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An analysis of port congestion alleviation strategy based on system dynamics

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ABSTRACT

Port congestion has become a key factor restricting the international trade and economic development, especially during the COVID-19 epidemic. It is essential for the port to implement the effective alleviation strategies for handling the uncertain congestion. This paper aims to investigate the performance of the epidemic prevention alliance strategy (EPAS), shared berths strategy (SBS) around adjacent ports and their hybrid strategy in alleviating the port congestion. To simulate the effect of these three strategies, a system dynamics model of dual-port operation is developed considering the factors of the integrated service level of liner routes, empty container allocation, port congestion and regional economics, and so forth. The results indicate that the key issue of port congestion stems from the implementation of epidemic preventive measures. Among these three strategies, the hybrid strategy performs the best in alleviating the port congestion, improving integrated service levels, and curbing the fluctuation of container price. Moreover, the measures of investing more human resources and fixed assets are always taken in many current ports to alleviate the issue of port congestion. Therefore, the impacts of various investment in human resources and fixed assets on alleviating the port congestion are discussed. Finally, some suggestions are provided for the government to strengthen the cooperation between ports and promote the construction of port facility resources.

1. Introduction

Due to the strong infectivity and high concealment, COVID-19 has become a Public Health Emergency of International Concern (PHEIC), which has significantly affected the development of human society in every aspect (The Lancet Public Health, 2020). After initial exposure to the COVID-19, people have gradually recognized that the way of COVID-19 transmission is not limited to the human-to-human transmission, and also includes the goods-to-human transmission, especially in the trans-regional logistics transportation including the sea logistics and air logistics (Calatayud et al., 2022). The uncertainty of epidemic spread increases with the mobility of cargo, which leads to the necessary strengthening of epidemic prevention and control in some regions centered on port.

The hub ports in many countries have taken strict measures to prevent the spread of COVID-19. For instance, ships calling at ports or replacing crew in the region affected by the COVID-19 are prohibited from boarding Tianjin Port within 14 days. In addition to the above restrictions, crew members are required to conduct nucleic acid tests for many times in Ningbo Port. The prevention period is extended to 28 days in Fangcheng Port. The similar precautions are implemented in the United States, India, Turkey, Australia and other countries (Steinbach, 2022). The strict preventive policies make many ships extend their voyage periods and lead to the congestion of ships at the anchorage. According to the data of sea explorer disruption indicator from Kuehne & Nagel in 2021, “Due to the COVID-19, a total of 612 container ships are berthing or drifting outside ports including Los Angeles, Long Beach, Seattle, Vancouver, Prince Rupert, Auckland, New York, Savannah, Hong Kong, Shenzhen, Shanghai, Ningbo, Rotterdam and Antwerp”¹. The average waiting time of the ship is 17.7 days in the most congested ports of Los Angeles port and Long Beach port.²

In response to the increased extent of congestion, some alleviation

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² FACT SHEET: “Waiting for berthing for an average of 17.7 days, the port is heavily congested! The ship company suspended the Asia-Los Angeles route.”. https://www.163.com/dy/article/GUFM4A0805520U9L.html

FACT SHEET: “612 ships congested worldwide! 11.6 million TEUs cumulatively affected at nine major ports! Los Angeles and Long Beach ports 103 ships”; https://news.sohu.com/a/501895710_100246553,
strategies can be taken in the ports to reduce the pressure on the port operations. The epidemic prevention alliance strategy (EPAS) and the shared berths strategy (SBS) around adjacent ports attracted much attention (Wang and Gan, 2018; Li et al., 2020). As a kind of collaboration mechanism and partnership, the port alliance strategy indicates the advantages of sharing the information and resources among ports. As one type of the port alliance strategy, the EPAS is implemented between ports to prevent the spread of COVID-19 through ships during the special period of the epidemic outbreak. By establishing a mutual trust system and information communication mechanism, the exchange of epidemic information among ports can be achieved to reduce the isolation time and control the spread of the epidemic. For instance, in the ports of Guangdong, Hong Kong, and Macau, a mutual recognition mechanism for nucleic acid testing of COVID-19 is introduced and utilized for monitoring the movement of people at ports. Based on this mutual recognition mechanism, the port epidemic prevention alliance system is established by incorporating the epidemic information sharing, mutual recognition of isolation measures, prevention and control mechanisms. This EPAS has improved the capability of ports in Guangdong, Hong Kong, and Macau in responding to the epidemic. Meanwhile, when the port congestion has occurred, the SBS is designed to alleviate the congestion in the port by forming a sharing mechanism with adjacent ports and temporarily renting the idle port resources. The SBS was adopted in Zhongshan Port to deal with the shortage of port production resources. According to the relevant research, the EPAS and SBS have the following advantages: First, the formation of an epidemic prevention alliance in ports is conducive to the exchange of epidemic information and operational data between ports. In addition, the EPAS also facilitates ports to take preventive measures against epidemic-related vessels in advance. Second, the SBS can integrate the resources of the port berth in the region, which helps alleviate the congestion pressure of hub ports. Moreover, the SBS can improve the competitive edge of bilateral ports and create the economic value for regional ports. Third, when the EPAS and SBS are implemented simultaneously, the hybrid strategy indicates the advantages of both strategies, i.e., the hybrid strategy not only enables the sharing of epidemic prevention information and cooperative prevention and control of epidemics, but also improves the utilization of idle port resources, thus improving the ability of handling the port congestion problems.

Although both of EPAS and SBS have the advantage of alleviating the port congestion, their actual impacts on port operations remain uncertain. In particular, the EPAS or SBS is always implemented individually by port managers for port governance efforts. The impacts of simultaneously applying the two strategies to mitigate the port congestion mitigation need to be further studied. On the other hand, in the post-COVID-19 era, the port congestion may occur occasionally with the spread of the COVID-19. To eliminate the economic losses, a reasonable solution for the spread of the epidemic through the marine transportation network has become an urgent need for port managers. However, these problems need to be handled not only from the perspective of a single port, but also from the perspective of the shipping network and supply chain. Therefore, it is very necessary to propose a normalized alleviation strategy for port epidemic prevention in the post-COVID-19 era to alleviate port congestion and improve the operational efficiency of ports.

