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Port integration method in multi-port regions (MPRs) based on the maximal social welfare of the external transport system

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Abstract: The port integration problem in a multi-port region (MPR) is studied from the perspective of maximizing the social welfare of the external transport system in a closed region in which the ports are regarded as external transport hubs. First, the economic principle of maximizing the social welfare of the external transport system is analysed, and a method to calculate the total internal transport cost of the external transport system is proposed. Second, the optimal scale of the port group in an MPR is determined by comparing the total internal transport costs for different scales of the port group. An integration method with multi-period investment and asset idling is also proposed that takes into account excess port resources in MPRs. Finally, ports in northeast China are selected for an empirical study. Based on the findings, suggestions regarding port resource integration and cooperative operation in MPRs are presented.

Keywords: port integration; social welfare; multi-port region; external transport system; internal transport cost

1. Introduction

For the past twenty years, Chinese port cities have invested substantially in expanding their local ports with the "promoting the local economy through port" strategy (Monios and Wilmsmeier, 2012; Zheng and Negenborn, 2014). By the end of 2015, five port clusters were formed along the 18,000 km coastline from north to south along the coast of Mainland China. Among these clusters, seven container ports rank in the top ten in the world in terms of total throughput. Currently, the Chinese coastal regions are all multi-port regions (MPRs) because the ports in these regions are contiguous. To expand their hinterland scope, the ports must strengthen their investment effort with the aim of improving the level of service and expand their capacity to attract more cargo accordingly (Song and Geenhuizen, 2014; Figueiredo, Oliveira, and Cariou, 2015). Nevertheless, with the slowdown in growth of hinterland's freight demand, excess port capacity, wasted shoreline resources, and the idleness of port assets are becoming an increasingly serious problem. For example, nearly 50% of port assets are idle in some of the 40 ports in the Liaoning Province of China (PortNews, 2012).

With overcapacity and wasted resources becoming increasingly severe, the integration of port resources and cooperative operation have become important issues in the field of Chinese port operation and management (Notteboom and Yang, 2016). Certain local governments have already started to employ administrative intervention or state-owned asset reorganization strategies to integrate the ports so they can achieve a common level of development (Wang, Ducruet, and Wang, 2015). For example, in 2007, Fangchenggang Port, Beihai Port and Qinzhou Port in Guangxi Province restructured their assets to form the Beibu Gulf Port Group; this port group now plans infrastructure construction projects and provides pricing guidance. In 2015, The Ningbo-Zhoushan Port Group was formed with the complete transfer of Zhoushan Port's equity to Ningbo Port. Consequently, the Ningbo-Zhoushan Port Group has become the largest port in the world, handling more than 880 million tons of cargo. Administrative intervention and state-owned asset reorganization aims to accelerate the port resource integration process and avoid homogeneous competition. Note that the current measures can only integrate the administrative system and realize the sharing of technology and resources. These measures can barely optimize the scale and number of ports in present MPRs to meet hinterland freight demand and are insufficient to solve port resource waste and reconstruction problems. Therefore, local governments and the newly founded port corporations are seeking methods to further promote port integration.

With this background in mind, this paper aims to explore the optimal scale of the port group in MPRs (e.g., the port number, scale, and hinterland scope of each port), and to propose an effective method to integrate the ports in a present MPR. The work described herein considers the MPR in northeast China as real investigation case. The novelty of this work lies in that it proposes the method for dividing the hinterland for the ports in different port layouts of MPRs with the utility theory. It determines the optimal scale of the port group in MPRs with maximizing the social welfare. Moreover, it designs the multi-period investment and quit mechanism to integrate the present ports in the MPR, so as to construct the port group structure that maximizes the social welfare. This research angle and applied method of this paper are new and can enrich the previous literatures concerning port integration/cooperation problems. It can be applied to many similar problems.

The reminder of this paper is organized as follows. Section 2 presents a literature review on the issue of port integration/cooperation. Section 3 presents the economic principle of maximizing the social welfare. Section 4 proposes the principle of ports' hinterland division and the method to calculate the internal cost of the external transport system. Section 5 determines the optimal scale of port group in a MPR. Section 6 designs multi-period investment and quit integration mechanism. Two main gateway ports in Liaoning Province in northeast China are selected for an empirical study in section 7. Section 8 discusses the main issue in our paper and presents the policy/practical implications. Finally, section 9 concludes the study.

2. Literature review

Port integration/cooperation problems have become an important topic in the study of maritime or shipping economies (Woo et al., 2011; Asgari, Farahani, and Goh, 2015; Lee and Song, 2017). Many scholars have investigated integration/cooperation problems based on economic models, game theory and operations research (Notteboom and Yang, 2016). According to decision makers in the integration/cooperation process, research related to port integration/cooperation can be divided into two types: 1) cooperation or integration among the stakeholders in one port and 2) cooperation or integration among different ports or port authorities. Regarding cooperation/integration in one port, Saeed and Larsen (2010a) applied the concept of "core theory" in a two-stage cooperative game to analyze the stability of the coalitions which involves three container terminals located in Karachi Port in Pakistan. In the same year, Saeed and Larsen (2010b) also used the game theory to analyze the effect of the type of concession contracts on port user surplus and on profits of terminal operators (or port authorities) within the three terminals. The results reveal that in the long run it is profitable for the Karachi Port to establish a same fixed fee contract with its private terminals. Saurí and Robusté (2012) designed an incentive cooperation mechanism based on principal-agent theory for encouraging a private terminal operator and a stevedore company to reduce tariffs and increase the terminal's productivity. The results suggest that an improvement both in the terminal's productivity and in tariffs is possible through an annual fee. Wang and Pallis (2014) identified the post contractual moral hazard problem in port concession agreements with game theory, and provides a model involving performance-based concession fees to align successfully the Port Authorities' interests with those of the terminal operators. To match theory and practice, the paper reviewed factual information of recent projects in Europe and the US, and the results indicate that the port authority needs to identify clearly the objectives undertaken to avoid transaction failures in a Greenfield concession. It is found that research regarding cooperation/integration in one port has focused primarily on the influence of cooperation among the stakeholders on port efficiency, the benefits to port enterprises, and the other factors; game theory was found to be a popular method for investigating the above problems.

