The demand includes exports and domestic demand. The reserves are regulated according to supply and demand (Figure 1). For imports, set two scenarios: steady economic development and supply chain crisis. When the upstream import industry changes, the supply chain recovery capacity is further analyzed according to the changes of mineral resources industry supply and reserve.

Since the data of mineral resources industry is more comprehensive after 2002, the output value, total input, import, and export from 2002 to 2018 are used for model analysis. The output value is used to represent the domestic supply and the total input is used to represent the domestic demand. The total output value data is from the "China Industrial Statistical Yearbook." For the year with missing data, we refer to the sales output value. The total input, import, and export are mainly from the input-output table from 2002 to 2017 published by the National Bureau of statistics. For years with missing data, use the GDP growth rate to estimate the demand growth rate, and use the mineral resource industry import and export growth rate to estimate the import and export volume.

Based on the available mineral resources industry-related information and the National Mineral Resources Plan (2021–2025), the time boundary of the model simulation is set as 2002–2035. Due to the limitation of data, the

Table 1: Survey of supply chain resilience and mineral resource reserves.

References	Methodology	Strategy	Research focus	Industry
[4]	Hybrid fuzzy and data-driven robust optimization	Vendor-managed inventory	Supply inventory management	Health care
[5]	A systematic literature review	Three resilience dimensions analysis	Measurement of supply chain resilience	—
[6]	Partial least squares-based structural equation modelling	Three dimensions analysis	Scale of supply chain resilience	Global supply chains
[7]	Total interpretive structural modelling	Test the proposed methodology	Driving factors of supply chain resilience	COVID-19
[8]	AHP and fuzzy	Consider the drivers of the resilience and vulnerability	Driving factors of supply chain resilience	E-commerce
[9]	Quality function deployment	Identify the major risks and vulnerability factors	Improving supply chain resilience	Agricultural food
[10]	Fuzzy cognitive maps	Analyze the domino effect	Driving factors of supply chain resilience	Fashion
[11]	Evaluation of extraction and processing parameters	Discuss mineral economic implications relevant to coltan supply	Mineral economic implications related to the supply chain	Tantalum
[12]	—	Provide a holistic complex system governance	Supply chain resilience assessment	Oil and gas
[14]	GIS remote sensing technology	Builds a resource reserve management information system	Mineral resource reserve system	Mineral resources
[15]	—	Analyze many ways to increase the scale of reserves	Mineral resource reserve scale	Copper
[16]	Reserves assessment and resource optimization	Discovery of resource rich areas	Optimal reserve	Oil and gas
[17]	—	Estimate future ore reserves and energy consumption	Optimal reserve	Copper ore
Present study	SD	Analysis of supply chain resilience by simulating mineral resource reserves	Supply chain resilience	Mineral resources

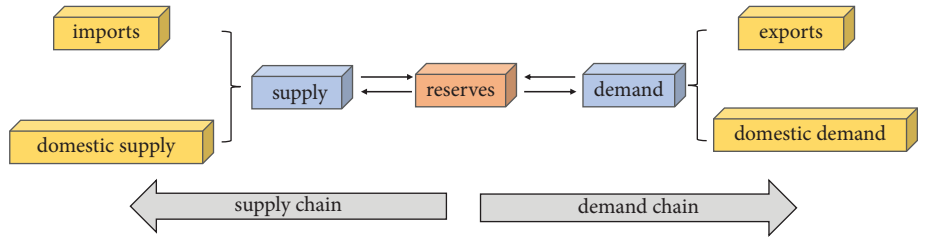

Figure 1: Relationship between supply chain, demand chain, and reserve of mineral resources industry.

simulation history period is 2002–2018, and the model forecast period is 2019–2035. The simulation time step is set to 1 year. The spatial boundary of the model is 30 provinces of China (excluding Hong Kong, Macao, Taiwan, and Tibet).

3.2. Model Assumptions. Based on the analysis of the relationship between supply, demand, and reserves of the mineral resources industry, and in order to facilitate the analysis of supply chain resilience by simulating the mineral resources reserve situation, the model needs to be simplified by making the following assumptions.