In this paper, facing the increasing pressure from intense congestion, we explore the effectiveness of strategies in alleviating the port congestion and the impacts of strategies on the port operations. Specifically, a port operation system consisting of dual-port on the same liner routes is considered. Both ports can choose whether to use the EPAS, SBS or their hybrid strategy to deal with the port congestion. It is worth noting that the two ports in the model are in the same macro environment but different hinterland environment. Hence, the system truly reflects the impacts of different strategies on various aspects of port operations. In addition, we discuss the impacts of existing strategies on relieving the port congestion based on the dual-port operation model. Accordingly, it is necessary to answer some important questions as follows. (1) What are the impacts of three different strategies (including the EPAS, SBS and their hybrid strategy) on the port operations, respectively? (2) Which strategy is more effective to alleviate the port congestion? (3) How will the different strategies, such as the EPAS, SBS and their hybrid strategy, affect port operations in the future? (4) What is the performance of adopting the existing strategies and joint strategies (i.e., implement the existing strategies and the hybrid strategy simultaneously) in reducing the port congestion?

Utilizing the system dynamics, a model of dual-port operation is developed in this paper. For this model, there are three subsystems (i.e., the integrated service level subsystem, the congestion subsystem and the container allocation subsystem) in the single-port operation system. And we collect monthly data from 2019 to 2021 to truly reflect the port operation, including the total import and export, container throughput, liner service level and container freight index, and so forth. Based on this model, we investigate the impacts of the EPAS, SBS and their hybrid strategy on the port congestion, and then explore the key issues affecting the port congestion. Moreover, the impacts of existing strategies on port operations are studied by varying the coefficients of the investment in human resource and fixed asset in the model. The main contributions of this paper are summarized as follows.

First, this study explores the effectiveness of strategies in alleviating the port congestion during the epidemic by using the system dynamics. Different from previous studies, we construct a system dynamics model from the perspective of dual-port operations. Facing the port congestion, the operations of two ports on the same route are simulated. Various factors affecting port operations are considered in the model to show the impacts of different mitigation strategies on port congestion. In particular, the statistical data on port operations after the epidemic, is utilized to explore the effective ways for addressing the port congestion in the post-epidemic period. It is rarely paid attention in the previous literature. Moreover, this study analyzes the causal relationship between the port congestion and port operation, as well as the relationship between the regional economy and the macro environment. Hence, the theoretical support for discussing the effectiveness of alleviation strategies is provided from a systematic perspective. The final results can provide policy implications for the port congestion during the epidemic.

Second, three alleviation strategies are compared on a system with two ports on the same liner route located in different regions, where the adjacent ports of each port can provide shared berths. The effectiveness of mitigation strategies is discussed in most existing literature from the perspective of a single alleviation strategy for a single port operation. Different from previous studies, this study compares the effectiveness of alleviation strategies in the framework of dual-port operations. Moreover, the effectiveness of different strategies is discussed with regard to the level of integrated service, fluctuations of container rental price and container allocations. Among three studied strategies, the hybrid strategy of EPAS and SBS is shown to perform the best in alleviating the port congestion. And the prevention and control of epidemics is shown to be crucial to alleviate the port congestion.

Third, the existing alleviation strategies (i.e., the investment in more human resources or fixed assets) are explored using a system dynamics model of dual-port operations. Meanwhile, we also compare the existing alleviation strategies with the three strategies, and then apply them jointly. In this study, these strategies are applied to the part of marine shipping chain consisting of routes and ports, and then the effectiveness of port congestion alleviation with these strategies is investigated. The results show that the combination of these existing strategies with the hybrid strategy of EPAS and SBS has a significant impact on alleviating the port congestion.

Additionally, we also obtain some managerial insights of this study. First, the effectiveness of three different strategies (i.e., the EPAS, SBS and their hybrid strategy) on the serious port congestion is studied from the perspective of system dynamics. The results indicate that the key issue of port congestion stems from the implementation of epidemic
preventive measures. And the hybrid strategy is shown to perform the best in alleviating the port congestion among three studied strategies. In addition, the alleviation strategies are not only effective in reducing the port congestion, but also have a significant effect on stabilizing the supply of empty containers and curbing the fluctuations of container rental price. Second, this study can help ports evaluate the impacts of the alleviation strategies of port congestion on port operations, and provide the related policy recommendations. The expand of port’s intrinsic resource endowment is shown to play an important role in enhancing the integrated service level of port in the future. The integrated service level of the port is significantly improved when the production resources in the region are enhanced by using the SBS or investing more fixed assets. But the coordination and cooperation of relevant departments is required. Increasing investment in human resources has a slight effect on alleviating congestion, which is limited by the relationship between the human resources and production berths.

The remainder of the paper is organized as follows. Section 2 reviews the existing literature about the port congestion and system dynamics; Section 3 introduces the research framework, model construction and the data, and in Section 4, the simulation results of port congestion under different strategies are discussed; Section 5 analyzes the performance of existing measures (i.e., investment in human resource and fixed asset) and joint strategies (i.e., implement the existing strategies and the hybrid strategy simultaneously) implemented by some ports in alleviating the port congestion; Section 6 concludes this paper.

2. Literature review

In this section, there are two subsections about reviewing two aspects of related literature: (1) port congestion issues and alleviation strategies; (2) system dynamics. The first subsection discusses the impacts of port congestion issues and alleviation strategies on regional economies and ports under the COVID-19 outbreak, while the second subsection reviews the literature about the system dynamics.

2.1. Port congestion issues and alleviation strategies

In the past decade, the research on port congestion has always been a key issue in the field of port, especially in the case of global emergencies, such as natural disasters, financial crises and epidemics. Considerable studies are focused on the impacts of congestion on regional economies and ports under emergencies. Taking the monthly trade data from the United States into account, Steinbach (2022) evaluated the results of port congestion and container shortage on the west coast of the United States under COVID-19. Similarly, by collecting the panel data of 14 major ports in China, Xu et al. (2021) investigated the effects of macroeconomic, epidemic changes and government measures on port operations during the epidemic period. The time costs and economic costs will be increased by the congestion. Then the congestion will be transferred to the other ports (Fan et al., 2012). Therefore, several studies reached the same viewpoint that the COVID-19 pandemic brought devastating results to ports, goods, and regions. This result also propagates through the global supply chain, value chain and logistics operation (Ferrari et al., 2021). Additionally, the level of port integrated competitiveness is also related to port congestion. For ports, they are facing uncertain challenges in the global container transportation system and the congestion will also have an impact on port competitiveness (Halim et al., 2016). Zhou et al. (2022) took Shanghai port as the research object to explore the impacts of COVID-19 on container port operation, clarify the potential economic losses of the port and especially point out the importance of port handling efficiency in reducing economic losses and competitiveness.

