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Evaluating the economic impacts of COVID-19 pandemic on shipping and port industry: A case study of the port of Shanghai

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ABSTRACT

The stability of shipping and port operations are crucial for international trade and global supply chain. However, the COVID-19 pandemic hit the shipping and port industry enormously in late 2019, and continues till now. It is important to identify the impacts of the pandemic on shipping and port operations and evaluate the potential economic impacts for better setting future development strategies and policies. A System Dynamics (SD) model is proposed to depict the impact transmission within the supply chain considering 5 sub-systems (shipping, port, transportation, manufacturing and social). Potential economic impacts which are represented by the shipping loss and port loss will be assessed. 6 scenarios with different epidemic durations and capacity recovery degrees have been set to investigate the economic impacts. The port of Shanghai, together with the container shipping business is selected as input for case study. Results indicate that in the first few months the port and carriers may suffer economic loss due to shrunken demand caused by COVID-19. But later carriers may enjoy an increase of income compared to non-pandemic scenario owing to strong recovery in most scenarios. Moreover, we found that manufacturing, transportation and port operation capacities would jointly affect the recovery process and economic impacts. The findings can facilitate policy makers in making port management and future industry development decisions.

1. Introduction

Within the globalized economy and international supply chain, seaports are acting as critical nodes that help facilitate international shipping and trade (Zhang and Lam, 2016; Zheng et al., 2022). Besides, as the shipping industry contributes nearly 90% of the global trade volume (IMO, 2015), this indicates that the stability of port operations is extremely crucial for international trade. However, according to Rodrigues et al. (2010), port is regarded as one of the most uncertain components within the global supply chain due to its vulnerability to external shocks. Thus, port disruption is one of the key threats affecting the overall resilience of the global economy (Chopra and Sodhi, 2004). A port disruption is defined as an event which could cause a sudden interruption on cargo flows in the transport system and may lead to a stoppage in cargo movement (Wilson, 2007). Usually, such kinds of events would be classified as natural hazards (e.g., typhoons, earthquakes), man-made catastrophes (e.g., chemical plant explosions, terrorist attacks) or strikes of port workers (Ivanov and Dolgui, 2019). However, there is another kind of event which could bring severe impacts to the port, that is the epidemic outbreak. In contrast to other disruption events, epidemic outbreak may impose longer duration of negative impacts on ports and all other nodes and parties throughout the whole supply chain (Ivanov, 2020).

The recent case of COVID-19/SARS-CoV-2 pandemic has nearly caused a halt to the world and especially to the whole country of China at the beginning of year 2020 and China’s domestic economic activities have all been affected. The manufacturing industries and exports of China were heavily hurt and the global supply chain was severely affected in turn (Xu et al., 2021; Fei, 2020). As critical nodes of the global trade, the disruption of ports reinforces the failures on global supply chain, especially in the beginning of the COVID-19 outbreak, when for safety concerns that many ports were unavailable to accommodate calling foreign ships (Chen, 2022). Consequently, the shipping industry suffered heavy loss due to port disruptions. Since then, with the global dispersion of COVID-19, more and more international ports were unable to provide full services and most of the ports are suffering from economic losses. A large body of past research has paid attention on port disruption risk analysis and management under natural or man-made

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hazards, while little has been done on evaluating the economic losses of ports and related shipping industries under epidemic outbreaks. Clearly identifying and assessing the economic losses of ports and shipping industries under the strike of COVID-19 is crucial for policy makers and port authorities dealing with the current dilemma and making future recovery strategies. Some existing research has investigated the economic losses of ports under natural hazards (e.g., typhoon, Zhang and Lam, 2016), while there is a lack of research on establishing a systematic framework of evaluating the overall economic impact of port and shipping activities under COVID-19 pandemic. Most of the current research on COVID-19 are focused on processing statistic data to show the impacts of COVID-19. A model that can depict the transmission mechanism of COVID-19 and evaluate the economic impacts is needed.

To address the research gaps, this article aims to establish a systematic framework for evaluating the potential economic losses of ports and shipping industries under the impact of COVID-19 pandemic. A System Dynamics (SD) based model is proposed to depict the risk propagation and interactions of COVID-19 between key aspects of port, government, ships, road transportation, manufacturing bases, etc. within the whole supply chain. Estimations on port’s and shipping companies’ economic losses have been conducted based on numerical calculations of cargo throughput and recovery assumptions under various scenarios.

The rest of this paper is organized as follows: an overview of port disruption risk analysis and port disruption economic loss estimation will be given in the literature review part. Then the SD model for identifying the key causal loops and for evaluating the economic losses will be proposed in the methodology section. The container port of Shanghai in China will be selected as the case study for assessing the economic losses in the results and discussion part. Conclusions and policy implications are given in the last section.

2. Literature review

As this paper targets to establish a system based economic assessment framework for port and shipping industry under the impact of COVID-19 epidemic outbreak, the related literature will be reviewed from three parts: the first is port disruption risk aspect analysis and risk propagation within the global supply chain, the other is port disruption economic loss assessment.

2.1. Port disruption risk analysis

As a critical node within the global supply chain, the disruption of a port could spread to neighboring industries, such as shipping and transportation, then eventually spread to the upstream suppliers and downstream shipping companies, distributors and end users. This could be depicted as the risk propagation, or sometimes also called as ripple effect (Li and Zobel, 2020; Zhang and Lam, 2016). From the supply chain management level, relatively abundant research has been done to explore the impacts of supply chain risk propagation and mitigation strategies. For example, Dolgui et al. (2017) systematically analyzed the ripple effect in the supply chain and proposed some critical research avenues for future research. Scheibe and Blackhurst (2017) qualitatively identified the driving forces of supply chain risk propagation. Bueno-Solano and Cedillo-Campos (2014) proposed a System Dynamics (SD) model to simulate the risk propagation and the potential impacts on the supply side under terrorist attacks. As per Bueno-Solano and Cedillo-Campos (2014), SD is suitable to assess the propagation of disruptive risks derived from various events. Previous researches revealed that impact of risk in the supply chain spreads through information steam, product stream and capital flow. No matter which streams the risk happens on, all these three streams will be influenced. In different scenarios, the order of being influenced for these streams may be different, but the propagation routes will form a ring finally. Moreover, because of bullwhip effect and reverse bullwhip effect, the impact will be even enlarged in the whole propagation process.

Chang (2000) found that due to the earthquake in Kobe, Japan in 1995, the disruption of the port of Kobe restricted the full-service capability of the port, leading to a reduction in the transshipment traffic and the shipping service providers suffered from severe economic losses. Some others found that man-made port disruptions, such as terrorist attacks could also seriously interrupt the normal trade activities, that the risk of port disruption directly transfers to the shipping and transportation part within the supply chain (Rosoff and von Winterfeldt, 2007; Park, 2008). Lam and Su (2015) investigated the trend of port disruption and proposed risk mitigation strategies for reducing the risk likelihood and severity of different types of disruptive events. Zhang and Lam (2016) analyzed the propagation of port disruption within the industry cluster and proposed a Petri Net model to simulate the potential impacts of the port disruption due to natural hazards.