(1) Considering the comparability and availability of data, the import and output value of the mineral resources industry can adequately represent the supply of the mineral resources industry. Furthermore, the reserve amount can effectively measure the overall reserve of the mineral resources industry.

(2) The initial year of the model is 2002, and the mineral resources is reserved according to the goal of meeting the demand of three months

(3) The amount of mineral resources reserve is mainly influenced by the amount of supply and demand, when the two are basically balanced, no reserve is made; when the amount of supply is much larger than the amount of demand, reserve is made; when the amount of supply is much smaller than the amount of reserve, the reserve bank is released.

3.3. Model Construction. An SD model is used to simulate the reserve scale in the next 20 years according to the

historical data, and the supply chain resilience of mineral resources industry is analyzed by setting two scenarios: steady economic development and supply chain crisis. Due to the wide variety of minerals and the large difference in reserves and prices of mineral resources, the reserve amount is selected to describe the reserve of mineral resources. The total demand and total supply of mineral resources industry are both measured by price. Total demand includes domestic demand and export, and total supply includes output and import.

Based on the relationship between the supply, demand, and reserves of the mineral resources industry, VENSIM PLE software was used to construct an SD model of the mineral resources industry supply chain resilience. The specific flow diagram is shown in Figure 2.

3.4. Model Structure. The system flow diagram contains three subsystems (the mineral resources industry supply chain subsystem, demand chain subsystem, and reserve subsystem), with a total of 19 variables. 5 are horizontal variables (import value, output value, export value, domestic demand value, and reserve value); 5 are rate variables(import value added, output value added, export value added, domestic demand value added and stock in amount); and the other 9 are auxiliary variables. By constructing three subsystems and establishing the relationship among them, we can better simulate the relationship among import, supply chain and reserve of mineral resources industry, laying the foundation for accurate analysis of supply chain resilience.

3.4.1. Mineral Resources Industry Supply Chain Subsystem

(1) Supply value

The supply of mineral resources industry is described by the supply value, and the annual supply value is calculated by the import value in the current year and the total output value in the current year.

$$S_t = S_{tImp} + S_{tOut}, \tag{1}$$

where S_t is the supply value of the mineral resources industry in the current year, S_{tImp} is the import value of the mineral resources industry in the current year, and S_{tOut} is the total output value of the mineral resources industry in the current year.

(2) Imports value

$$S_{tImp} = S_{(t-1)Imp} + S_{tImpadd}, \tag{2}$$

where $S_{(t-1)Imp}$ is the import value of the mineral resources industry in the previous year, and $S_{tImpadd}$ is the increase in the import value of the mineral resources industry in the current year compared with the previous year.

(3) Import value added

$$S_{tImpadd} = S_{tImp} \cdot v_{Imp}, \tag{3}$$

where v_{Imp} is the growth rate of import value of the mineral resources industry. The growth rates for the years 2012–2018 were the actual growth rates. The growth rate under different scenarios will be adopted in 2019–2035.

(4) Total output value

$$S_{tOut} = S_{(t-1)Out} + S_{tOutadd}, \tag{4}$$

where $S_{(t-1)Out}$ is the total output value of the mineral resources industry in the previous year and $S_{tOutadd}$ is the increase in the total output value of the mineral resources industry in the current year compared with the previous year.

(5) Output value added

$$S_{tOutadd} = S_{tOut} \cdot v_{Out}, \tag{5}$$

where v_{Out} is the growth rate of output value of the mineral resources industry. The growth rates for the years 2012–2018 were the actual growth rates.

3.4.2. Mineral Resources Industry Demand Chain Subsystem

(1) Demand value

The demand of the mineral resources industry is described by the demand value, and the annual demand value is calculated by the export value in the current year and the domestic demand value in the current year.

$$D_t = D_{tExp} + D_{tDem}, \tag{6}$$

where D_t is the demand value for the mineral resources industry in the current year, D_{tExp} is the export value of the mineral resources industry in the current year, and D_{tDem} is the domestic demand value of the mineral resources industry in the current year.