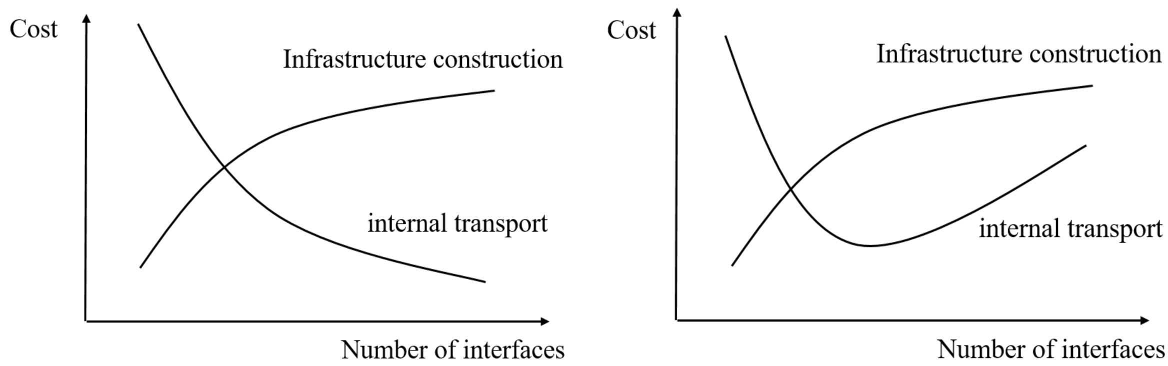
For the second type of port cooperation/integration among different ports or port authorities, Song (2003) proposed a new strategic option known as co-opetition, the combination of competition and co-operation, for the port industry, and explains a case of co-opetition between the container ports in Hong Kong and South China. Panayides and Song (2009) defined and empirically developed measures of seaport integration in global supply chains and inferred implications for maritime logistics. Donselaar and Kolkman (2010) elaborated on the question how cooperation between port authorities can contribute to the societal welfare and what role the national government can play in promoting this cooperation. Wang et al. (2012) investigated the factors and conditions affecting regional port governance in South China (i.e. alliance formation for ports serving partially overlapping hinterlands) by developing a game theory model and calibrated the model on the basis of the Pearl River Delta (PRD) context. Zhuang, Luo, and Fu (2014) applied the game theory approach to study port specialization and government regulations in China. They concluded that if there is a clear market leader, policy intervention may not be necessary. However, if no port has clear market power, then government coordination and intervention may be needed in order to prevent overcapacity and to encourage specialization. Song, Cheon, and Pire (2015) investigated the motivations for the ports of Flanders (Antwerp, Zeebrugge, Ghent and Ostend) to choose coopetition (competition and cooperation) as an emerging strategy to react towards the rapidly changing market environment, and consider whether the size of port is a factor having an impact on the cooperative strategy. From a qualitative analysis on the matter, the paper concludes that size is not an important factor for the motivations to establish coopetition since ports are mainly aimed at achieving a win–win situation. Wang, Ducruet, and Wang (2015) examined the nature of port integration in China, including associated temporal pathways, spatial patterns and dynamics. Results indicate that port integration in China has been characterized by a significant increase at the turn of the 21st century, comprising thirteen distinguishable pathways typified by differing dynamics, particularly between the northern and southern ports. The existing literature focuses primarily on analysing or investigating the positive effect of cooperation among ports on regional development and social welfare.

Rational port investment for capacity management is regarded as a useful method for facilitating cooperation among different ports. Currently, there is a growing body of literature studying port investment or port group investment. For example, Luo, Liu, and Gao (2012) developed a two-stage duopoly model that comprises the pricing and capacity decisions to evaluate port capacity expansion with application to container port competition between Hong Kong and Shenzhen. Song and Geenhuizen (2014) used the panel data analysis for the period of 1999–2010 to investigate what extent port infrastructure investment in China can contributes to growth of the regional economies. Wan, Leonardo, and Zhang (2016) analyzed the incentives for and welfare implications of collaboration among local governments in landside port accessibility investment, and found that there is a conflict of interest between the port governments and inland government in terms of their jointly making accessibility investment decisions, and that each region's preference over various coalitions is highly affected by ownership type of the competing ports. Wu et al. (2016) investigated the influence of the local government on the investment decision-making related to port expansion. From the empirical results, it was found that investment in port capacity contributes greatly to the local government's performance. Meanwhile, different investment ceilings are discovered for the port enterprise and the local government. Despite the efforts of previous work, it was concluded that most research related to port investment did not present effective investment measures (e.g., investment volumes and investment planning periods) to integrate the ports in an MPR.

The focus of our study is to propose effective measures to integrate resources and ultimately realize cooperation among the ports in an MPR, which has not been addressed before. To achieve this objective, a new method is proposed to divide the hinterland of the ports and then to determine the optimal port group size and layout in an MPR. A multi-period investment and quit mechanism for integrating the present ports in the MPR is discussed. The proposed model is verified by conducting a case analysis of the MPR in northeast China. This research is expected to help decision makers achieve optimal integration processes within an MPR.

3. Economic principle of maximizing the social welfare

When we construct an optimal external transport system in a closed MPR from the perspective of maximizing social welfare, the focus should be to minimize the total cost which containing transport infrastructure construction and operational costs and the internal transport cost from each hinterland origin to the gateway ports. If the ports mutually cooperate, then the larger number of ports will result in shorter transportation distances for cargo originating in the hinterland and lower internal transport cost simultaneously. However, infrastructure construction costs will be higher (Figure 1-a). At this time, obtaining a balance between internal transport costs and the cost of infrastructure construction has become essential to optimizing the external transport system in MPRs. If these ports compete with each other, the problem will increase in complexity. A larger number of ports will result in more port choices for cargo from the hinterland and a larger possibility of crossover transportation. Consequently, the external transport system will fall into disordered competition, and internal transport costs and infrastructure construction costs will increase together (Figure 1-b). With the possibility of the waste of resources and the idleness of assets increasing in severity, the balance of competition among the ports becomes the most important topic to consider in constructing an external transport system.