When considering the epidemic outbreaks (such as SARS, Ebola), the research on how supply chains coping with epidemic outbreaks is relatively mature (Ivanov, 2020). For example, Johanis (2007) proposed a pandemic response plan based on the lesson learned from the SARS epidemic outbreak in 2002–2003. Calnan et al. (2018) summarized the experiences coping with Ebola and proposed a decision-support framework for better predicting the impacts of epidemic outbreaks on supply chains. While the research on how ports dealing with the epidemic outbreaks is relatively scarce.

Although many studies have been conducted to assess the supply chain risks due to port disruptions, few studies have systematically discussed the port and shipping industry along with the adjacent industry clusters, considering their relationships with each other. SD, as an effective model to assess the propagation of risks from various events, can help to systematically clarify the mechanism of the impact of the epidemic on the port and shipping industry and the propagation route, which in turn can help to explore reasonable response policies.

2.2. Port economic loss assessment

Ports are vulnerable to external disruptive events, especially natural hazards, some researchers have focused on evaluating the economic losses of ports and provide advices for port authorities for post-disaster recovery. Paul and Maloni (2010) applied a simulation-based approach to assess the economic losses of ports under natural and terrorism-related disasters and found that disruptions did increase the costs of operations in port. Kajitani et al. (2013) investigated the impact and economic losses of the port of Singapore due to a chemical explosion. The port of Tianjin, China also suffered from a heavy chemical explosion in 2015, Cao and Lam (2019) proposed a fast reaction-based port vulnerability assessment framework to assess the vulnerability of the port. Zhang and Lam (2015) developed an approach of estimating the economic losses of port and related business operators due to the disruptions induced by extreme wind events. They classify the economic losses into four parts: reputational loss, loss to the shippers, loss to the carriers and loss to the ports. Zhang and Lam (2016) proposed a simulation-based economic loss assessment framework for assessing not only the economic losses of ports, but also the economic losses of port related industry clusters. Their model is based on Petri Nets. Cao and Lam (2018) developed a catastrophe-induced port loss estimation framework based on a port operation simulation model. The simulation-based model would accommodate more scenarios and generate more scenario-based results, which would help port authorities clearly identifying potential losses. Xu et al. (2021) analyzed the economic impacts of COVID-19 on shipping trade from the macro level using panel data.

In general, the hierarchical structure is helpful when quantifying economic losses to the port and shipping industry. However, unlike other events that lead to fluctuations in the port and shipping industry, the development trend of the port and shipping industry under the influence of the epidemic is unclear. A dynamic assessment of economic
losses considering the development of the epidemic is necessary.

2.3. COVID-19 impact assessment in shipping and port industry

For the quantification of the impact of COVID-19, Xu (2021) constructed a panel regression model to analyze how the macro economy, the severity of the epidemic, and government control measures affect port operations. Gui et al. (2021) employed a multi-sectoral computable general equilibrium model of China, CHINAGEM, with highly disaggregated transport sectors to examine the impacts of the COVID-19 pandemic on China’s transport sectors. Narasimha et al. (2021) established a system consists of secondary data, and compared the current value to year-over-year value to analyze the performance indicators of major seaports in India before and during the COVID-19 crisis. Shi and Weng (2021) concluded the overview of the merchant shipping activity in Shanghai port waters based on AIS data using statistical analysis.

As a method can be applied to both qualitative and quantitative analysis, many scholars have used SD in the research about the impact of COVID-19. Kontogiannis (2020) established a causal loop to reflect the interactions among government, social service agencies and public under the impact of COVID-19. Venkateswara and Duman (2020) presented an SD model of the COVID-19 pandemic spread in India, and explicitly modeled the effects of different policies by using independent time-variant levers. Based on SD, Struben (2020) developed a flexible behavioral, dynamic, and sectorial epidemic policy model comprising both endogenous virus transmission and public health and citizen responses.

Most studies on assessing the impact of COVID-19 on ports are based on the current situation for comparison and discussion, and lack the necessary forecasting and planning.

To summarize, for the past literature, even though some studies have developed comprehensive frameworks to assess the economic losses of ports under natural or man-made disruptive catastrophes, little research has been done to 1) organize the impacts and interactions of key aspects within the global supply chain under epidemic outbreaks (e.g. COVID-19), and 2) systematically assess the economic impacts of ports and shipping industry under epidemic outbreaks and predict the economic loss or unanticipated extra income in following stages. As this paper aims to assess the economic loss of ports and shipping industry under COVID-19 outbreak, there is a strong need of research to fill the research gap.

3. Methodology

3.1. Model hypothesis

System Dynamics model is recognized as a suitable tool to solve problems with nonlinear and feedback features in an explicit visual format (Jing et al., 2021). It is advantageous in investigating large-scale socio-economic systems of high complexity with industry experience inputs (Jia et al., 2019). Since the operation of port and shipping industry is related to many factors in various fields like economy, social and environment (Kong et al., 2022), SD is a proper theory for modeling such comprehensive system. This research aims to develop a SD model to depict the complex interactions between different parties within the global supply chain network and then evaluate the potential economic losses of port and shipping system. Before the model is fully introduced, some hypotheses are listed as below:

1) The general COVID-19 impact propagation mechanism is assumed as: firstly, the epidemic outbreaks and spreads, and this directly alarms the government. Then the government reacts and issues coping policies (Li et al., 2021). These policies may have direct impacts on industries throughout the whole supply chain, such as the shut-down policy for markets and cities, as well as quarantine policy for individuals (Magableh, 2021).

2) China is assumed as the global manufacturing base (Mckay and Song, 2010), the product flow of a global supply chain in this paper is considered as: Chinese manufacturers import raw materials and energy products, then they produce products in China. Finally, manufactured products are exported to all over the world (Ref.: https://www.volza.com/).

3) Different categories of vessels transport different cargoes. Crude oil tankers are used for transporting crude oil, which is the source for the fuel of manufacturing industries, bulk carriers transport raw materials, containerships transport manufactured products. Among all these cargoes, container service is crucial to many global ports and suffered serious damage under the pandemic (Ref.: http://www.chinaports.com/portlspnews/3737). Therefore, this article will focus on the container service and seeks to figure out the potential economic loss of the container related port and shipping business.

4) The total income structure of the port and shipping industry consists of two parts: 1) shipping income for the shipping companies and 2) port income for the port. Shipping income comes from shipping freight (Notteboom, 2021), and port income includes the sub-incomes from the berthing service, port service and handling service fee (Ref.: https://www.portshanghai.com.cn).

5) Demand of production, manufacturing capacity (labor), inventory of fuel and material under the COVID-19 pandemic will affect the actual production jointly (Chatha and Jalil, 2022; Vahedi-Nouri et al., 2022).