(2) Export value

$$D_{tExp} = D_{(t-1)Exp} + D_{tExpadd}, \tag{7}$$

where $D_{(t-1)Exp}$ is the export value of the mineral resources industry in the previous year and $D_{tExpadd}$ is the increase in the export value of the mineral resources industry in the current year compared with the previous year.

(3) Export value added

$$D_{tExpadd} = D_{tExp} \cdot v_{Exp}, \tag{8}$$

where v_{Exp} is the growth rate of export value of the mineral resources industry. The growth rates for the years 2012–2018 were the actual growth rates.

(4) Domestic demand value

$$D_{tDem} = D_{(t-1)Dem} + D_{tDemadd}, \tag{9}$$

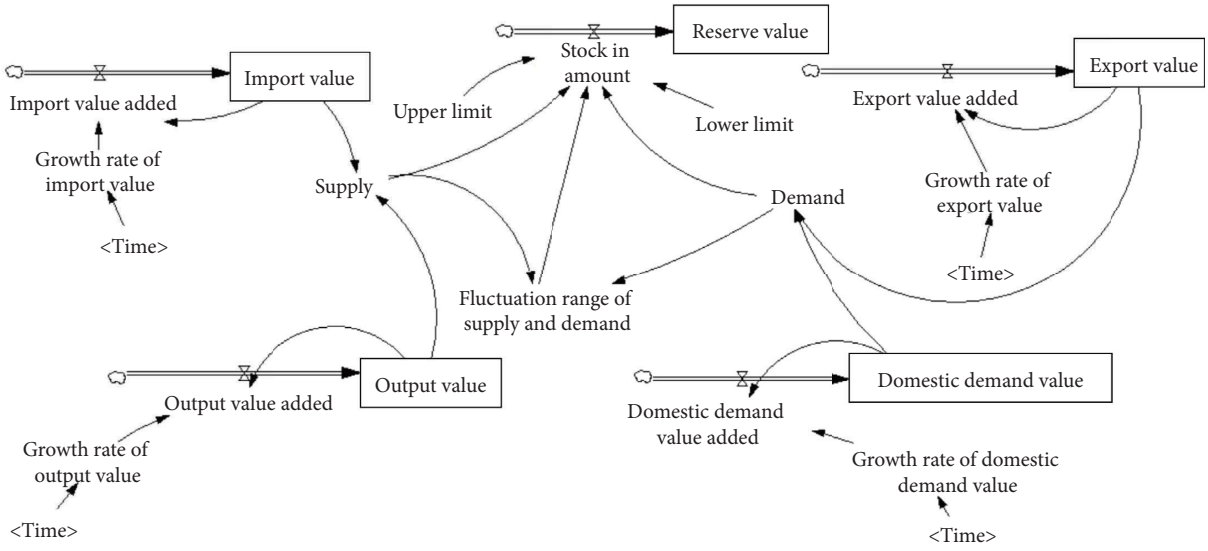

Figure 2: Flow chart of supply chain resilience system of mineral resources industry.

where $D_{(t-1)Dem}$ is the domestic demand value of the mineral resources industry in the previous year and $D_{tDemadd}$ is the increase in domestic demand value of the mineral resources industry in the current year compared with the previous year.

(5) Demand value added

$$D_{tDemadd} = D_{tDem} \cdot v_{Dem}, \tag{10}$$

where v_{Dem} is the growth rate of demand value of the mineral resources industry. The growth rates for the years 2012–2018 were the actual growth rates.