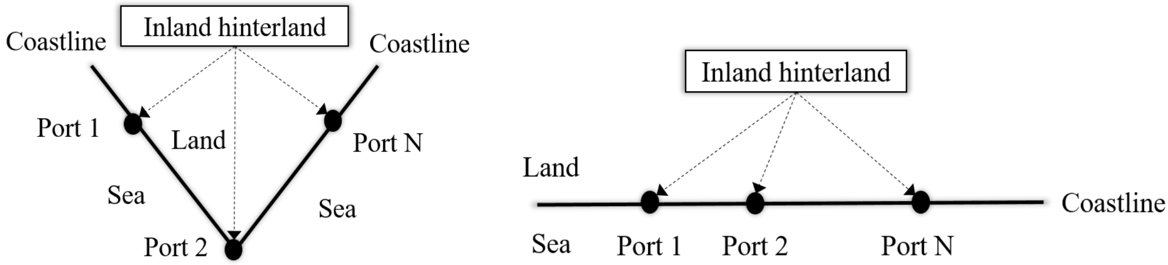
a Cooperation among ports b Competition among ports

Figure 1 Cost structure of the external transport system in a closed MPR

The optimization of the port group scale in an MPR involves determining the needed number of ports, the scale of each port and its hinterland scope. The optimization approach assumes that the ports will cooperate and make joint efforts to transport goods to external markets with the aim of minimizing costs (including infrastructure construction costs and internal transport costs). The aim of applying port resource integration and cooperative operation is to use administrative, economic, or management measures (e.g. adjusting or even cancelling the function of certain ports) to change the layout of the present port group and to maximize social welfare.

4. Calculation method for the internal cost of the external transport system

Based on the spatial relationship between the hinterland and the coastal ports, the layout of the ports of a closed MPR can be classified into two categories as follows: 1) funnel type (e.g., Liaodong Peninsula and Shandong Peninsula); and 2) section type (e.g., the majority of Chinese coastal regions). A funnel-type coastline is shown in Figure 2-a; the ports are located on the funnel-type coastline, and each port services its own direct hinterland. Moreover, each port also services the indirect inland hinterland together with other ports. A port located on the top of the funnel-type coastline has short transport distances and low transport costs to the inland hinterland, and therefore, has an advantage when competing with ports located on the bottom of the coastline. A section-type coastline is shown in Figure 2-b; a port located on this type of coastline services its own direct hinterland and services the indirect inland hinterland together with other ports, which is similar to the funnel-type coastline. However, under these circumstances, the transport distance and cost of transportation from each port to the inland hinterland is almost the same, and no port has a clear advantage in terms of hinterland access cost. With these differences in mind, in the next section, we will present a method for computing the total internal cost of the two type of port group layout based on the shippers' behaviour regarding port choice.

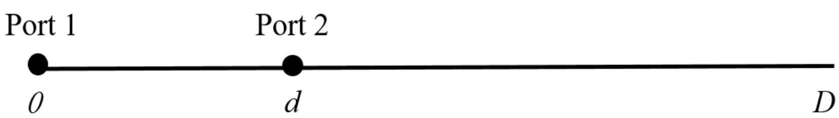


a Funnel-type b Section-type

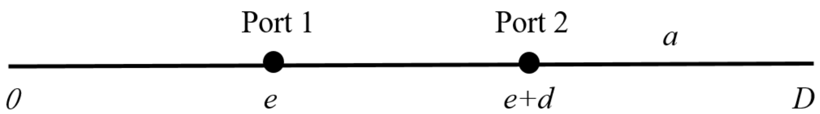
Figure 2 two kinds of port group layout in MPRs

4.1 Internal transport cost

As suggested by Álvarez-SanJaime et al. (2015) and Wan, Leonardo, and Zhang (2016), when determining the hinterland scope of the ports based on the shippers' port choice behaviour, it can generally be assumed that the hinterland is linearly distributed and that the freight demand of the hinterland is uniform with a constant density. As shown in Figure 3, the hinterland freight demand of the MPR is linearly distributed at the linear segment of interval $[0, D]$, and the demand density on the segment is a. It is assumed that only two ports are located at the linear hinterland. In the funnel-type port layout (Figure 3-a), Port 1 is located at zero (the bottom of the funnel), and Port 2 is located at d; in the section-type port layout (Figure 3-b), Port 1 is located at e, and Port 2 is located at $(e+d)$. The two ports are identical in all respects except for their location and capacity.



a funnel-type



b section-type

Figure 3 hinterland distribution in MPR

The hinterland should be divided before calculating the internal transport cost of the MPR. Because the funnel-type port layout can be regarded as a special case in which Port 1 is located at zero in the section-type port layout, we investigate the hinterland division method in the funnel-type port layout only. The consignor (or shipper) typically uses the generalized cost approach to choose the gateway port for their cargo since there are two main segments for transporting the cargo from the inland hinterland to the gateway ports. Thus, the generalized cost consists of the port fee plus the hinterland access cost. The detailed expression is as follows:

$$C_r = \begin{cases} T_c \cdot |x_r - e| + \lambda_1 \dfrac{X_1}{K_1} & \text{if using port 1} \\ T_c \cdot |x_r - (e+d)| + \lambda_2 \dfrac{X_2}{K_2} & \text{if using port 2} \end{cases} \tag{1}$$