To alleviate the challenges of port congestion from the COVID-19 outbreak, several papers proposed different solutions and formed a basic research consensus. On the one hand, some researchers argued that port congestion can be alleviated through a port alliance or alliance between ports and shipping companies. Ports in the same region should form a comprehensive multi-port system and strengthen cooperation (Li et al., 2022a,b), which helps to integrate the production resources of ports in the region, solves the problem of a structural surplus of berth resources (Li et al., 2020) and improves the competitiveness of ports (Luo et al., 2022; Shi et al., 2020). In addition, the port alliance mechanism could make a positive contribution toward constructing a collecting and dispatching system (Wang and Gan, 2018) and bring benefits such as trade facilitation and revenue maximization to ports (Dong et al., 2018). Meanwhile, the strategy of the port alliance made a positive effect on port governance (Oliveira et al., 2021). On the other hand, some studies proposed the viewpoint from the perspective of port management and construction to alleviate the problem of congestion. Port berths are considered as essential production resources, which need to be rationally managed. Saeed and Larsen (2010,2016) used the queuing theory to alleviate the congestion of container terminals. This research observed that increasing the number of berths can expand the production capacity and reduce the waiting time for ships. Hjørnaes et al. (2017) discussed that from the perspective of empty container transportation and flow, it can help to alleviate port congestion. Leachman and Jula (2011) indicated that evaluating the infrastructure, managing staffing level and planning operation schedule also need to be considered in port management. Compared with above studies, the existing port berths should increase utilization and service availability (García-Morales et al., 2015; Kim et al., 2022).

By summarizing the literature on port congestion issue and alleviation strategies show that there are more solutions for port congestion, but the application of different schemes has special scenarios. In most cases, port alliance and shared berths are adopted to deal with port congestion. Then, how to test the effectiveness of the strategies is the key to the problem. Furthermore, much of the previous literature has focused on congestion mitigation at a single port, and rarely studied it from the perspective of route operations and multi-port operations. Therefore, our study focuses on the strategies adopted by two ports on the same route to cope with congestion and examines the effectiveness of the strategies.

2.2. System dynamics

System dynamics is considered as a powerful method of system simulation, which is used to describe, visualize and analyze the complex dynamic system problems with nonlinear relationships (Wu and Zheng, 2022; Li et al., 2015). System dynamics is widely used to analyze complex system problems, such as subsidy, energy and enterprise operation. In terms of the study of government subsidy, Jin and Zheng (2022) used system dynamics to study the strategic choice of core enterprises to subsidize small and medium-sized enterprises under government regulation to achieve pollution co-governance. By using the same theory, Wang et al. (2014) also discussed the impacts of government subsidies on automobile manufacturing enterprises. In addition, this method also plays a great role in energy research, such as the effects of electric vehicles on greenhouse gas emissions and climate change (Kim et al., 2021), and the effects of photovoltaic industry policy (Zhao et al., 2021).

System dynamics is also expanded in port research. Hou (2010) developed the system dynamics model of the port economy from the perspective of the dynamic mechanism of sustainable development. The study indicated that port economic development depends on the functions of the port and the expansion of functions need economic development support. The port group economy, environmental pollution and shared berths are considered by Zheng et al. (2020), and they constructed a system dynamics model to describe these three subsystems. They found that reasonably setting the berth service mode of each port and the berth proportion can effectively reduce the final pollution of the port group and realize the green economic growth of the port group. Similarly, by using the system dynamics model, Li and Zhen (2016)
constructed a container route transportation complex system, including a demand subsystem and capacity subsystem.

Most studies have applied the system dynamics to the development of energy, subsidies, and regional economic. Although there are a small minority of studies applying the system dynamics to the field of port group development, a relatively smaller number of studies have applied the system dynamics to the port congestion strategies. In this study, the issue of port congestion and its solution strategies are considered as essentially a complex giant system, which is accompanied by complex dynamics such as dynamics, time delay and nonlinearity. Due to the wide range of promising achievements of system dynamics in modeling complex systems, we apply this method to study the port congestion problem.

3. Methodology

3.1. Research framework

The purpose of this paper is to explore the impacts of EPAS, SBS and their hybrid strategy on port congestion and operation. Therefore, this paper constructs a dynamic model based on system dynamics to discuss the impacts of different strategies on port congestion. The research framework of this paper is shown in Fig. 1.

3.2. Model framework

The objective of this study is to apply the system dynamics to develop a dual-port operations model and then analyze the impacts of EPAS, SBS and their hybrid strategy on the port congestion. Therefore, this model is established based on the following settings: (1) Two ports are affected by the same macro situation, such as changes in the situation of COVID-19, changes in route freight rates and container rental prices. (2) Two ports can choose whether to form an alliance for epidemic and use shared berths provided by adjacent ports. (3) Some adjacent ports of the two ports each offer shared berths. (4) Empty containers can be transferred between A and B by the liner. Based on this, this paper draws the causality diagram of single port operation, as shown in Fig. 2.

The explanations of the causality diagram (Lee et al., 2020) of the model are as follows.

(1) Port congestion is a driving force in the adoption of the EPAS in the port. When the port is congested, it will bring tremendous pressure to the port operation and adversely affect the stability of the supply chain (Ferrari et al., 2021; Narasimha et al., 2021). Under the strict epidemic preventive and control measures, the port is more willing to ally to reduce the increase in waiting time and economic cost caused by epidemic prevention (Fan et al., 2012). The port alliance can increase the throughput of ports, promote the development of the regional economy and improve the level of integrated service (Guo et al., 2021).

(2) The utilization of port resources is improved by the SBS. By forming a cooperation mechanism between the ports, the resources of berths in adjacent ports can be integrated, which can alleviate the congestion problems faced by hub ports (Li et al., 2018, 2022a,b; Li et al., 2022a,b). By using the SBS, the problem of congestion can be alleviated at hub ports and the supply chain can be stabilized (Li et al., 2020).