3.4.3. Mineral Resources Industry Reserve Subsystem

(1) Fluctuation range of supply and demand

The fluctuation range of supply and demand indicates the degree to which the supply deviates from the demand. The greater the value, the more unbalanced between supply and demand. When it exceeds a certain range, it is necessary to rely on reserves to adjust, so as to stabilize the market price and the balance between supply and demand. The calculation formula of fluctuation range of supply and demand is as follows:

$$v_t = \frac{(S_t - D_t)}{D_t}. \tag{11}$$

(2) Stock in amount

When the supply and demand are basically the same, there is no need to reserve or release mineral resources. When the supply is greater than the demand, it is necessary to reserve. When the supply is less than the demand, release of reserves is required.

$$R_t = \begin{cases} S_t - (1+\alpha)D_t, & 0 \le \alpha \le v_t, \\ 0, & \beta \le v_t \le \alpha, \\ S_t - (1+\beta)D_t, & v_t \le \beta \le 0, \end{cases} \tag{12}$$

where R_t is the reserve value of mineral resource. When $\beta \le v_t \le \alpha$, that is, the fluctuation range of supply and demand is small, and mineral resources are not reserved or released. When $0 \le \alpha \le v_t$, that is, the fluctuation range of supply and demand is greater than the upper limit, the supply is greater than the demand, and mineral resources reserve is required. When $v_t \le \beta \le 0$, that is, the fluctuation range of supply and demand is less than the lower limit, the supply is less than the demand, and mineral resources reserve need to be released to meet demand. In this study, α was set as 5% and β as −5%.

(3) Reserve value

$$M_t = M_{t-1} + R_t, \tag{13}$$

where M_t is the reserve value of the mineral resources industry and M_{t-1} is the reserve value of the mineral resources industry in the previous year.

An initial value is needed for the reserve value of mineral resource. With reference to the mineral resource reserve target of some countries, Japan has a reserve target of two months' domestic demand for some rare and other metals. In the US, the reserve target is three months' domestic demand. The initial value of mineral resource reserves in China was set as three months' domestic demand in the first year.

4. Results and Discussion

4.1. Scenarios Setting. Under the two scenarios of steady economic development and supply chain crisis, the import

and reserve of mineral resources industry before 2035 are predicted according to the historical data from 2002 to 2018. If the supply chain can cope with extreme situations, there will be no significant impact on reserves, indicating that the supply chain of mineral resources industry is resilient. In order to analyze the industrial heterogeneity, that is, the difference in supply chain resilience between mining industry and smelting and processing industry, the flow chart shown in Figure 1 is also used for simulation.

The forecast period (2019–2035) in the model needed to be set up for four indicators: growth rate of imports, of exports, of output, and of domestic demand (Table 2). Under the scenario of steady development of the global economy, the mineral resources industry would have an import growth rate of 5.15% and an export growth rate of 4.54% after 2018, based on the growth rate of imports and exports in the last four to five years, excluding years with large fluctuating growth rates. According to a forecast of China's demand for major mineral resources by Wen et al. [18], the average annual growth rate of domestic demand for the mineral resources industry between 2019 and 2035 will be approximately 6.79%. The output growth rate was mainly determined based on China's GDP growth rate. The real GDP growth rates were used for 2019, 2020, and 2021 (6.1%, 2.3%, and 8.1%, respectively). From 2021 to 2035, this value is replaced by China's potential economic growth rate: 7.29% in 2021–2025, 6.97% in 2026–2030, and 6.49% in 2031–2035.

There is significant overcapacity in the mining industry, therefore, output growth rate should be reduced. According to the growth rate of output value in recent years, it is set to dissolve the overcapacity at the rate of −0.0714% for five consecutive years. In order to prevent the continuous growth of production capacity, half of the average growth rate 1.875% is taken as the future development according to the growth rate of output value in recent 10 years. According to the growth rate of import value and export value in recent years, it is determined that after 2018, the growth rate of import is 7.43%, of exports is 3.44%, and of demand is 6.97%.

The supply and demand of smelting and processing industry accounts for about 70% of the mineral resources industry. The growth rates of imports, exports, output, and domestic demand of smelting and processing industry were determined in the same method as for the mineral resources industry. The import growth rate is 5.7%, export growth rate is 4.78%, and the domestic demand and output growth rates are the same as those for the mineral resources industry.