where C_r is the generalized transport cost from the hinterland r to the gateway port, x_r is the location of hinterland r in the linear hinterland, and T_c is the constant inland transport cost per unit distance. $\lambda_1 \frac{X_1}{K_1}$ and $\lambda_2 \frac{X_2}{K_2}$ are the port fees of the two ports that the shipper pays in terms of different port capacity, where λ_1 and λ_2 are the basic port fees of the two ports when the port supply equals the port demand; X_1 and X_2 is the demand for freight transit through the two ports; and K_1 and K_2 are the capacity of the two ports. The terms $\frac{X_1}{K_1}$ and $\frac{X_2}{K_2}$ can be used to measure the node impedance of the ports. If the port capacity is fixed, a higher demand for freight transit through the port will result in higher port fees, whereas if the demand for freight transit through the port is fixed, an increase in port capacity will lead to a decrease in port fees. The purpose of dividing the hinterland is to find the location x_r^* where the generalized transport cost from the location to the two ports are equal. Next, we use C_{r1} and C_{r2} to represent the generalized transport cost from location r to the two ports. For clarity, we adopt the variables $g_1 = \lambda_1 / K_1$ and $g_2 = \lambda_2 / K_2$; then, the hinterland is divided based on the port choice behaviour of the shippers located in the linear hinterland.

1) When $x_r \in [0, e]$, then $C_{r1} - C_{r2} = g_1 X_1 - g_2 X_2 - T_c \cdot d$. If there exists a value of d to make $C_{r1} \ge C_{r2}$ (i.e., $d \le \frac{(g_1+g_2)ae - g_2 aD}{T_c}$), then setting $C_{r1} = C_{r2}$ (i.e., $g_1 a \cdot x'_r - g_2 a \cdot (D - x'_r) = T_c \cdot d$) yields $x_r^* = x'_r = \frac{g_2 aD + T_c d}{(g_1+g_2)a}$. In this case, the origins in the

interval [0, x_r'] are the hinterland for Port 1, and the origins in the interval [x_r', D] are the hinterland for Port 2. If there does not exist a value of d to make $C_{r1} \geq C_{r2}$ (i.e., $d > \frac{(g_1+g_2)ae - g_2aD}{T_c}$), then the origins in the interval [*0*, *e*] are the hinterland for Port 1.

2) When $x_r \in [e+d, D]$, then $C_{r1} - C_{r2} = T_c \cdot d + g_1X_1 - g_2X_2$. If there exists a value of d to make $C_{r1} \leq C_{r2}$ (i.e., $d \leq \frac{g_2aD - (g_1+g_2)ae}{T_c + g_1a + g_2a}$), then setting $C_{r1} = C_{r2}$ (i.e., $g_1a \cdot x_r'' - g_2a \cdot (D - x_r'') = -T_c \cdot d$) yields $x_r^* = x_r'' = \frac{g_2aD - T_cd}{(g_1+g_2)a}$. In this case, the origins in the interval [0, x_r''] are the hinterland for Port 1, and the origins in the interval [x_r'', D] are the hinterland for Port 2. If there does not exist a value of d to make $C_{r1} \leq C_{r2}$ (i.e., $d > \frac{g_2aD - (g_1+g_2)ae}{T_c + g_1a + g_2a}$), then the origins in the interval [*e*+*d*, *D*] are the hinterland for Port 2.

3) When $x_r \in (e, e+d)$, then $C_{r1} - C_{r2} = T_c \cdot (2x_r - 2e - d) + g_1X_1 - g_2X_2$. If there exists a value of d to make $C_{r1} = C_{r2}$ (i.e., $d > \frac{g_2aD - (g_1+g_2)ae}{T_c + g_1a + g_2a}$ and $d > \frac{(g_1+g_2)ae - g_2aD}{T_c}$), then from $C_{r1} = C_{r2}$, we obtain $x_r^* = x_r''' = \frac{T_c(d+2e) + g_2aD}{2T_c + g_1a + g_2a}$. Thus, the origins in the interval [0, x_r'''] are the hinterland for Port 1, and the origins in the interval [x_r''', D] are the hinterland for Port 2. If there does not exist a value of d to make $C_{r1} = C_{r2}$ (i.e., $d \leq \frac{(g_1+g_2)ae - g_2aD}{T_c}$ or $d \leq \frac{g_2aD - (g_1+g_2)ae}{T_c + g_1a + g_2a}$), then the origins in the interval (*e*, *e*+*d*) are the hinterland for only one port. If $d \leq \frac{g_2aD - (g_1+g_2)ae}{T_c + g_1a + g_2a}$, then the origins in the

interval (e, $e+d$) are the hinterland for Port 1; if $d \leq \frac{(g_1+g_2)ae - g_2 aD}{T_c}$, then the origins in the interval (e, $e+d$) are the hinterland for Port 2.

In summary, if $d \leq \frac{(g_1+g_2)ae - g_2 aD}{T_c}$, then the freight demand for transit through the two ports is as follows: $X_1 = a \cdot x_r' = \frac{a(g_2 aD + T_c d)}{(g_1+g_2)a}$ and $X_2 = a \cdot (D - x_r') = \frac{a(g_1 aD - T_c d)}{(g_1+g_2)a}$; if $d \leq \frac{g_2 aD - (g_1+g_2)ae}{T_c + g_1 a + g_2 a}$, then $X_1 = a \cdot x_r'' = \frac{a(g_2 aD - T_c d)}{(g_1+g_2)a}$, and $X_2 = a \cdot (D - x_r'') = \frac{a(g_1 aD + T_c d)}{(g_1+g_2)a}$; if $d > \frac{g_2 aD - (g_1+g_2)ae}{T_c + g_1 a + g_2 a}$ and $d > \frac{(g_1+g_2)ae - g_2 aD}{T_c}$, then $X_1 = \frac{T_c a(d+2e) + g_2 a^2 D}{2T_c + g_1 a + g_2 a}$, and $X_2 = \frac{T_c a(d-2e) + g_1 a^2 D}{2T_c + g_1 a + g_2 a}$.