6) Mobility restrictions may cause labor shortage in transportation, shipping and port service (Vahedi-Nouri et al., 2022), so the actual available exported products volume is not equal to the actual production volume during the pandemic.

7) As China is the manufacturing base, during the pandemic, the number of exporting containership voyages should be determined by the actual exported products considering both the supply and demand side (Wang and Meng, 2021) while supply and demand are balanced without a pandemic.

3.2. Model framework

The SD model in this research is developed in a modular manner, which consists five core subsystems (social subsystem, manufacturing subsystem, transportation subsystem, port subsystem and shipping subsystem) that are developed based on the elements within a supply chain and from the government administrative perspective. Among the available studies, the factors related to the operational performance of the port and shipping industry basically could be categorized into these fields. The logic of the SD model is to estimate the potential economic impact of the port that will serve fewer calling ships and less containers due to the epidemic outbreak. However, different subsystems are not isolated, and the quarantine policies issued by the government may reduce the labor and material supplies of both the upstream manufacturing industry and the middle-stream shipping and port industries. The road transportation supply (available trucks) will also be affected.

All the relevant factors in the SD model are listed in Table 1. Social subsystem covers the areas of 1) government policy (which includes the government issued policy constraints on port operations, road traffic and shipping activities), 2) economy (which includes the overall economic indicators: the total income structure and detailed sub-components of the incomes of port and the shipping industry), 3) labor supply (which is directly affected by the government policy and has direct impacts on the normal operations of ports, road transportation and ships) and 4) consumer demand (which consists of psychological and behavioral parts). The port subsystem contains factors of port operations and port income, and port operations are affected by port handling capacity, turn over efficiency and the number of calling ships.
The shipping subsystem covers elements of shipping operations and some economic indicators of the shipping industry. The transportation subsystem contains the transportation capacity which can influence the actual road transportation freight volume. The manufacturing subsystem is the upstream market to the shipping industry, which includes the factors of production capability, inventory and demand.

3.3. Model development

3.3.1. Causal loop

The general causal loop shows the interactions among all related factors. The detailed drawing of causal loop among all the factors is shown in Fig. 1a. And causal loops for different subsystems are identified and explained as below. It needs to be emphasized that each sub image only focuses on one specific subsystem, and only direct relationships with this subsystem are shown, so relationships among the other subsystems are ignored.

(1) Social subsystem

Social subsystem is shown as Fig. 1b. It can be considered as the link point of start and end in this whole system. As a start, the impact of COVID will influence consumer demand on the one hand. And on the other hand, the impact will lead to traffic and port constraints, so transportation and port subsystem will be affected. As an end, policy effects will act on the epidemic finally. Proper policies can acquire better health and economic benefit, which means the society is under a good recovery status, and quarantine measures can be eased. Conversely, if the epidemic situation is unsatisfactory, some policies need to be strengthened.

(2) Transportation subsystem

As Fig. 1c shows, traffic constraints mainly refer to domestic traffic constraints in this paper. It can limit public travel and road transportation, then reduce labor supply in many industries.

(3) Manufacturing subsystem

It can be seen from Fig. 1d that manufacturing industry is affected by social subsystem for demand of products and transportation subsystem for the manufacturing capacity. However, compared to shipping and
port industry, it’s an up-stream industry, because the demand of fuel and raw material determine the import shipping demand, and actual production determines the import and export volume.

(4) Port subsystem

Ports can achieve income by offering different services to ships. As is shown in Fig. 1e, the service capacity is limited by transportation subsystem, and service demand is affected by shipping subsystem directly. For epidemic prevention reasons, port operation procedures under epidemic are more stringent and cumbersome, which affects port turnover efficiency to a certain extent.

(5) Shipping subsystem

Fig. 1f shows the detail of shipping subsystem. Shipping industry generates income from freight, which is influenced by 2 factors: shipping demand and shipping capacity. On the one hand, shipping demand and capacity determined the actual shipping volume together. On the other hand, they both effect the unit freight, especially under the epidemic, while many voyages are concealed.

Some critical loops are identified and explained as below.

(1) Impact → labor → actual production → shipping demand of container → freight → shipping income → total income → economic development → policy

COVID-19 pandemic affects the health of workers, so the supply of workforce would decline. Actual goods production is influenced by the supply of labor and the export container volume would decrease in turn. As a result, the freight volume shrinks and income of shipping business may decrease. While as shipping a key link for trade and economic development, then the economic development is affected. It represents a poor epidemic control situation, so governments will introduce polices like quarantine and constraints to control the outbreak.

(2) Impact → policy → traffic constraints → labor → port capacity → port call → port income → total income → economic development → policy

This loop shows the impact propagation mechanism of COVID-19 pandemic impact on port operations and economic performance. The spread of COVID-19 urges the government to introduce policies to restrict the movement of people, so the supply of available labor shrinks. Then the operation capacity at port is limited and port call decreases. Service income of the port declines, then the economic development and policy development trend evolve in the same way as depicted above.

(3) Impact → demand of products → actual production → shipping demand of container → port call → shipping income → total income → economic development → policy

Under the COVID-19 pandemic, the demands for products would decline in the initial stage, which may induce a decline in the production volume. Then the shipping demand of containers also declines. A reduce in container shipping demand may lead to a reduce in number of sailing ships, which may result in a reduce of number of ports calls in the port. But in the later period, the foreign goods consumption may bonus back. Thus, the logic of shipping income development trend is the same as mentioned before.
(4) Impact → demand of products → demand of fuel → fuel inventory → actual production → shipping demand of container → port call → shipping income → total income → economic development → policy

Apart for the product demand, in the supply side, fuel and raw materials can also influence the actual production capability. Normal production capability can be maintained only if there are enough raw materials and fuel supply. When demand of products increases, factories need more fuel and raw materials to product, this may lead a reduction in the current inventory level, which may constrain the later production capability.

3.3.2. Stock-flow model

As container shipping is one of the most affected business under the COVID-19 pandemic, together with the consideration of data availability and model tractability, container service will be selected as the example for further economic loss assessment of port and shipping industry in this research. The detailed calculation logic and the stock flow chart of the SD model are shown in Fig. 2. The equations are clarified as below and the parameters are listed in Table 7.