Due to the changeable international situation, it is assumed that there will be a supply chain crisis in 2025 and the import will be blocked. Referring to the existing research results [19], the decrease after a large impact is set at 50%, and the import will recover in the next year. Other parameters are consistent with the steady economic development.

4.2. Simulation Results. Figure 3 shows the import, supply, and reserve of mineral resources industry from 2002 to 2018. The import and supply show an overall rise. The import account for a relatively small proportion of the supply in mineral resources industry and smelting and processing industry, so the fluctuation in import will not have a great impact on supply. The import accounts for a very large proportion of the supply in mining industry. The stability of import will directly affect the stability of the supply chain of mining industry. The reserve is the cumulative value over the years. There has been overcapacity in the mineral resources industry and the smelting and processing industry since 2011. The supply of mining industry accounts for a relatively small proportion in the mineral resources industry, but the overcapacity is more serious.

According to the set parameters, under the condition of steady economic development and supply chain crisis scenarios (Table 3), the reserve of mineral resources industry and smelting and processing industry are the same, indicating that the supply chain crisis has basically no impact on the reserve. The supply chains of mineral resources industry and smelting and processing industry exhibit strong resilience.

By contrast, the mining industry needs to adopt a low-speed growth due to its large overcapacity. According to the set parameters, under the steady economic development scenario, with the implementation of a de-capacity policy, the reserve continues to decrease, which can meet China's demand for more than three months. Under the supply chain crisis scenario, the release of reserves would accelerate, and it is necessary to improve the growth rate of supply to meet China's demand.

4.3. Sensitivity Analysis. Sensitivity analysis is presented in a simulation. In the process, you can observe the sensitivity of A variable to B variable. In general, A can only be a constant. In this study, since the constants in the model are not the main variables, different time steps are used to analyze the sensitivity. In addition to the 1-year time step in the simulation, the simulation with 0.5-year and 0.25-year time steps are added. The sensitivity analysis of mineral resources industry, mining industry, and smelting and processing industry under different scenarios has little difference, so take the mineral resources industry under the supply chain crisis scenario as a representative to analyze the simulation results of imports and reserves under different time steps (Figure 4).

It can be seen that the sensitivity of the reserve is greater than that of the import. In addition, the sensitivity of output, export, domestic demand, and other variables is similar to that of import, and the sensitivity is low. It shows that the system is insensitive to most parameter changes, the model has good stability, and can well simulate the actual system.

4.4. Analysis of Results. According to the simulation results of import, supply, and reserve of the mineral resources industry, the supply of mineral resources industry and smelting and processing industry is weakly affected by import, whereas the supply of the mining industry is greatly influenced. After 2009, the reserves of the mineral resources increased. The reserve has far exceeded the target of three months' domestic demand, with production overcapacity. In

Table 2: Parameters under steady economic development and supply chain crisis from 2019 to 2035.

*S*1	Mineral resources industry	GR import: 5.15%. GR export: 4.54%. GR demand: 6.79%. GR output: 6.1% in 2019, 2.3% in 2020, 8.1% in 2021, 7.29% in 2022–2025, 6.97% in 2026–2030, 6.49% in 2031–2035.
	Mining industry	GR import: 7.43%. GR export: 3.44%. GR demand: 6.79%. GR output: −0.0714% in 2019–2021, 1.875% in 2022–2035.
	Smelting and processing industry	GR import: 5.70%. GR export: 4.78%. GR demand: 6.79%. GR output: 6.1% in 2019, 2.3% in 2020, 8.1% in 2021, 7.29% in 2022–2025, 6.97% in 2026–2030, 6.49% in 2031–2035.
*S*2	Mineral resources industry, mining industry, and smelting and processing industry	GR import: 2025: −50%, other years are consistent with *S*1. GR export: consistent with *S*1. GR demand: consistent with *S*1. GR output: consistent with *S*1.

Note. GR represents the growth rate, *S*1 represents the scenario 1 (steady economic development), and *S*2 represents the scenario 2 (supply chain crisis).