After dividing the port hinterland in terms of different d (i.e., the origins in the interval [0, x_r^*] are the hinterland for Port 1, and the origins in interval [x_r^*, D] are the hinterland for Port 2), then the total internal transport cost from the origins in the closed linear hinterland to the gateway ports can be calculated as follows:

$$C = \int_0^{x_r^*} T_c a|x-e|dx + \int_{x_r^*}^{D} T_c a|x-e-d|dx \ (x_r^* = x_r', x_r'', x_r''').$$

4.2 Port construction cost

Generally, infrastructure investments are characterized by economies of scale (Dekker, 2010). Economies of scale for port investment (used for expanding capacity) means that when the capacity reaches a certain level, then the capacity increases with investment at a decreasing rate. The proposed function for measuring the relationship between fixed port assets and port capacity can be defined as follows:

$$B = h \cdot K^m \quad (0 < m < 1) \tag{2}$$

where B is the scale of fixed port asset (i.e., the construction cost), K is the port capacity, h is a parameter, and m is a scale factor.

According to Sections 3.1 and 3.2, the total internal cost of the external transport system in an MPR can be expressed as follows:

$$A = C + B = \int_0^{x_r^*} T_c a|x-e|dx + \int_{x_r^*}^{D} T_c a|x-e-d|dx + B(K) \ (x_r^* = x_r', x_r'', x_r''').$$

5. Optimal scale of the port group in a closed MPR

The maximum social welfare of the external transport system in a closed region is determined as follows: the sum of transport costs and infrastructure construction costs is minimized within the context of the freight demand from the hinterland that is effectively served. The optimization of the scale of the port group is to determine the number of ports, the scale of each port, and the locations maximizing the social welfare. The dynamic relationship between hinterland division and the number and scale of the ports in a section-type MPR is complex. Here, we study the problem of determining the optimal scale of the port group in a funnel-type MPR only.

As shown in Figure 4, we assume that in the interval [*0*, *D*] of the linear hinterland of a funnel-type port layout, the demand density is *a*, and the hinterland scope that can be used to construct the port is the interval [*0*, *s*]. If only one port is constructed, because the capacity equals the freight demand (i.e., $K = aD$), then we find using Eq. (1) and Eq. (2) that the total internal cost of the external transport system is minimized if the port is constructed at site *s*. The total internal cost can be expressed as follows:

$$A_1^* = \int_0^s T_c axdx + \int_0^{D-s} T_c axdx + B(aD) \tag{3}$$

where $B(aD)$ is the port construction cost. Simplifying Eq. (3), we obtain Eq. (4):

$$A_1^* = \frac{1}{2}T_c as^2 + \frac{1}{2}T_c a(D-s)^2 + B(aD) \tag{4}$$

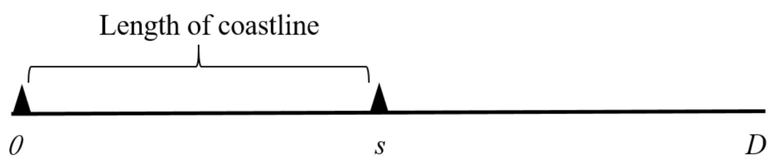


Figure 4 funnel-type port layout

If two ports are constructed, then their combined capacity should equal the hinterland freight demand. We observe that the total internal cost is minimized if Port 1 is built at site *0* (the corresponding capacity is $a\frac{s}{2}$) and Port 2 is built at site *s* (the corresponding capacity is $a\left(D-\frac{s}{2}\right)$). The total internal cost then can be expressed as

$$A_2^* = 2\cdot\int_0^{s/2} T_c axdx + \int_0^{D-s} T_c axdx + \left[B\left(\frac{as}{2}\right) + B\left(\frac{2aD-as}{2}\right)\right] \tag{5}$$

where $B\left(\frac{as}{2}\right)$ and $B\left(\frac{2aD-as}{2}\right)$ are the construction costs of the two ports. Simplifying

Eq. (5), we obtain Eq. (6):

$$A_2^* = \frac{1}{4}T_c as^2 + \frac{1}{2}T_c a(D-s)^2 + \left[B\left(\frac{as}{2}\right) + B\left(\frac{2aD-as}{2}\right)\right] \tag{6}$$

The above example indicates that the number of ports required is determined by the freight demand. Here, we use the construction of one or two ports as an example to investigate the decision-making process. The difference between A_1^* and A_2^* is as follows:

$$\Delta A = A_1^* - A_2^* = \frac{1}{4}T_c as^2 + \left[B(aD) - B\left(\frac{as}{2}\right) - B\left(\frac{2aD-as}{2}\right)\right] \tag{7}$$

From Eq. (2), we obtain $\frac{\partial B}{\partial K} > 0$ and $\frac{\partial^2 B}{\partial K^2} < 0$; thus, $B(aD) - B\left(\frac{as}{2}\right) - B\left(\frac{2aD-as}{2}\right) < 0$. Assuming that a is an endogenous variable, then setting $\Delta A = 0$, we find that the critical value of the demand density occurs when the minimal total internal cost for constructing one or two ports equals as:

$$a^* = \left(\frac{4h}{T_c s^2}\right)^{\frac{1}{1-m}} \left[\left(\frac{s}{2}\right)^m + \left(D - \frac{s}{2}\right)^m - D^m\right]^{\frac{1}{1-m}} \tag{8}$$

With a^*, the optimal scale of the port group in the MPR in terms of varying demand density can be determined as follows:

1) When $a > a^*$, then $A_1^* > A_2^*$, and two ports should be constructed. When Port 1 is constructed at site 0 (the corresponding capacity is $a\frac{s}{2}$) and Port 2 is constructed at site s (the corresponding capacity is $a\left(D - \frac{s}{2}\right)$), the total internal cost is then minimized as follows:

$$\frac{1}{4}T_c as^2 + \frac{1}{2}T_c a(D-s)^2 + \left[B\left(\frac{as}{2}\right) + B\left(\frac{2aD-as}{2}\right)\right] \tag{9}$$

2) When $a < a^*$, then $A_1^* < A_2^*$; one port should constructed at site *s*, and the corresponding capacity is aD. The total internal cost is then minimized as follows:

$$\frac{1}{2}T_c as^2 + \frac{1}{2}T_c a(D-s)^2 + B(aD) \tag{10}$$

Following this method, problems for three or more ports can also be solved. When the savings in inland transport cost cannot cover the increases in port construction costs, then no more ports should be constructed. If the savings in inland transport costs can cover the increasing port construction costs and have a positive relationship with the hinterland freight demand, a higher freight demand density may mean that more ports will need to be constructed in the hinterland.