(1) Total loss of the port and related shipping industry

Total loss of the port and shipping industry is the loss during the total outbreak duration, and it can be modeled as:

\[ L_T = \int_0^D L_M dt \]  

(1)

(2) Monthly loss

In this research, the unit time span is set as one month, all the losses mentioned above are calculated on a monthly basis. Thus, the monthly
loss can be modeled as:

\[ L_{st} = L_s + L_P \]  \hspace{1cm} (2)

(3) Economic loss of the shipping industry

Economic loss of the shipping industry \((L_{st})\) is defined as the difference between the projected income without the impact of the COVID-19 and the projected income under the epidemic outbreak, and it can be modeled as:

\[ L_s = I_{st0} - I_s \]  \hspace{1cm} (3)

Where:

\[ I_{st0} = FR_0 \cdot CEV_0 \]  \hspace{1cm} (4)

\[ I_s = FR \cdot CEV \]  \hspace{1cm} (5)

(4) Freight rate

Freight rate \((FR)\) is defined as the container freight rate under the impact of COVID-19 pandemic, which is different from the freight rate \((FR_0)\) without the impact of COVID-19. As \(FR\) is a key variable of the model and is a time-varying variable, the estimation of \(FR\) is critical. In this research, it is assumed that \(FR\) is modeled as a proportion to \(FR_0\), the ratio is set as \(r_F\), which also is a time-varying coefficient that depicts the characteristics of the development trend of \(FR\). For example, in the beginning of COVID-19 pandemic, the overall container shipping business is depressed, thus the ratio \(r_F\) is on a relatively low level indicating that the freight rate market is experiencing a poor recovery. While as time goes by, the overall trade has recovered, the freight rate would recover to the normal level that \(r_F\) would be near to 100%. And when shipping capacity cannot catch up with the recovery of global trade, \(r_F\) would be over 100%. The detailed formulation is modeled as:

\[ FR = r_F \cdot FR_0 \]  \hspace{1cm} (6)

(5) Container export volume

Container export volume means the predicted export volume that undertook by container ships under the impact of COVID-19. As mentioned above, the export procedures can be divided into 3 stages in this research. Firstly, factories produce goods. Then, trucks convey goods from factories to ports. Finally, containers are loaded on board at the port. Therefore, the container export volume is constrained in three ways. The production capacity of factories is affected during the pandemic, so there might be not enough products for export. The pandemic also decreases the transportation capacity and port service capacity, transportation industry and port industry also face a labor shortage. It is possible that not all the products can be delivered to the port. Moreover, when many liner voyages are concealed under the epidemic, the shipping volume is very limited. Above all, actual container export volume is constrained by several variables and can be modeled as:

\[ CEV = \min\{AP, FV, PV, SV\} \]  \hspace{1cm} (7)

(6) Actual production volume

Actual production means the volume of products that are actually produced by Chinese factories under COVID-19 pandemic. The actual production capability of Chinese factories will be constrained by the shortage of labor and raw materials supply. To measure these constraints, a coefficient named manufacturing capacity recovery parameter \((\beta_M)\) was set to represent the recovery degree of manufacturing capacity under COVID-19 compared to the original manufacturing capacity regardless of the pandemic impacts. \(\beta_M\) is a time-varying coefficient that with the gradual recovery of the whole supply chain, the value of \(\beta_M\) will increase. The formulation of actual production volume \((AP)\) is modeled as follows:

\[ AP = P_0 \cdot \beta_M \]  \hspace{1cm} (8)

Where:

\[ P_0 = CEV_0 \]  \hspace{1cm} (9)

(7) Actual freight volume

Actual freight volume \((FV)\) is defined as the volume of manufactured products that are actually delivered from factories to ports by trucks. Apparently, \(FV\) is constrained by the actual supply of available trucks, which is determined by the available driver under the quarantine policy. Similar to the setting of manufacturing capacity recovery parameter \((\beta_M)\), the transportation capacity recovery parameter \((\beta_T)\) is set to represent the degree of the recovery of land transportation capacity by trucks. \(\beta_T\) is a time-varying coefficient that with the gradual easy of quarantine policy and the recovery of supply chain, the value of \(\beta_T\) will increase. The formulation of actual freight volume \((FV)\) is modeled as follows:

\[ FV = P_T \cdot \beta_T \]  \hspace{1cm} (10)

(8) Actual port service volume

Actual port service volume \((PV)\) is defined as the volume that a port actually handled under the impact of COVID-19 pandemic. \(PV\) is also dependent on the actual labor supply of available workforce, which is affected by the quarantine policy. Similar to the settings of \(\beta_M\) and \(\beta_T\), the port capacity recovery parameter \((\beta_P)\) is set to represent the degree of the recovery of port handling service capacity. \(\beta_P\) is a time-varying coefficient that with the easy of quarantine policy and the recovery of overall economy, the value of \(\beta_P\) will rise. Moreover, the turn over efficiency affected by the necessary epidemic prevention and control measures also matters, with \(\beta_T\) set to be the fluctuated ratio. The formulation of actual port service volume \((PV)\) is modeled as follows:

\[ PV = P_P \cdot \beta_P \cdot \beta_T \]  \hspace{1cm} (11)

(9) Actual shipping volume

Actual shipping volume \((SV)\) is defined as the actual volume that container ships transport considering both demand and supply side. On one hand, the actual shipping volume aims to satisfy the shipping demand for goods, which depends on the changeable goods consumption of the importer. On the other, under the impact of COVID-19, many shipping companies concealed liner voyages. Therefore, actual shipping capacity probably cannot meet the demand. It’s necessary to introduce a factor to describe the actual capacity. The shipping capacity recovery parameter \((\beta_s)\) is set to represent the degree of the recovery of shipping capacity. The formulation of actual shipping volume \((SV)\) is modeled as follows:

\[ SV = \min\{P'_{SV} \cdot \beta_s, P_0 \cdot \beta_3\} \]  \hspace{1cm} (12)

(10) Economic loss of the port

Economic loss of the port could be deemed as the difference between the projected income of the port by providing berthing service, port service and handling service without the impact of the COVID-19 and the projected income under the epidemic outbreak. So, the loss consists...
3 parts: berthing service loss, port service loss and handling service loss. The details are modeled as below:

\[ L_P = L_{bs} + L_{hs} + L_{ps} \]  

(13)

(11) Berthing service loss

As berthing service charge includes pilotage fee, towage fee and berthing charge, berthing service loss \( (L_{bs}) \) consist 3 parts: namely the loss of pilotage fee, the loss of towage fee and the loss of berthing charge. The detailed calculations are shown as below:

\[ L_{bs} = I_{bs0} - I_{bs} \]  

(14)

Where:

\[ I_{bs} = I_{bs} + I_{fs} + I_{bc} \]  

(15)

\[ I_{bs0} = I_{bs} + I_{fs0} + I_{bc0} \]  

(16)

\[ I_{fs} = SC \cdot NT \cdot r_{fs} \]  

(17)

\[ I_{fs0} = SC \cdot NT \cdot r_{fs0} \]  

(18)

\[ I_{bc} = SC \cdot r_{bc} \]  

(19)

\[ I_{bc0} = SC \cdot r_{bc0} \]  

(20)

\[ I_{bc} = SC \cdot NT \cdot r_{bc} \cdot T_b \]  

(21)

\[ I_{bs0} = SC \cdot NT \cdot r_{bs0} \cdot T_{bs0} \]  

(22)

\[ T_b = T_{bs0} / \beta_E \]  

(23)

(12) Port serviced ship call

The number of port serviced ship calls depends on the actual container export volume. And container ships are not usually in fully loaded condition, so the loading factor is introduced into this equation. It could be modeled as:

\[ SC = CEV / (U \cdot LR) \]  