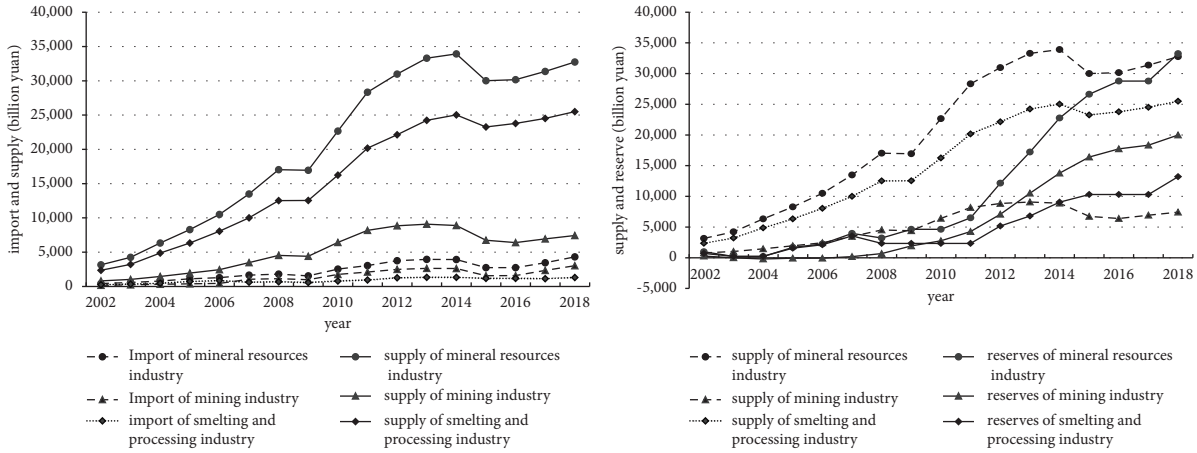

Figure 3: Changes in import, supply, and demand of mineral resources industry from 2002 to 2018.

Table 3: Model results of mineral resources industrial reserve system (trillion yuan).

Year	Import						Reserves			
	*S*1: *M*	*S*2: *M*	*S*1: *E*	*S*2: *E*	*S*1: *S*	*S*2: *S*	*S*1 and *S*2: *M*	*S*1: *E*	*S*2: *E*	*S*1 and *S*2: *S*
2019	4.53	4.53	3.24	3.24	1.37	1.37	35.79	21.82	21.82	13.2
2020	4.76	4.76	3.48	3.48	1.45	1.45	38.26	23.19	23.19	13.2
2021	5.01	5.01	3.74	3.74	1.53	1.53	38.26	24.1	24.1	13.2
2022	5.26	5.26	4.01	4.01	1.61	1.61	38.26	24.56	24.56	13.2
2023	5.54	5.54	4.31	4.31	1.71	1.71	38.26	24.56	24.56	13.2
2024	5.82	5.82	4.63	4.63	1.8	1.8	38.26	24.17	24.17	13.2
2025	6.12	2.91	4.98	2.32	0.9	0.9	38.26	23.63	23.63	13.2
2026	6.44	6.12	5.35	4.98	1.91	1.91	38.26	22.93	20.27	13.2
2027	6.77	6.44	5.74	5.35	2.02	2.02	38.26	22.06	19.03	13.2
2028	7.12	6.77	6.17	5.74	2.13	2.13	38.26	21.01	17.58	13.2
2029	7.48	7.12	6.63	6.17	2.25	2.25	38.26	19.76	15.91	13.2
2030	7.87	7.48	7.12	6.63	2.38	2.38	38.26	18.31	14	13.2
2031	8.27	7.87	7.65	7.12	2.52	2.52	38.26	16.64	11.84	13.2
2032	8.7	8.27	8.22	7.65	2.66	2.66	38.26	14.73	9.4	13.2
2033	9.15	8.7	8.83	8.22	2.81	2.81	38.26	12.57	6.68	13.2
2034	9.62	9.15	9.48	8.83	2.97	2.97	38.26	10.14	3.64	13.2
2035	10.11	9.62	10.19	9.49	3.14	3.14	38.26	7.43	0.27	13.2

Note. *S*1 represents the scenario 1, *S*2 represents the scenario 2, *M* represents the mineral resources industry, *E* represents the mining industry, and *S* represents the smelting and processing industry. The reserves of mineral resources industry and smelting and processing industry are the same under scenario 1 and scenario 2.