6. Multi-period investment and quit mechanism for port integration

Section 4 presented a method to determine the number of needed ports and the scale and location of each port with maximizing the social welfare when the port capacity meets the freight demand in an MPR. Nevertheless, in the real world, the optimal number, scale, and location of the ports in an MPR cannot be easily realized in short time. These problems only can be solved in the long term. In this section, we propose a method and procedure for determining a multi-period investment and quit mechanism for gradually realizing port integration and cooperative operation in a funnel-type MPR.

Assume that there exist two ports in the coastline [*0*, *s*] in the interval [*0*, *D*], as shown in Figure 5. Port 1 is located at site *0*, Port 2 is located at site *b*, and their combined capacity just meets the hinterland freight demand. We assume that the capacity of Port 1 is much higher than that of Port 2. Dividing the hinterland based on the theory of stochastic utility maximization discussed in Section 3, we determine that Port 1's capacity is higher than its hinterland freight demand; therefore, the port resources will be idle. In contrast, Port 2's capacity cannot meet its hinterland freight demand; thus, if all the demand in Port 2's hinterland transfers to Port 2, Port 2 will suffer severe congestion. In the real world, Port 1 will acquire a certain amount of demand from Port 2's hinterland with its capacity to remedy Port 2's lack of service.

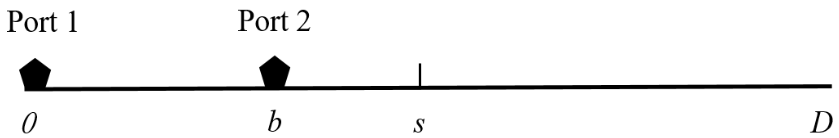


Figure 5 Present port layout in MPR

In the abovementioned context, the internal land transport cost of the closed MPR is not minimized. To minimize the cost, the basic idea of port resource integration and cooperative operation can be described as follows: 1) increase Port 2's capacity (i.e., invest in expanding the port) so that the port can obtain more hinterland freight demand and decrease the inland transport costs, and 2) leave a certain part of Port 1's capacity idle to withdraw the port's excess capacity from the market.

Here, we will use the multi-period port integration decision model to solve these two problems. Assume that the time interval of each period for Port 2's capacity expansion and Port 1's capacity idling are the same. At the end of each period, Port 2's capacity will increase because of the investment, and Port 1's idle capacity will be withdrawed from the market. Figure 6 describes the capacity change of the two ports, and the mathematical expressions are as follows:

$$K_2^t - K_2^{t-1} = \Delta K_2^t = f'(B_{20} + (t-1)\cdot x)\cdot x \qquad (11)$$

$$K_1^{t-1} - K_1^t = \Delta K_1^t = f'(B_{10} - (t-1) \cdot y) \cdot y \tag{12}$$

where K_1^t and K_2^t are the capacity of the two ports in period *t*; ΔK_1^t and ΔK_2^t are the decreased capacity of Port 1 and the increased capacity of Port 2 from period (t-1) to period t, respectively; B_{10} and B_{20} are the corresponding fixed assets of the two ports in period 0; *x* is the investment scale of each period for Port 2; *y* is the asset idling scale of each period for Port 1; and $f(B)$ is an inverse function of the relationship between the port's fixed assets and capacity (i.e., $B = h \cdot K^m$).

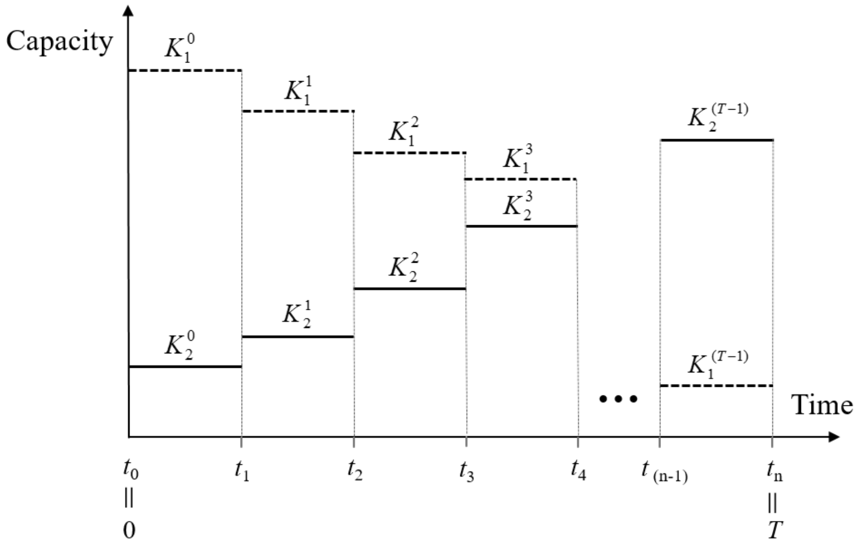


Figure 6 The capacity change after implementing the integration mechanism

Port 2's capacity will increase with the sustained investment, whereas Port 1's capacity will decrease because of asset idling. Then, the demand for transit through Port 2 will increase, while the demand for transit through Port 1 will decrease. The savings on inland transport of each period can be expressed as