(3) The port congestion has a significant impact on the economics of the international trade system for container shipping, especially the freight price of liner routes and the container rental price. When the congestion occurs, it directly leads to a serious shortage of shipping service supply and a grave imbalance between supply and demand. Then, the freight price of the liner route will continue to change with the severity of congestion (Muravev et al., 2021). Meanwhile, the containers for shipping will also be over-stacked in a single port. For these reasons, the phenomenon of “One container is difficult to find” will occur in other ports on the same liner route, which leads to the soaring rental price of containers and promotes the willingness of ports to stabilize the
price of the liner route and containers by using liner ships to container allocation. Taking the Sino-US west coast container line transportation as an example, port congestion still exists at present and will continue for a long time in the future.

3.3. Model flow diagram

By drawing the causality diagram, the main modules involve in the system of single port operations are determined. Then the system of single port operations is expanded into the system of dual-port operation. We draw the stock-flow diagram of the dual-port operation system with Vensim PLE (as shown in Fig. 3.). The key variables in this paper are the integrated service level of the port, the cumulative usage of shared berths, the cumulative quantity of the container inventory and cumulative surplus of container allocation. Therefore, this model sets 8 state variables in the system dynamics model: Integrated service level (A, B), cumulative usage of shared berths (A, B), cumulative quantity of container inventory (A, B) and cumulative surplus of container allocation (A, B). Due to the space limitation, the main equations are listed in this paper.

3.3.1. Integrated service level of port subsystem

The integrated service level subsystem primarily focuses on evaluating the port service level in the process of port operation, as well as the impacts on other subsystems. According to the relevant literature (Kaliszewski et al., 2020; Zhou et al., 2022), the level of the integrated service is influenced by many factors, including the throughput of the container, the investment in the fixed assets and the integrated service level of the liners. Based on historical data, the total import and export trade, the number of berths, the quantity of container throughput and the fixed asset investment have been in growth in the past, which contribute to the change in the integrated service level of the port (Garcia Morales et al., 2015). Meanwhile, the integrated service level of the liners, the container freight index and other factors will constantly fluctuate with the change in the macro-environment. However, during the epidemic period, the preventive and control measures will be a new challenge to the integrated service of the port. Therefore, the variable’s equations in this subsystem can be expressed as follows.

According to the relevant researches (Beşikçi et al., 2016; Zhang et al., 2022), the construction of an evaluation index system for the port is a scientific way to evaluate the integrated service level. The introduction of an evaluation index system aids in fully understanding the characteristics of port operations and reasonably assessing the impacts of mitigation strategies on port operations. Therefore, based on previous studies, we select some statistical indicators (as shown in Table 1.) and obtain the data fitting equation characterizing the change rate of the integrated service level (Zhang et al., 2021):

\[
\text{Change rate of integrated service level} = 0.01 \times \log (\text{Integrated service level of liner} + \text{Fixed asset investment} + \text{Total volume of import and export trade} + \text{Container throughput} \times (1/\text{Container freight index}) + \text{Number of effective berths} - \text{Isolation time} + \text{Operation time delay})
\]

(1)

The level of integrated service is accumulated with the change rate of the integrated service level. The rate of change is a dynamic variable with regard to the time and resource investment so that it denotes the flow. On the contrary, the level of the integrated service is gradually accumulated with the change rate so that it denotes the stock. Moreover, according to the calculation using the CRITIC method, the initial value

Fig. 3. SD model flow diagram.
of the integrated service level in December 2019 is 0.068 and 0.080 for Port A and Port B, respectively. The equation of integrated service level can be obtained as:

\[
\text{Integrated service level} = \text{INTEG (Change rate of value service level); Initial value } = 0.068 \text{ for Port A and 0.080 for Port B (2)}
\]

If the EPAS is adopted between two ports, an equation can be obtained to indicate the alliance or non-alliance. “0” and “1” indicate “not to adopt” and “to adopt”, respectively. Thus, the equation can be expressed as:

\[
\text{Epidemic Prevention Alliance} = (0 \text{ or } 1) \quad (3)
\]

### 3.3.2. Port congestion subsystem

The situation of congestion can be dynamically described by the subsystem of port congestion. The congestion mainly depends on the unloading rate and the loading rate in the unit berth which are constrained by employees, berths and the efficiency of the port operation (Loh et al., 2017). In addition, this subsystem is also disciplined by other conditions under the epidemic: On the one hand, the epidemic preventive measures are taken to inbound vessels to avoid epidemic, which have a negative impact on the unloading rate. Specifically, the measure of 14-day quarantine is used to describe the isolation time in this model. On the other hand, the rate of loading is not only limited by the above conditions but also needs to have sufficient inventory of empty container to satisfy the market demand. Therefore, the subsystem of the container allocation is applied in the model to supply the demand for export. The equations in the subsystem of port congestion are expressed as follows.

The unloading rate and the loading rate are the direct factors affecting port congestion. The liners need to be inspected and quarantined after arriving at the port of destination. However, the waiting time will be prolonged for vessels by increasing with segregation time, which leads the unloading rate to be reduced. The liners have to prolong the shipping schedule and cause the liners to delay on the same route, resulting in the “Bullwhip Effect” will be happened in the marine chain (Hall and O’Brien T., 2018). This phenomenon leads to the rapid rise of the number of containers isolated at the anchorage of the destination port. The number of containers that can be unloaded through the berths are declined significantly in the current period. Therefore, the container unloading rate of the unit production berth can be expressed as the relationship between the total amount of operation and isolation time is consumed by the number of containers in the current period at the effective berth (Nam and Kim, 2021), and the equation can be expressed as:

\[
\text{Unloading rate} = \frac{\text{Number of effective berths}}{\text{(Rate of import*Container throughput*(Operation time delay + Isolation time))}} \quad (4)
\]

The port needs to ensure that enough empty containers are available to satisfy the loading demand of the goods. The impacts of the number of empty containers owned by the port in the current period on the loading rate needs to be considered. Thus, it is necessary to make a conditional judgment on the empty container quantity and the number of export containers. Then the equation can be expressed as:

\[
\text{Loading rate} = \frac{\text{Number of effective berths}}{\left((\text{IF THEN ELSE (Container throughput-Rate of export)} \leq \text{Cumulative quantity of container inventory, Container throughput-Rate of export, Cumulative quantity of container inventory)} \right) * (\text{Operation time delay})} \quad (5)
\]