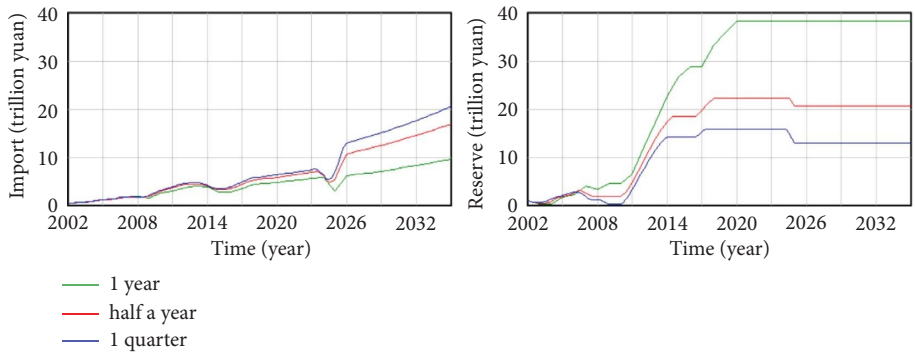

Figure 4: Sensitivity analysis of mineral resources industry under supply chain crisis.

2016, China's Ministry of Land and Resources and various provinces have gradually implemented policies to resolve the problem of overcapacity in the mineral resources industry. It is estimated that by 2035, the supply and demand of the mineral resources industry will basically be balanced, and the reserve of mineral resources will remain unchanged. Owing to the continuous growth of demand, the reserve will be able to meet the demand for more than three months, but the ratio of reserve to demand will decline year by year. If the economy continues to develop steadily, after 2035, it will be necessary to increase the supply by increasing the output or import to ensure the ratio of reserve to demand does not continue to decline.

In recent years, China's economy has developed rapidly, the output value of mineral resources is relatively stable, and the fluctuations are within a reasonable range. Imports will be mainly affected by foreign economic and political situations in China. Assuming there is a large shock (set as a 50% decline) to the import in a given year (set as 2025), our analysis indicates the results of the reserve under the two scenarios are basically the same. The reason is that from 2002 to 2018, the import accounted for a relatively small proportion of the supply, ranging from 9% to 16%. The sudden decline in import basically has no impact on the supply and reserve of the mineral resources industry in China. The supply chain of the mineral resources industry has strong resilience. In real life, there are substantial differences between mineral species in China. Only a small amount of mineral resources, such as lead-zinc ore, can be self-sufficient, and about 2/3 of the strategic minerals have more than 70% dependence on foreign countries. Overall, there is a contradiction between the large demand for imported mineral products and the strong resilience of mineral resources industry in China, which needs to be analyzed at different industry.

From the perspective of the mining industry, from 2002 to 2018, the reserve was much larger than demand. Compared with the mineral resources industry, the problem of overcapacity is more serious in mining industry. Although the output value has shown negative growth in recent years, the problem of overcapacity has not been completely solved. In the steady economic development scenario, in order to resolve the problem of overcapacity, first maintain the negative growth trend, and then set the future growth rate according to the slight rise. The results of the model show that the reserve in amount continues to decrease after 2018. From 2023, it is mainly the release of reserves. By 2035, the proportion of reserves in the demand will be 43.65%, which can meet the basic demand. Although there is overcapacity under the steady economic development, there are great differences among different minerals. For example, there are long-term shortages of domestic supplies of crude oil, natural gas, coal, iron ore, and copper concentrate. In 2019, these minerals accounted for approximately 85% of China's total imports of minerals.