(24)

(13) Handling service loss

Handling service income is directly affected by the number of handled containers, and Handling service loss \( (L_{hs}) \) could be modeled as:

\[ L_{hs} = I_{hs0} - I_{hs} \]  

(25)

Where:

\[ I_{hs} = I_{hs} + I_{fs} + I_{bc} \]  

(26)

\[ I_{hs0} = I_{hs} + I_{fs0} + I_{bc0} \]  

(27)

(14) Port service loss

Port service charge includes 3 parts: port due, port facility security fee, and oil containment boom usage fee. Thus, port service loss \( (L_{ps}) \) also consists 3 parts. The details could be modeled as:

\[ L_{ps} = I_{ps0} - I_{ps} \]  

(28)

Where:

\[ I_{ps} = I_{ps} + I_{fs} + I_{bc} \]  

(29)

\[ I_{ps0} = I_{ps} + I_{fs0} + I_{bc0} \]  

(30)

\[ I_{ps} = SC \cdot U \cdot r_{ps} \]  

(31)

\[ I_{ps0} = SC \cdot U \cdot r_{ps0} \]  

(32)

\[ I_{ps} = SC \cdot U \cdot r_{ps} \]  

(33)

\[ I_{ps0} = SC \cdot U \cdot r_{ps0} \]  

(34)

\[ I_{ps} = SC \cdot r_{ps} \]  

(35)

\[ I_{ps0} = SC \cdot r_{ps0} \]  

(36)

3.3.3. Scenario design

(1) Epidemic duration

To estimate the total economic losses caused by COVID-19 pandemic, the duration of the pandemic needs to be pre-determined. Since this impact has lasted for 18 months, two kinds of recovery durations are set in this research based on relative industry expert knowledge (Clarksons Research, 2020). The 1st kind is set as a moderate kind with a recovery duration of 24 months. This indicates that for some well-prepared countries and ports, the trade and business could be back to normal condition after 24 months. The 2nd kind is the pessimistic one that the pandemic will last for 36 months, then trade and business would turn to normal.

(2) Degrees of various recovery parameters

The set of degrees of different recovery parameters are critical for assessing the economic losses of port and shipping businesses. In general, we set three kinds of recovery speed with different shapes: V-shape for the fastest speed, U-shape for the moderate speed, and L-shape for the lowest speed (IMF, 2020). From the aspect of specific industry, transportation industry is mainly engaged in the domestic business, so its recovery is only related with China’s outbreak dynamic. That means transportation industry may have a relatively quick recovery. Port is faced with both domestic and foreign business, so the quarantine measures will be strict, which will hinder the recovery. Moreover, stricter port operating regulations and more onerous quarantine policies can affect turnaround efficiency, which is also related to the responsiveness of the port. As is mentioned above, factories need foreign raw materials and fuel to produce goods, and this is a complex import process involving more countries. Therefore, manufacturing is also a vulnerable spot for the recovery of whole supply chain system in this research. Shipping capacity, which is closely related to international market and foreign port capacity, is the most uncontrollable factor. And foreign demand for shipping, which usually depends on changeable commodity consumption demand, also limits the actual shipping volume simultaneously. Above all, three different modes of recovery degrees are set.

Based on the above analysis, six different scenarios are set in this study. Considering the current status of COVID-19 pandemic, the scenario with neutral mode and 24-month duration is set as the baseline scenario. Under the baseline scenario, values of \( \beta_{ps}, \beta_{hs} \) and \( \beta_{ps} \) are set based on factual situation. Influenced by the rapid rise in container market, \( r_P \) is determined by the ratio of actual freight rate from Jan 2020 to Jun 2021 to the predicted value of freight rate without the impact of COVID-19. The parameters are listed in Table 2 in details.

Scenario 1 is set as the most moderate condition. After the first year, most industries recover to the nearly normal level. Due to a more complex process covering domestic and international coordination, manufacturing and shipping capacity don’t fully recover. Scenario 2 is more optimistic than Scenario 1. In this scenario, the global outbreak is controlled successfully. So, the import of fuel and raw materials is smooth. The value of manufacturing capacity recovery coefficient (\( \beta_{ps} \)) and shipping capacity recovery coefficient (\( \beta_{ps} \)) would be larger. Scenario
Table 2  Parameters of different scenarios.

| Scenarios | Indicators               | Time (month) |
|-----------|--------------------------|--------------|
|           |                          | 1-3 | 4-6 | 7-12 | 13-24 | 25-36 |
| Scenario 1| Manufacturing capacity $\beta_M$  | 50  | 70  | 85  | 95   |  |
| Scenario 1| Transportation capacity $\beta_T$ | 50  | 70  | 90  | 100  |  |
| Scenario 1| Shipping capacity $\beta_S$       | 50  | 70  | 85  | 95   |  |
| Scenario 1| Port capacity $\beta_P$          | 50  | 70  | 85  | 95   |  |
| Scenario 1| Turn over efficiency $\beta_E$   | 80  | 85  | 90  | 95   |  |
| Scenario 1| Freight influence coefficient $\gamma_F$ | 103 | 100 | 172 | 355  |  |
| Scenario 1| Goods consumption coefficient $\gamma_C$ | 99  | 95  | 97  | 101  |  |
| Scenario 2| Manufacturing capacity $\beta_M$  | 50  | 90  | 90  | 95   |  |
| Scenario 2| Transportation capacity $\beta_T$ | 50  | 90  | 95  | 100  |  |
| Scenario 2| Shipping capacity $\beta_S$       | 50  | 90  | 95  | 100  |  |
| Scenario 2| Port capacity $\beta_P$          | 50  | 90  | 95  | 100  |  |
| Scenario 2| Turn over efficiency $\beta_E$   | 80  | 90  | 95  | 100  |  |
| Scenario 2| Freight influence coefficient $\gamma_F$ | 103 | 90  | 155 | 248  |  |
| Scenario 2| Goods consumption coefficient $\gamma_C$ | 99  | 95  | 97  | 101  |  |
| Scenario 3| Manufacturing capacity $\beta_M$  | 50  | 60  | 80  | 90   |  |
| Scenario 3| Transportation capacity $\beta_T$ | 50  | 50  | 80  | 90   |  |
| Scenario 3| Shipping capacity $\beta_S$       | 50  | 60  | 60  | 80   |  |
| Scenario 3| Port capacity $\beta_P$          | 50  | 60  | 70  | 90   |  |
| Scenario 3| Turn over efficiency $\beta_E$   | 80  | 80  | 85  | 90   |  |
| Scenario 3| Freight influence coefficient $\gamma_F$ | 103 | 110 | 189 | 426  |  |
| Scenario 3| Goods consumption coefficient $\gamma_C$ | 99  | 95  | 97  | 101  |  |
| Scenario 4| Manufacturing capacity $\beta_M$  | 50  | 65  | 80  | 90   |  |
| Scenario 4| Transportation capacity $\beta_T$ | 50  | 70  | 90  | 95   | 100 |
| Scenario 4| Shipping capacity $\beta_S$       | 50  | 70  | 85  | 90   | 95  |
| Scenario 4| Port capacity $\beta_P$          | 50  | 70  | 85  | 90   | 95  |
| Scenario 4| Turn over efficiency $\beta_E$   | 80  | 85  | 90  | 95   | 100 |
| Scenario 4| Freight influence coefficient $\gamma_F$ | 103 | 90  | 155 | 284  | 260 |
| Scenario 4| Goods consumption coefficient $\gamma_C$ | 99  | 95  | 97  | 101  | 101 |
| Scenario 5| Manufacturing capacity $\beta_M$  | 50  | 90  | 90  | 95   | 95  |
| Scenario 5| Transportation capacity $\beta_T$ | 50  | 80  | 90  | 100  | 100 |
| Scenario 5| Shipping capacity $\beta_S$       | 50  | 90  | 95  | 100  | 100 |
| Scenario 5| Port capacity $\beta_P$          | 50  | 80  | 90  | 100  | 100 |
| Scenario 5| Turn over efficiency $\beta_E$   | 80  | 90  | 95  | 100  | 100 |
| Scenario 5| Freight influence coefficient $\gamma_F$ | 103 | 90  | 155 | 284  | 260 |
| Scenario 5| Goods consumption coefficient $\gamma_C$ | 99  | 95  | 97  | 101  | 101 |
| Scenario 6| Manufacturing capacity $\beta_M$  | 50  | 60  | 75  | 80   | 90  |
| Scenario 6| Transportation capacity $\beta_T$ | 50  | 50  | 80  | 90   | 100 |
| Scenario 6| Shipping capacity $\beta_S$       | 50  | 60  | 60  | 50   | 80  |
| Scenario 6| Port capacity $\beta_P$          | 50  | 50  | 75  | 90   | 95  |
| Scenario 6| Turn over efficiency $\beta_E$   | 80  | 80  | 85  | 85   | 95  |
| Scenario 6| Freight influence coefficient $\gamma_F$ | 103 | 100 | 189 | 426  | 390 |
| Scenario 6| Goods consumption coefficient $\gamma_C$ | 99  | 95  | 97  | 101  | 101 |