The index of the port congestion is the core factor of the port congestion subsystem. According to the container congestion index and combined with the requirements of the study, the equation of congestion index can be obtained:

\[
\text{Congestion index} = \frac{\text{Loading rate}}{\left(\text{Loading rate} + \text{Unloading rate}\right)} \quad (6)
\]

In addition, the congestion index is influenced by using the SBS to change the number of berths (Zheng et al., 2020). The SBS is introduced by using the condition function in this study. The rate of loading is greater than the rate of unloading when the congestion index is greater than 0.5. It indicates the containers are a backlog at the anchorage. The port needs the idle berth resources provided by the adjacent port to alleviate congestion. In the study, the volume of idle berth resources is set to 5. Thus, the equation can be expressed as:

\[
\text{Cumulative usage of shared berths} = \text{IF THEN ELSE (Congestion index >0.5,0 or 5,0)} \quad (7)
\]

### 3.3.3. Port container allocation subsystem

The port container allocation subsystem is an indispensable part of the dual-port operation system. Using containers to load the goods for shipping transportation not only reduces the losses but also facilitates the handling of goods. Therefore, the shippers prefer to choose containers for cargo transportation. As mentioned in 3.4.2, this subsystem mainly supplies the demand of packing on export. The quantity of empty containers in the port is essential to stabilize the price of container rentals (Hjortnaes et al., 2016). The quantity of empty container mainly comes from two aspects: On the one hand, the resources of the empty containers come from the storage of empty containers after unloading goods at the port. On the other hand, they also come from the transportation between ports, which can be through the long-distance allocation of liner routes and the short-distance allocation of sea-rail intermodal transport (Li and Zhen, 2016). In the study, the inventory rate of the port for inbound containers is between 10% and 20%. Thus, the equation of the cumulative inventory of empty containers and the inventory rate can be expressed as follow.

\[
\text{Cumulative quantity of container inventory} = \text{INTEG (Inventory rate, cumulative surplus of container allocation)} \quad (8)
\]

\[
\text{Inventory rate} = \frac{\text{RANDOM UNIFORM (0.1,0.2, 0.15)}}{\text{Unloading rate}} \quad (9)
\]

The cumulative surplus of container allocation is the state variable regarding the conditions of container allocation. The allocation
condition is “1”, which indicates that the container needs to be allocated. We set that the number of containers to allocate is 10% of the cumulative surplus of container allocation from another port. The equation of the cumulative surplus of container allocation can be expressed as follows.

Cumulative surplus of container allocation (Port A) = INTEG (IF THEN ELSE (Container allocation conditions (Port A) = 1, Cumulative surplus of container allocation (Port B)*0.1, 0)); Initial value = 10

(10)

In addition, the demand of container allocation depends on the congestion index. When the degree of congestion is greater than 0.5, it indicates that the container demand at the port is strong in the current period. The port needs to allocate more containers from adjacent port to satisfy the export demand. Thus, the equation can be expressed as:

Container allocation conditions = IF THEN ELSE ("Congestion index (Port A or Port B)" > 0.5, 1, 0)

(11)

The fluctuation of the container rental price is a comprehensive index, which is dynamically changed by other variables in the model. The influences of the container rental price fluctuation not only come from aggravating effects of the container rental price index and the container backlog caused by port congestion, but also depend on the inhibitory effects of the integrated service level of the port, the integrated service level of the liner routes and the volume of the empty containers (Gavalas et al., 2022). Therefore, according to the previous study (Chen et al., 2018; Loh et al., 2017), the equation can be expressed as follows.

Fluctuation of container rental price = 0.01 * LN (Container freight index / Integrated service level) * (1/Cumulative quantity of container inventory) * Congestion index * Container charter index

(12)

3.4. Data

3.4.1. Data source and acquisition

According to the relevant researches (Lonza et al., 2016; Luo et al., 2022; Kim et al., 2022; Zhou et al., 2022; Xu et al., 2021) and combined with the availability and accuracy of data, this study selects representative data to construct the data index. The data index system includes the total import and export trade, import volume, export volume, fixed asset investment, container throughput, container freight rate index, integrated service level of liner, etc. The sources of the data are mainly from National Bureau of statistics, CElNet Statistics Database (CEI) and RESSET’s industry database (RESSET). In particular, the data indicators can be divided into three categories: port operations, regional economies, and macro environment. The explanations of the data indicators are classified as follows:

1. Port operations: Port operations are an important criterion to evaluate the port’s operational capacity. In previous literature (Lonza et al., 2016; Luo et al., 2022; Kim et al., 2022; Zhou et al., 2022), the production activity data such as total production berths, the number of employees and the integrated service level of liner are usually used. The statistical reporting period of the data is usually annual or monthly. Therefore, these data are considered comprehensively in the study to describe the integrated service level of the port.

2. Regional economies: The regional economy of the area where the port is located relates to the port development and the port operations. The investments of port construction are supported by the regional economies. Then the port also provides the logistics channel of foreign trade for the regional economic development. Therefore, based on the previous studies (Luo et al., 2022), we choose the total import and export trade, import volume, export volume, fixed asset investment to described the regional economies. These data record the information on economic activities by using the port, which can indicate macroeconomic developments.

3. Macro environment: Macro-environmental data are specifically considered in our study to estimate the impacts of COVID-19 on the global marine shipping industry. In particular, the impacts on the marine shipping network which can make a significant influence on the price of transportation and rental container (Qu et al., 2021). Hence, we use container charter index and container freight index to describe the macro environment.

Additionally, some rules of data selection need to be specially explained. First, the data used in the study are mostly production operation data with a long-time span. Therefore, in order to ensure data integrity and availability, we use relevant data from Tianjin and Guangzhou ports in China. Second, this paper focuses on the port operation under the background of COVID-19, so the data sources should include the port operation after the epidemic outbreak, which is more appropriate to select the monthly data from December 2019 to December 2021. Due to the differences in the statistical time span between the data, so the statistical data by 2020 is chosen as the annual data in this study. Third, in order to truly reflect the port congestion under the same liner route, we select the most congested liner route (the Sino-US west coast container line transportation) after the epidemic as the research background data (Steinbach, 2022; TAKEBAYASHI and HANAOKA, 2021).