When the import of mining industry is greatly impacted and decreases by 50%, the supply decreases significantly, indicating that the supply chain resilience is insufficient. From the perspective of reserve, after the impact, by 2035, the reserve would account for 23.79% of the demand, which is less than the three months' domestic demand target. It would be necessary to increase the output or import. The lack of supply chain resilience in mining industry is due to the large share of import in the supply, between 18.02%–40.19%, and shows a continuous growth trend. The larger the proportion of import in the supply, the higher the degree of control by the foreign market and the weaker the supply chain resilience. In the period of global economic stability, more strategic minerals should be stockpiled to meet domestic demand for mineral products during supply chain crises.

From the perspective of smelting and processing industry, it is basically consistent with the change trend of mineral resources industry. The total supply of the smelting and processing industry accounts for more than 70% of the mineral resources industry and continues to grow, which has a great impact on the change trend of mineral resources industry. Under the two scenarios of steady economic development and supply chain crisis, the reserve of the smelting and processing industry has not changed, and the supply chain has strong resilient.

Analysis of imports of the mining industry and smelting and processing industry reveals that China's imports of mineral resources are mainly in the mining industry, and growth of imports is accelerating. The ratio of import of mining industry to smelting and processing industry increased from 0.68 in 2002 to 2.33 in 2018. For the following reasons: first, although China is rich in mineral resources,

some minerals are of low grade and difficult to mine. As the demand for mineral products continues to grow, the domestic output cannot meet the demand. Secondly, the process from discovery to mining of mineral resources is complex. The mining cost is high, so it is better to import high-grade raw ore directly. Finally, with the continuous improvement of smelting and processing technology in China, the cost can be saved by importing raw ore and domestic processing. This also explains the lack of supply chain resilience in the mining industry, while the supply chain resilience in the mineral resources industry is strong and less affected by the impact of emergencies. It is notable that the mining industry is an upstream industry of the smelting and processing industry. The lack of supply chain resilience in the former will affect the supply chain resilience of the latter. In order to ensure the supply chain security of China's mineral resources industry, it is necessary to stockpile important mineral products in time.

5. Conclusions and Managerial Insights

Based on the SD model, this paper analyzes the supply chain resilience of the mineral resources industry, mining industry, and smelting and processing industry. The research content is more comprehensive. In addition, by simulating the changes of import, supply, and reserve of mineral resources industry under the scenario of steady economic development and the scenario of supply chain crisis, and then analyzing the supply chain resilience, the research perspective is more novel, which can better serve the supply chain management of mineral resources industry.

The results of this research and managerial insights are as follows:

(1) The supply of smelting and processing industry accounts for more than 70% of the mineral resources industry. Under the two scenarios of steady economic development and supply chain crisis, the reserves of the two industries have basically not changed, and the supply chains have strong resilience.

(2) The mining industry is highly dependent on imports. During a supply chain crisis, the sharp decline of import will continuously reduce the reserves of the mining industry. It is necessary to continuously make up for the shortage of supply by increasing import or output after the crisis. Supply chain resilience is insufficient.

(3) From the relationship between the mining industry and the smelting and processing industry, the import mode of mineral resources industry has changed from directly importing a large number of mineral products after smelting and processing to mainly importing raw ores for deep processing in China. Although the results show that the supply chain resilience of the smelting and processing industry is strong, its upstream industry is dominated by the mining industry. The lack of supply chain resilience of the mining industry will affect the supply chain resilience of the smelting and processing and the mineral resources industry.

The managerial insights are as follows: in China's mineral resources reserve, the resource reserves of mining industry should be given priority attention, and the reserve of raw ores should be appropriately increased to reduce the dependence of mining industry on imports during the supply chain crisis. In order to ensure supply chain security and improve supply chain resilience, the scale of strategic mineral resources reserves should be appropriately increased. For mineral species with high import dependence, the import from one country will be changed to multi-country import to weaken resource monopoly and price monopoly.

The main limitation of the study is simulation analysis of important mineral reserves and supply chain resilience. For future studies, it is suggested to use SD model to accurately simulate the reserves and supply chain resilience of many important minerals. It is better to use exact algorithms such as Lagrange relaxation and meta-heuristic algorithms [4, 20].

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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