Source: China Ports (2020), Jiang and Wang (2020), Clarkson Research (2020), Soyres et al. (2022).

* $\gamma_F$ is the ratio of the container freight rate under the COVID-19 impact to that without COVID-19 impact, with the values in Scenario 1 are obtained by SCFI prediction and others are adjusted around the benchmark.

* Since different scenarios are discussed for the port and shipping industry in China, and the demand side refers to foreign consumer demand, the values of $r_C$ in all scenarios are referenced to Soyres et al. (2022).

4. Numerical results and discussion

4.1. Numerical results

4.1.1. Sample port selection

With the container export volume of 43.3 million TEUs, the port of Shanghai has been the largest container port around the world for 10 years up to 2019 (Lloyd’s List, 2019). As the container shipping business is heavily hurt in the COVID-19 pandemic, the container port of Shanghai is selected as the sample port for case study in this research.

(1) Container export volume (CEV$_0$) forecast

Linear regression analysis has been widely used in port throughput forecast (Bai, 2010). Based on the historical data of container throughput of the port of Shanghai in past 10 years, a clear linear trend could be observed regardless of the COVID-19 pandemic, as shown in Fig. 3. The linear regression model is organized as equation (43) shows.

$$CEV_0 = 1.5121 \times t - 3010$$

(37)

$$R^2 = 0.9833$$

(38)

According to equation (37), the value of CEV$_0$ in 2020 is estimated as 22.23 million FEUs regardless of the impact of COVID-19 pandemic. The value of average monthly export volume is 1.81 million FEUs.

(2) Shanghai Container Freight Index (SCFI) forecast

As an index that reflects the freight rate level of container shipping, the Shanghai Container Freight Index (SCFI) is selected to represent the freight rate (FR) in this research. As Fig. 4 shows, SCFI is a nonlinear and nonstationary time series data. An ARIMA (2,1,2) model of SCFI can be obtained by constructing ARIMA model (Li et al., 2019). The predicted values of SCFI (FR$_0$) are listed in Table 3.

4.1.2. Sample vessel selection

To calculate the economic loss, some parameters of container ships calling at the port of Shanghai should be specified. A virtual container ship on an average size based on historical statistics is constructed in this paper to simplify the calculation. The size of this sample vessel is on the average size of global total container ships. The parameters are listed in Table 4 in details. The detailed charge rates of port services are listed in Table 5, according to relevant regulations by Chinese maritime administrations.

4.1.3. Model validation and numerical analysis results

To verify the model structure and parameter setting reasonability, model validation is necessary. The indicator port loss ($L_P$) is selected to compare with the reference value. Some related parameters are listed in Table 6. The reference value contains the overall income from all kinds of ship services, is from the annual report of Shanghai International Port (Group) Co., Ltd. (2019). As Table 6 shows, the simulated value of port loss is $1.05 \times 10^8$ USD, which equals to 31% of the official port service income. Apart from container ships, there are many other kinds of ships calling at the port of Shanghai, e.g., oil tankers. Thus, the ratio of
simulated value of port loss to port revenue values about 0.31 is acceptable for further research. Under S1, total economic income both from the port and shipping sector worth $1.707 \times 10^{11}$ USD during the 24-month pandemic assumption. It should be noticed that income from shipping and port industry are not in the same order of magnitudes. Nearly all of the monthly income consists of shipping income, while port income only accounts for less than 1%.

Fig. 5 shows the evolution trend of port and shipping monthly income difference compared to condition without the epidemic. If the difference value is positive, the income under the epidemic is higher than the condition without impact. Conversely, if the difference value is
negative, income after outbreak is lower than it should be without impact. And economic loss appears. There are mainly three stages during twenty-four months. Social production recovers gradually after the quarantine measures in the first six months after outbreak. It can be seen that port loss in the 4–6 month is less than the first three months. However, all the industries maintain a low level in the first six months, so the income is still lower than normal level. In the next six months, with continuous rising production capacities and recovering efficiency, the actual export volume also rises. Besides higher port service income, booming shipping demand leads to higher freight rate. As the figure shows, shipping income gradually returns to normal and even increases to several times than normal level at the end of 2021. In the second year after the outbreak, shipping freight rate stays high, because global port and shipping system is inefficient. For port income, although transportation industry recovers thoroughly, it is still below the level without impact. That’s because shipping industry and manufacturing industry don’t return to the normal capacity. And the restricted turn over efficiency also presents a challenge.