3.4.2. Data processing

In ensuring the working of the system dynamics model, it is necessary to fit or predict some data to ensure that the data conforms to the actual situation. According to the previous research (Jia et al., 2021), we use Eviews10.0 to fit the data of import volume, export volume and container throughput with total import and export trade. The fitting results are shown in Table 2. From the results, the confidence probability of the data fitting results is less than 0.05, indicating that the confidence level of the data fitting is greater than 95%. Therefore, the fitting results are in perfect agreement with the actual data.

The impacts of alleviation strategies to alleviate the port congestion are predicted in the future. A forecast period of 12-month (Time ≥ 25) are set in this study, which is conducted on the obtained historical data to test the effects of the two strategies in the future. In this study, the total import and export trade, fixed assets investment, container freight rate index and container charter index are predicted by using the exponential smoothing method (Wang et al., 2021). For comparisons, the single exponential smoothing method, double exponential smoothing method, Holt winter (No seasonal), Holt winter (Additive) and Holt winter (Multiplicative) methods are also tested on the same data, respectively (Zhang et al., 2021). The Spearman test is used to calculate

| Table 2 | Result of data fitting test. |
|-------------------|-----------------------------|
| **Target (Port)** | **Independent variable (X)** | **Dependent variable (Y)** | **Equation** | **Probability (F-statistic)** |
| Port A Total volume of import and export trade | Volume of import | Y = 0.576656X + 1.38235 | 0.00 |
| Port B Total volume of import and export trade | Volume of import | Y = 0.423344X + 1.38235 | 0.00 |
| Port A Total volume of import and export trade | Volume of export | Y = 11.2351X + 50.1023 | 0.00 |
| Port B Total volume of import and export trade | Volume of export | Y = 0.036142X - 4.95089 | 0.00 |
| Port A Total volume of import and export trade | Container throughput | Y = -0.663858X + 4.95089 | 0.00 |
| Port B Total volume of import and export trade | Container throughput | Y = -1.00928X + 100.958 | 0.04 |
the correlation coefficient between the original data and the predicted data. The forecasting results of all tested methods are recorded in Table 3. Notice that, due to the limitation of data availability, this study uses monthly historical data after the COVID-19 outbreak to predict the container freight index and container charter index, while this study uses monthly historical data from 2001 to 2021 to predict the total import and export trade by using the Holt winter (Multiplicative) methods, to ensure the authenticity and reliability of the prediction.

4. Result in analysis

4.1. Impact of epidemic prevention alliance strategy

The results of simulation are shown in Fig. 4, the EPAS has a positive effect on relieving the port congestion caused by the epidemic prevention and control. If the EPAS is not adopted between the two ports, the rate of unloading the container is much lower than the loading rate. Although the degree of the congestion is a certain decline in the forecast period, it is still at a high level (Pérez et al., 2020). On the contrary, the index of the congestion is significantly decreased after using the EPAS. The degrees of the congestion in the two ports are about 0.70 and 0.45, respectively. In the prediction period, a downward trend of the congestion index is shown. Therefore, by using EPAS, the port congestion can be noticeably alleviated and the unloading rate of the port can be improved.

As shown from Fig. 5, the quarantine time of ships can be shortened and the operational efficiency of the port are improved by using the EPAS (Shi et al., 2019; Dong et al., 2018). Meanwhile, the level of comprehensive service increase positively during the prediction period. Moreover, due to the difference in hinterland factors in the region where the port is located, the growth rate of the level of integrated service of Port B is much higher than that of Port A (Hou, 2010). In general, the comprehensive service levels of ports A and B increase with the passage of time, which is closely related to the port construction.

As shown in Fig. 6, the EPAS is essential to the impacts of container rental price fluctuation. The simulation results of adopting the EPAS are significantly lower than those without this strategy, which facilitates the stabilization of container rental prices. As indicated by Figs. 6 and 7, if the EPAS is implemented between two ports, the cumulative inventory of empty containers can be increased to ensure the demand of export goods. Then the fluctuation of container rental price can be stabilized by using the EPAS. The phenomenon of “One container is difficult to find” in export goods will be controlled.

4.2. Impact of shared berths strategy

Compared with the EPAS, the congestion of port is less alleviated by using the SBS. Since the impacts of the epidemic preventive policy cannot be neutralized, the low rate of unloading cannot be changed by using the SBS, and then ships still need to quarantine at the anchorage. Although the SBS is adopted among the ports, the vessels congested at the anchorage are simply allocated to adjacent ports. The rate of loading is still much higher than that of unloading, which makes the problem of

| Table 3 | Data prediction method and results. |
| --- | --- |
| Target (Port) | Index | Exponential Smoothing (Spearman) | Holt-winter (Additive) | Holt-winter (Multiplicative) | Method |
| Port A | Fixed asset investment | | | | |
| | | 0.316 | 0.067 | 0.202 | 0.415 | 0.417* | Holt-winter (Multiplicative) |
| | Total volume of import and export trade | 0.934 | 0.937 | 0.935 | 0.967 | 0.970* | Holt-winter (Multiplicative) |
| Port B | Fixed asset investment | | | | |
| | | 0.302 | 0.018 | 0.238 | 0.662 | 0.668* | Holt-winter (Multiplicative) |
| | Total volume of import and export trade | 0.907 | 0.895 | 0.906 | 0.963 | 0.9728 | Holt-winter (Multiplicative) |
| Environment | Container charter index | 0.975 | 0.978 | 0.992* | 0.833 | 0.528 | Holt-winter (No seasonal) |
| | Container freight index | 0.961 | 0.962 | 0.980 | 0.993* | 0.985 | Holt-winter (Additive) |

Note: “*” representative optimal predict method.
congestion still prominent. As shown in Fig. 8, the port congestion shows a downward trend over time and the congestion is slightly relieved. But the degree of congestion is still at a high level of 0.9.

The integrated service level of port is noticeably increased by using the SBS in ports. Since the SBS is to expropriate the remaining resources of port berth in the region through the cooperation between adjacent ports, then the idle productive resources are shared among ports by implementing the SBS. There is a positive correlation between the number of effective berths and the comprehensive service capacity of the port (Li et al., 2020). Therefore, the SBS can indirectly expand the production capacity of port and increase the internal resource endowment through the resource integration of ports in the region. Then the level of comprehensive service can be significantly improved by using the SBS (Saeed and Larsen, 2010; Kim et al., 2022). In addition, due to the different hinterland conditions in the port region, the growth rate of comprehensive service of Port B is much higher than that of Port A, which is identical to the results by using the EPAS (as shown in Fig. 9).