$$C^t = C\left(X_1^{t-1}, X_2^{t-1}\right) - C\left(X_1^t, X_2^t\right) \tag{13}$$

where $C\left(X_1^t, X_2^t\right)$ is the land transport cost from the hinterland to the ports at the end of period *t* and X_1^t and X_2^t are the demand for transit through the two ports. Since X_1^t and X_2^t are determined by x_r^{*t} in the hinterland division, then $C\left(X_1^t, X_2^t\right)$ can also be expressed as $C\left(x_r^{*t}\right)$. As indicated in Section 3, in the funnel-type MPR, when $b > \dfrac{g_2^t aD}{T_c + g_1^t a + g_2^t a}$, we obtain $X_1^t = a \cdot x_r^{*t} = \frac{a\left(T_c b + g_2^t aD\right)}{2T_c + g_1^t a + g_2^t a}$ and $X_2^t = a \cdot \left(D - x_r^{*t}\right) = \frac{a\left(2T_c D - T_c b + g_1^t aD\right)}{2T_c + g_1^t a + g_2^t a}$; thus, $C\left(X_1^t, X_2^t\right)$ is expressed as

$$C\left(x_r^{*t}\right) = \int_0^{x_r^{*t}} T_c axdx + \int_{x_r^{*t}}^{b} T_c a(b-x)dx + \int_b^D T_c a(x-b)dx \tag{14}$$

Simplifying the equation yields

$$C\left(x_r^{*t}\right) = \frac{T_c}{2} a\left(x_r^{*t}\right)^2 + \frac{T_c}{2} a\left(b - x_r^{*t}\right)^2 + \frac{T_c}{2} a\left(D-b\right)^2 \tag{15}$$

When $b \le \frac{g_2^t aD}{T_c + g_1^t a + g_2^t a}$, we obtain $X_1^t = a \cdot x_r''^t = \frac{a\left(g_2^t aD - T_c b\right)}{\left(g_1^t + g_2^t\right)a}$ and $X_2^t = a \cdot (D - x_r''^t) = \frac{a\left(g_1^t aD + T_c b\right)}{\left(g_1^t + g_2^t\right)a}$; then

$$C\left(x_r^{*t}\right) = \int_0^{x_r''^t} T_c axdx + \int_{x_r''^t}^{D} T_c a(x-b)dx = \frac{T_c}{2} a\left(x_r''^t\right)^2 + \frac{T_c}{2} a\left(D-b\right)^2 - \frac{T_c}{2} a\left(x_r''^t - b\right)^2 \tag{16}$$

Moreover, with the decrease of Port 1's capacity, its asset idling cost in each period can be calculated as

$$L_t = y - y \cdot r \cdot (t-1) \tag{17}$$

where L_t is Port 1's asset idle cost in period t and r is the depreciation rate.

Based on the above analysis, the multi-period investment and quit model with maximizing the social welfare can be expressed as

$$\begin{aligned} Min \quad Z = {} & C\left(x_r^{*T}\right) + (B_{10} - \sum_{t=1}^{T} y/(1+i)^t)/P(F,i,n) + (B_{20}/P(F,i,n) + x) \\ & - C^* - B^*/P(F,i,n) \end{aligned} \tag{18}$$

$$S.T.: \quad \sum_{t=1}^{T}\left(C\left(x_r^{*(t-1)}\right)\big/(1+i)^{t-1} - C\left(x_r^{*t}\right)\big/(1+i)^t\right) \ge \sum_{t=1}^{T} L_t\big/(1+i)^t + \sum_{t=1}^{T} x\big/(1+i)^t \tag{19}$$

$$f(B_{10} - y \cdot t) = K_1^t \tag{20}$$

$$f(B_{20} + x \cdot t) = K_2^t \tag{21}$$

$$K_1^T + K_2^T = a \cdot D \tag{22}$$

$$x_r^{*t} = \begin{cases} \dfrac{T_c b + g_2^t aD}{2T_c + g_1^t a + g_2^t a}, & b > \dfrac{g_2^t aD}{T_c + g_1^t a + g_2^t a} \\ \dfrac{g_2^t aD - T_c b}{\left(g_1^t + g_2^t\right)a}, & b \le \dfrac{g_2^t aD}{T_c + g_1^t a + g_2^t a} \end{cases} \quad (23)$$

$$0 < T \le n \quad (24)$$

$$x, y, T \in R_{++} \quad (25)$$

The decision variables in the model are T, x, and y; where T is the planning integration period; x is port 2's investment volume in each period; y is port 1's asset idle scale in each period. Eq.(18) is the objective function, which represents the difference between the total internal cost of the external transport system and the total cost in optimal port layout at the end of period T. Where i is discount rate, n is maximal planning integration period, $P(F,i,n)$ is present-value interest factors of annuity, C^* is the land transport cost in optimal port layout, B^* is the port construction cost in optimal port layout. Eq. (19) represents the total saving land transport cost, which should be not less than the sum of port 1's asset idle cost and port 2's investment cost. Eq.(20) and Eq.(21) represent the capacity of the two ports in period t, respectively. Eq.(22) indicates that the total capacity of the two ports should equal the hinterland freight demand at the end of planning integration period. Eq.(23) represents the hinterland division result in period t. Eq.(24) represents the planning integration period should not exceed maximal planning period. Eq.(25) is non-negativity constraint, which ensures that no decision variable takes on negative values.

7. Empirical study

Forty-one cities along the coastline in Liaoning Province of northeast China have formed a funnel-type MPR (Figure 7). The throughput of the top two ports in all the ports in this region accounts for a large proportion of the total throughput of the region (According to China Ports Year book (2016)). Here, we assume that there exist only two ports in the region, and their relevant data are presented below.