Economic losses under different scenarios are shown in Fig. 6a and b. For clarity, 6 scenarios are drawn in two figures according to different assumptions on epidemic duration. Fig. 6a shows the trend of monthly loss under the assumption that the impact of COVID-19 will end in twenty-four months. In the first three months, the development of these three lines is accessible. Scenario 2, as the most optimistic scenario, recovers fastest, while the most pessimistic Scenario 3 recovers relatively slower. And in the next nine months, income under Scenario 2 is slightly more than Scenario 1, in spite of the lower freight rate in Scenario 2. To be sure, the setting of freight rate in Scenario 2 is based on the consideration that global outbreak is under control, and all the ports can operate normally. Moreover, lack of container and shipping capacity alleviates, so the freight rate fall back. And with the lowest capacity in

Table 5
Service fee rate.

| Parameter | Unit | Value   |
|-----------|------|---------|
| \( r_{pl} \) | US$/ton | 0.06471 |
| \( r_{lw} \) | US$/ship call | 1581.823 |
| \( r_{bc} \) | US$/ton/day | 0.03595 |
| \( r_{pd} \) | US$/FEU | 4.8892 |
| \( r_{hs} \) | US$/ship call | 1.7256 |
| \( r_{pd} \) | US$/FEU | 575.2 |
| \( r_{bu} \) | US$/FEU | 2.5884 |
| \( T_{b} \) | day | 1 |

Source: Port of Shanghai (https://www.portshanghai.com.cn/tjsj/index.jhtml), Investing.com (https://cn.investing.com/currencies/usd-cny-historical-data). * USD/RMB exchange rate: 1: 6.954 (2020-08-14).

Table 6
Estimated port loss.

| Reference value of port service revenue (USD/year) | Simulated value of port loss in 2020 under BAU(USD/year) | Ratio (%) |
|---------------------------------------------------|---------------------------------------------------------|-----------|
| \( 3.384 \times 10^8 \)                          | \( 1.05 \times 10^8 \)                                   | 31%       |

Fig. 5. Economic loss under Scenario 1.

Fig. 6a. Monthly loss under Scenario 1-3.
all industries, Scenario 3 attains the minimum income, but monthly income is still $2.393 \times 10^9 \text{ USD}$ more than normal level in the 12th month. During the following twelve months (13–24), monthly income declines generally, but differences among 3 scenarios still exist. High freight rate in Scenario 3 offset lower capacities compared to Scenario 1. Scenario 3 attains the highest monthly income in these 3 scenarios, with $7.835 \times 10^9 \text{ USD}$ more than normal level in the 24th month, and Scenario 2 attains the lowest due to the return to normal freight rate. The shipping and port industry stops suffering economic loss at month 9, 8, and 10 respectively in these three recovery scenarios.

Fig. 6b is similar to Fig. 6a in general. Three modes may show different in detail, because of the setting of parameters. It needs to be emphasized that the surge of monthly income usually appears in the first year, and income may decline gently in the following months. In general, the recovery speed is highest in the first few months, and slows down gradually. Therefore, releasing traffic and port constraints in time is essential to loss reduction.

And both the containment of outbreaks and raising a blockade reasonably are important for resuming port and shipping industry. Moreover, cask effect is pronounced in the resumption of social production, which needs support from all these industries.

Fig. 7 shows the difference of total income ratios under different scenarios compared to BAU. The difference of income calculated in this figure is accounted during the whole epidemic duration. It’s clear that Scenario 4 achieves the highest income, which is nearly twice the BAU. It is worth mentioning that all of the four capacities mentioned in this scenario have a quick recovery, freight rate remains high for the longest duration. In contrast, under the fastest recovery condition, S2 produces economic income 41.28% lower than BAU. That’s the result of relatively lower freight rate.

This result indicates that the economic income is not always positively associated with the recovery speed. Because the shipping income is much larger than port income, the lack of production capacity can be offset by high freight from the aspect of total income.

4.2. Sensitivity analysis and discussion

Previous calculation results indicate the trend of economic losses from the view of industrial chain. However, microscopic constraints should also be considered. Therefore, 2 ship parameters are selected for a sensitivity analysis to investigate how ship conditions affect the overall economic loss of port and shipping business. Moreover, 1 port parameter is selected to investigate the significance of operation capability.

Figs. 8 and 9 show the economic losses with different loading rates and container carrying capacities under the BAU. Fig. 10 shows the impact of port turnover efficiency. To investigate the specific influence mechanism of shipping condition on port loss, 3 parts of port loss: loss of port service charge, loss of berthing service charge and loss of handling service charge are drawn separately.

4.2.1. Loading rate

Loading rate represents the utilization rate of ship carrying capacity (Sun et al., 1993). From Fig. 6, we would find that when the loading rate increases, economic loss rises obviously. The loading rate is set as 0.9 in BAU, with $1.30 \times 10^8 \text{ USD}$ port loss (reducing by 23.95% compared to the situation without COVID-19 impact). When loading rate decreases to 0.7, port loss brought by the epidemic can be nearly offset. With a 0.5 loading rate, port income can even increase $2 \times 10^8 \text{ USD}$ (increasing by 36.89%) compared to the situation without the impact of epidemic. And when loading rate is 1, which means all of container ships are fully loaded, port loss will have an increase of $1.713 \times 10^8 \text{ USD}$ (reducing by 31.56%). And this upward trend slows down with the increase of loading rate. From Equ.(24), it could be seen that the number of port serviced ship calls is inversely proportion to loading rate, so the value of ship calls declines as the value of loading rate increases. It means that with the increase of loading rate, the same difference of loading rate will lead to less difference of ship call ($SC_{SC_0}$). When the average loaded containers have reduced, to maintain the same number of handled containers, more containerships would be calling at the port, thus more revenue could be made by the port. It helps reduce the economic loss for
4.2.2. Container carrying capacity

Fig. 10 shows the economic loss under different container carrying capacity. Nine sample vessels with different capacities are selected for sensitivity analysis. It could be seen that loss of port service charge ($L_{ps}$) and loss of berthing service charge ($L_{bs}$) maintain a growing trend with the increase of container carrying capacity generally. While loss of handling service ($L_{hs}$) remains relatively stable. When the average carrying capacity increases to 7000 FEUs, port loss will increase by $1.306 \times 10^7$ USD compared to BAU (2.41% on the basis of normal situation) during the epidemic. Loss of berthing service charge contributes more than 80% to this increases within port loss. Loss of port service charge accounts for 19%, while loss of handling service charge doesn’t change. That’s because when the carrying capacity increases, the size of the whole ship enlarges besides net tonnage. Berthing service charges according to net tonnage, and when net tonnage increases, rates (USD/NT) will reduce.

In a word, the average berthing service charge rate declines with the increase of ship size. And this law also applies to port service charge. For handling service, it charges according to number of containers. With the total number of containers staying the same, port service charge doesn’t change. Conversely, when the average carrying capacity is 2000 FEUs, port loss will decrease by $1.306 \times 10^7$ USD compared to BAU (3.54% on the basis of normal situation) during the epidemic.