As shown from Fig. 10 and Fig. 11, the trend of the fluctuating container rental price shows a decrease only slightly over time between the situations of "No SBS" and "Use SBS", which is caused by the failure to improve the unloading rate of containers and the cumulative inventory of containers. Meanwhile, the demand of empty containers for export goods is increased, which leads to the destruction of the supply-demand balance of empty containers. The inventory of empty containers is difficult to satisfy the loading demand of containers. In addition, a portion of the containers are diverted to other adjacent ports for unloading by using SBS, which leads to a reduction in the quantity of containers entering the port (Li et al., 2022a,b). Due to the shortage of empty containers in the current period, the impacts of the SBS on curbing the fluctuation of container rental price is not obvious.

4.3. Impact of hybrid strategy

As shown in Fig. 12, the hybrid strategy has the best effects on alleviating the port congestion. The second one uses only the EPAS and the last adopts only the SBS. Comparing the results of simulation, the effects of the hybrid strategy by using the EPAS is better than that without this strategy. Therefore, it can be inferred that the core issue of port congestion is to solve the retention of ships due to epidemic prevention and control.

As shown from Fig. 13, the result shows that the hybrid strategy has the better positive effect on the promotion of integrated service level growth than the single strategy. Therefore, the hybrid strategy is clearly more appropriate for improving the integrated service level.
Additionally, the integrated service level of port will be significantly improved in the future, when the port’s own hinterland conditions are better than other ports’ (i.e., regional resources and hinterland economy).

The significant impact on the fluctuation of container rental prices is achieved by adopting the hybrid strategy. The cumulative quantity of container inventory shows a growth trend, while the downward trend is shown in the fluctuation of the container rental price. As shown in Fig. 14 and Fig. 15, with the empty containers fully supplied, the fluctuation of the container rental prices will be curbed. It indicates that the supply of empty containers will gradually balance with the demand in the future, which can satisfy the demand of the containers. As a result, the rental price of container is gradually stabilized and price fluctuation is greatly reduced.

5. Discussion

Nowadays, some major ports in many countries are facing severe port congestion (i.e., Long Beach and San Francisco). If these ports prefer to adopt the EPAS or the SBS, it takes a long period for ports to prepare for implementing it. Therefore, most ports get used to increasing the investment in human resources and fixed assets to alleviate the port congestion (Asteris et al., 2012). In 2021, the government of the United States promulgated the “Infrastructure Investment & Jobs Act”, which proposed to invest $17 billion dollars in improving the infrastructure of the port and solved the problem of congestion. In addition, in order to improve the operational efficiency of the port, some companies propose to attract more seasonal and temporary workers via generous benefits for improving the capacity of the port operation. In this section, by using the dual-port operation model, the effects of investing more human resources and fixed assets on alleviating the port congestion and improving the port operation are discussed in this study.

Fig. 10. Simulation results of fluctuation of container rental price under the SBS.

Fig. 11. Simulation results of cumulative quantity of container inventory under the SBS.

Fig. 12. Simulation results of congestion index under the hybrid strategy.

Fig. 13. Simulation results of port integrated service level under the hybrid strategy.

3 FACT SHEET: The Bipartisan Infrastructure Investment and Jobs Act Creates Good-Paying Jobs and Supports Workers: https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/03/fact-sheet-the-bipartisan-infrastructure-investment-and-jobs-act-creates-good-paying-jobs-and-supports-workers/.
Therefore, it can be inferred that the effects of human resources in investment in 2 and 3 on the port congestion cannot be observed. A significant alleviating effect of the coefficient of human resources trend of the congestion index is gradually shown in the future. However, when the coefficient of human resource investment reaches 3, the mitigation degree of congestion is the same as that when the coefficient is 2. A significant alleviating effect of the coefficient of human resources investment in 2 and 3 on the port congestion cannot be observed. Therefore, it can be inferred that the effects of human resources investment on port congestion are limited by the quantitative relationship between human resources and berths (Zheng et al., 2022). The human resources are fully supplied, which promotes production berths are completely used and improves the efficiency of the port operation. Due to the limitation of the number of production berths, the continuous increase of the investment in human resources can’t change the mitigation of port congestion. Thus, the investment in the human resources should follow the port production capacity and achieve a balance between the human resources and the berth resources.

The effects of the combination strategy (i.e., implementing the existing strategy and hybrid strategy simultaneously) on alleviating port congestion is also discussed in this study. As shown in Fig. 17, the hybrid strategy is more effective for alleviating the port congestion. Hence, we investigate the effect of using the hybrid strategy under two conditions, i.e., the human resource investment coefficient is (or isn’t) equal to 3.

The simulation results show that increasing human resources and adopting hybrid strategy simultaneously is more effective than other strategy. The reason is that, the increased investment of human resources improves the berth utilization, while using the hybrid strategy reduces the time of epidemic prevention and control of vessels in the port. Therefore, the simultaneous implementation of two strategies would inherit the advantage of each strategy.

### 5.2. Fixed assets investment

The measure of increasing investment in fixed assets is positively correlated with the level of integrated service and the competitiveness of the port (Asteris et al., 2012; Knatz, 2017). This initiative is a long-term work, such as expanding the number of production berths or improving the automation of machinery. Three different scenarios of the fixed asset investment are explored in this study. During the historical and forecast periods, the coefficient of fixed asset investment (FAI), without adopting any strategies, is adjusted to 1, 2, and 3 times. Then, the impacts of fixed asset investment on the level of integrated service are discussed in this section.

As shown in Fig. 18, the level of integrated service can be significantly improved by increasing the investment in fixed asset. The improvement effect of comprehensive service level is more significant with the increase of fixed asset investment (Asteris et al., 2012; Knatz, 2017). However, due to the time lag effect of the fixed asset investment, a long payback period is consumed by the improvement of the integrated service level. The objective of increasing the investment in fixed assets is constructing and upgrading the infrastructure in port, which needs a long construction period. Hence, the growth of the level of integrated service is slow in the initial period, but it will be significant in the future. In the post-epidemic era, the level of integrated service and the capacity of port production can be directly improved by increasing investment in ports.