4.2.3. Port turnover efficiency

The turnover efficiency reflects, to some extent, the port’s ability to respond to emergencies under an epidemic. It can be seen from Fig. 10 that generally the higher the efficiency, the lower the loss. With the increase in port turnover efficiency, the loss of port service charge ($L_{ps}$) and port handling service ($L_{hs}$) have significant decrease, with a 66.55% reduction from the worst to the best case. When the turnover efficiency is below 65%, the loss of handling service ($L_{hs}$) is lower than the loss of berthing service ($L_{bs}$) while the opposite is true when it is higher than 65%. The $L_{ps}$ remains the largest share of the three types of losses.
though. Therefore, it is necessary to improve the service resilience and emergency response capacity of the port.

5. Conclusion and policy implications

5.1. Conclusion

This article focuses on the effect mechanism of COVID-19 pandemic on shipping and port industry and calculating the economic losses. To evaluate the economic impact of COVID-19, different scenarios on epidemic durations and various capacity recovery rates are set. Main conclusions are drawn as bellow:

➢ As shipping and port industry is a complex system, a SD model with five subsystems is established to evaluate the potential economic losses induced by the COVID-19 pandemic. It could be found that cask effect is pronounced in the operation process. The actual container export volume under the impact is bound to four aspects directly: actual production, freight volume, port service volume and actual shipping volume determined by shipping capacity supply and demand. It means that the lack of any aspect will influence the export business.

➢ 6 scenarios with different conditions of epidemic duration and various capacity recovery rates have been set to investigate the trend of economic income. The reliability of the calculation results has been verified by the comparison of simulation data and reference data. Under the BAU scenario (a two-year duration recovery scenario), the model predicts that the total economic income of container business of the port of Shanghai and the container shipping business will be $1.707 \times 10^{11}$ USD. Shipping industry income is significantly larger than the port service income.

➢ The epidemic duration can affect the income effectively. However, duration is not the only decisive factor for income. Proper policies can also ease the impact of outbreak and even offset the loss brought by longer duration.

➢ Loading rate, ship capacity and port turnover efficiency can affect the port loss. It’s found that decreasing loading rate and improving turnover efficiency can reduce port loss effectively. Using smaller ships can also achieve the same trend, the effect is not obvious though.

5.2. Policy implications

As the simulation results show, the impact of COVID-19 pandemic can affect shipping and port income directly from many aspects, such as shipping capacity, port capacity and transportation capacity. And with proper policies and control measures, economic losses of the port and shipping system can be eased and even offset. Loss reduction in shipping and port industry needs joint efforts from the parties of related governments, port operators and shipping companies, etc.

From the perspective of regulative administrations, we suggest that a strict control policy should be issued in the early stage of this epidemic. When conditions are stable, some constraints can be removed gradually. As a result, the society can start to resume earlier after the temporary shock, which can cut down loss effectively. For port operators, ships with lower loading rate and smaller size can bring more service charge, and reduce some port loss. However, this assumption may conflict with ship owners whose preference is for vessels with higher loading rate and larger size for the control of operation cost. For port authorities, it is important to enhance the port’s service capacity resilience and emergency response capability, which is related to the management level, technical support, etc. For shipping companies, a smart plan of shipping routes arrangement is necessary, which can improve the operation efficiency and shorten the voyage time. Then the operation cost can be saved. Finally, as a crucial part of global supply chain, business activities of shipping and port industry are under the impact at home and abroad. The lack of any production factor in the world can affect its normal production process. And the inefficiency in one port can cause the fluctuation of freight rate in other countries. Different countries should work together to promote economic recovery thus.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.
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Appendix

Table 7
Notation table

| Parameter | Description |
|-----------|-------------|
| $L_T$     | Total loss in USD |
| $L_M$     | Monthly loss in USD |
| $D$       | Outbreak duration in months |
| $L_S$     | Economic loss of shipping industry in USD |
| $L_P$     | Economic loss of port in USD |
| $I_D$     | Projected income of shipping industry without impact of COVID-19 |
| $I_S$     | Economic loss of shipping industry in USD |
| $I_P$     | Economic loss of port in USD |
| $F_{RE}$  | Freight rate without impact of COVID-19 in USD/FEU |
| $CEV$     | Container export volume without impact of COVID-19 in FEU |
| $FR$      | Freight rate under impact of COVID-19 in USD/FEU |
| $AP$      | Actual production volume in FEU produced by factories |
| $PV$      | Actual freight volume in FEU carried by trucks |
| $SV$      | Actual shipping volume in FEU carried by ships |
| $P_0$     | Production volume without impact of COVID-19 in FEU |
| $P_M$     | Manufacturing capacity recovery parameter |
| $P_T$     | Transportation capacity recovery parameter |
| $P_{ps}$  | Port service capacity recovery parameter |
| $P_{IE}$  | Turn over efficiency recovery parameter |
| $P_S$     | Shipping capacity recovery parameter |
| $I_{pf}$  | Income of pilotage fee with impact of COVID-19 in USD |
| $I_{pf0}$ | Income of pilotage fee without impact of COVID-19 in USD |
| $I_{tf}$  | Income of towage fee with impact of COVID-19 in USD |
| $I_{tf0}$ | Income of towage fee without impact of COVID-19 in USD |
| $I_{bc}$  | Income of berthage charge with impact of COVID-19 in USD |
| $I_{bc0}$ | Income of berthage charge without impact of COVID-19 in USD |
| $I_{hs}$  | Income of handling service with impact of COVID-19 in USD |
| $I_{hs0}$ | Income of handling service without impact of COVID-19 in USD |
| $I_{pd}$  | Income of port due with impact of COVID-19 in USD |
| $I_{pd0}$ | Income of port due without impact of COVID-19 in USD |
| $I_{fd}$  | Income of port facility security fee with impact of COVID-19 in USD |
| $I_{fd0}$ | Income of port facility security fee without impact of COVID-19 in USD |
| $I_{bs}$  | Income of oil containment boom usage fee with impact of COVID-19 in USD |
| $I_{bs0}$ | Income of oil containment boom usage fee without impact of COVID-19 |
| $SC$      | Monthly number of ships calling at port without impact of COVID-19 |
| $SC_0$    | Monthly number of ships calling at port with impact of COVID-19 |
| $NT$      | Average net tonnage of ships in ton |
| $T_b$     | Average berthing time of a ship in port in days without impact of COVID-19 |
| $U$       | Average size of container ships in FEU |
| $LR$      | Average loading rate of container ships |
| $r_{pl}$  | Average unit pilotage fee rate in USD/ton |
| $r_{tw}$  | Average towage fee rate in USD per ship call |
| $r_{bc}$  | Average berthing charge rate in USD/ton/day |
| $r_{th}$  | Average terminal handling fee rate in USD/FEU |
| $r_{pd}$  | Average port due rate in USD/FEU |
| $r_{fs}$  | Average port facility security fee rate in USD/TEU |
| $r_{bo}$  | Average oil containment boom usage fee rate in USD per ship call |
| $t$       | Year |

References

Bai, W., 2010. Xiamen Port logistics development trend forecast and strategic positioning. China Water Transport 10 (12), 45–47.