Based on the above results, we can find that the level of integrated service is enhanced with the increased investments of fixed asset. Therefore, we compare the impacts with using hybrid strategy on the level of integrated service under the increased investments of fixed asset (as shown in Fig. 19). When the hybrid strategy is also adopted to the port operations under increasing the fixed asset investments, the level of integrated service can be improved significantly. On one hand, increasing investment in fixed assets has a significant effect on replacing the old equipment, adding terminal facilities and improving port management capacity, but this requires a longer payment return period. On the other hand, adopting a joint strategy has a greater effect on improving port congestion due to the epidemic in a short period of time, and so on the integrated service capacity of the port. In general, compared to other strategies, increasing fixed asset investment in the port and using the hybrid strategy simultaneously is the optimal strategy for improving the level of port’s integrated service.
6. Conclusions and policy implications

In this study, from the perspective of the dynamic operation of the dual-port system, we collect historical data of two ports in China from 2019 to 2021. Based on this data, the performance of EPAS, SBS and their hybrid strategy is investigated and compared for addressing the serious port congestion caused by the COVID-19 epidemic. Moreover, the impacts of existing measures of alleviating the congestion, including increasing the investment in human resources and fixed assets, is studied. According to the relevant theoretical and empirical analysis, the main conclusions can be summarized as follows.

(1) The COVID-19 has a significantly negative impact on the throughput of imports and exports. The impact of epidemic precautions on the unloading rate is greater than that of the loading rate. The reason is that, the incubation period of the epidemic and the epidemic preventive measures, have made ships quarantine in the anchorage, resulting in many unloaded ships congested in the
(3) By using the SBS, the level of integrated service is significantly improved in the future. The idle berth resources are integrated by the ports in the same region via the SBS, which can expand the reserve of production resources to the port and improve the level of integrated service. However, there are two issues associated with the SBS in alleviating the port congestion as follows. First, the rate of unloading the container can’t be improved by using the SBS, which leads to a large quantity of containers detained in the port. The pressure of congestion is shared by other ports in the same region adequately. On this basis, a mechanism of mutual trust between cross-regional ports should be established to avoid the transmission of false information among ports which may lead to the hindrance of epidemic prevention and control. Then the alliances among ports in the post-epidemic era to minimize the impacts of the epidemic preventive measures. Meanwhile, the processes of the transfer and customs operation should be simplified by relevant departments (i.e., the customs and ports), which will help liner companies to flexibly adjust their routes and alleviate the pressure of port congestion. Therefore, a coordination mechanism should be established among ports to make the ports in the same region work together and then utilize the idle port berth resources in the region adequately. On this basis, a mechanism of mutual trust between cross-regional ports should be established to avoid the transmission of false information among ports which may lead to the hindrance of epidemic prevention and control.

(4) Increasing the investment in human resources assists in alleviating the port congestion. The utilization rate of production berths is improved by the increased human resources. However, this measure leads to the increased probability of contact between port workers and foreign vessels, which will bring the pressure of epidemic prevention to the port. Moreover, increasing the investment in fixed assets can improve the integrated service level of the port. But most of the fixed asset investment belongs to the long-term investment. The return period of investing fixed assets is long, which is less helpful for immediately alleviating the port congestion. The implementation of both of the hybrid strategy and existing strategies performs better than only implementing the existing strategies, in the aspects of alleviating the port congestion and improving the integrated service level of the port.

Based on these conclusions, some corresponding policy recommendations are provided as follows.

(1) Promote the formation of trans-regional epidemic prevention alliances among ports in the post-epidemic era to minimize the impacts of the epidemic preventive measures. Meanwhile, the processes of the transfer and customs operation should be simplified by relevant departments (i.e., the customs and ports), which will help liner companies to flexibly adjust their routes and alleviate the pressure of port congestion. Therefore, a coordination mechanism should be established among ports to make the ports in the same region work together and then utilize the idle port berth resources in the region adequately. On this basis, a mechanism of mutual trust between cross-regional ports should be established to avoid the transmission of false information among ports which may lead to the hindrance of epidemic prevention and control.

(2) Increase the investment in the intelligence transformation to improve the efficiency of port operations. The developments of the port automation, digitalization and intelligence are considered to be important factors in enhancing the core competitiveness, which will be crucial to reducing the logistics costs and improving the logistics efficiency. The COVID-19 epidemic has a substantial impact on the port production and operation. Port operators should enhance the awareness to develop the intelligent ports and the advanced technologies applied to the port (including the 5G technology, blockchain, AI and computer vision), to promote the transformation and upgrading of the traditional terminals. Meanwhile, new technologies can help port managers capture the idle berth resources in the regional ports. This can allow managers to rationally allocate the vessel segregation and loading and unloading activities, which can alleviate the port congestion.

(3) Promote the “contactless” management in consideration of the risk of epidemic spread by the contact between port workers and inbound ships. For foreign ships, the port should make sure that the personnel on board do not get off the ship and the wharf staff do not get on the ship. The method of signing the electronic document shall be adopted to ensure that the documents are not signed on the ship and the paper documents are not transmitted. This can avoid the direct contact between the wharf operators and the ship staff. Additionally, it is necessary to strictly prevent and control the epidemic possessing the goods-to-human transmission in the port, including adopting the IoT technology to track goods, getting detailed information of goods and making the information electronic, enabling the staffs to grasp detailed information.
information through mobile terminal devices without touching the goods.

In this paper, we discuss the effects of implementing mitigation strategies in two ports under the same liner route. Actually, due to the routes of liner, the relationship between the ports is more like a network in practice. In future study, considering the impacts of the alleviation strategies on adopting in the network between the ports would be of practical interest also. Additionally, it would be useful to explore new technologies to improve the efficiency of alleviation strategies.

Ethical statement

The present manuscript has never been published before, and it is not under consideration by any other publisher. Its publication has been approved by all authors and, if accepted, it will not be published by other editors, nor in other languages without written authorization by the holder of the author’s rights.

Authorship contribution statement

Haonan Lin: Methodology, Formal analysis, Visualization, Data curation, Writing – original draft.
Weijun Zeng: Conceptualization, Methodology, Supervision.
Jian Luo: Supervision, Writing – review & editing.
Guofang Nan: Conceptualization, Methodology, Supervision, Writing – review & editing.

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

No data was used for the research described in the article.

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