Table 1 the relevant data of the two hub ports in 2015

Port	Fixed asset（100 million RMB）	Demand for transit through the port（100 million tons）	Capacity（100 million tons）	Basic port tariff（RMB/ton）
Port 1	1070.3	2.13	3.21	200
Port 2	571.7	1.87	1.62	200

Extending the above MPR to the linear region shown in Figure 5, we determine that the hinterland length D is 1661 km, the length of the coastline s is 380 km, Port 1 is located at zero, and Port 2 is located at location b (b = 197 km). The total freight demand in the entire region in 2015 was 400 million tons, and the demand density in the linear hinterland can be calculated as a = 0.24 million ton/km. Since the main hinterland access mode is road transport, the unit cost of land transport can be set to 0.5 RMB/ton based on the road transport tariff.

Using the fixed asset and capacity data from 2007 to 2015 for the listed ports in Liaoning Province to calibrate the function $B = h \cdot K^m$, we obtain $\ln B = 0.91 \ln K + 15.12$ ($R^2 = 0.83$, $p = 0.005$). The maximal planning integration period is 30 years, and the starting year for integration is 2015. The depreciation rate and discount rate are set to 0.05 (Depreciation Rate, 2015) and 0.04 (Discount Rate, 2016), respectively.

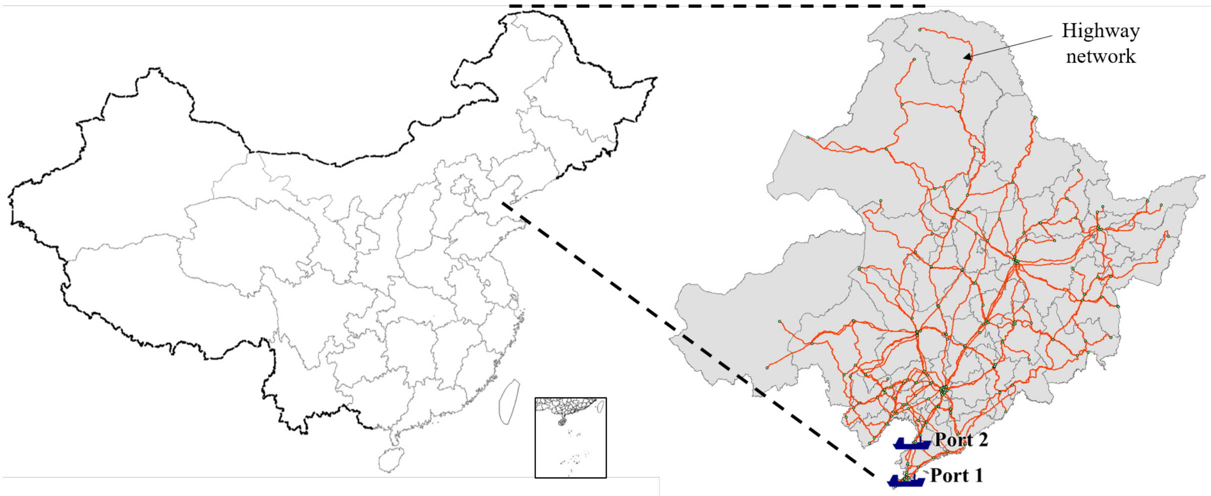


Figure 7 the layout of the main ports and their hinterland in the MPR of northeast China

7.1 Optimal scale of port group and optimal investment and quit mechanism

Using the C++ programming code to solve the port group scale optimization model and multi-port integration decision-making model. The results are shown in Table 2 and Table 3. Table 2 shows that to maximize social welfare, one port should be constructed at s which is 380 km far from site zero and its capacity should be equal to the hinterland total freight demand. The corresponding port investment cost is 130 billion RMB, the equivalent annual investment cost is 9.56 billion RMB, and the annual land transport cost is 127.2 billion RMB.

Table 2 optimal port group scale in MPR

Number of ports	Port location （km）	Port investment cost （billion RMB）	Land transport cost （billion RMB）	equivalent annual investment cost （billion RMB）
1	380	130	127.2	9.56

Table 3 shows that if the decision makers wish to realize the integration and cooperative operation of the two ports, 20 planning periods are needed for investment in the expansion of Port 2 (the amount of investment for Port 2 in each period is 3.2 billion RMB) and to leave Port 1's capacity idle (the idle fixed assets in each period are 4.7 billion RMB). At the end of period 20, Port 1's fixed assets are only 13.03 billion RMB, whereas Port 2's fixed assets have increased to 121.17 billion RMB. At this time, the total annual internal transport cost is 139.21 billion RMB, which is the smallest gap relative to the cost of the optimal port layout (exceeding that cost by only 2.45 billion RMB).

Table 3 Optimal port investment and quit mechanism

Integration planning period（year）	Port 2's investment volume in each period（billion RMB）	Port 1's asset idling scale in each period（billion RMB）	Gap between the total internal transport cost and the cost in optimal port layout（billion RMB）
20	4.5	6.6	2.45

7.2 The change of the ports' hinterland and capacity

Figure 8 presents the changes of freight demand and capacity for the two ports. Figure 9 indicates the changes to their hinterland scope. In the process of investing in the expansion of Port 2 and idling Port 1's capacity from period 0 to period 20, Port 1's capacity, hinterland scope, and freight demand decrease gradually, while that of Port 2 increases gradually. At the end of period 20, the capacity of both ports can serve the hinterland freight demand effectively. At this time, Port 1's freight demand has declined from 213 million tons in period 0 to 30 million tons in period 20, whereas Port 2's freight demand has increased from 187 million tons in period 0 to 370 million tons. Moreover, at the end of period 17, Port 1's hinterland scope (183 km) is less than b (197km), which means that crossover land transportation from the hinterland to the gateway ports has been significantly reduced. At the end of period 20, Port 1's hinterland scope (125 km) equals its servable hinterland scope, and the crossover land transportation has disappeared entirely. The above results indicate that a multi-period investment and quit mechanism for port integration has been realized and that the total internal transport cost of the external transport system has been reduced to a minimum through the creation of an optimal port layout.

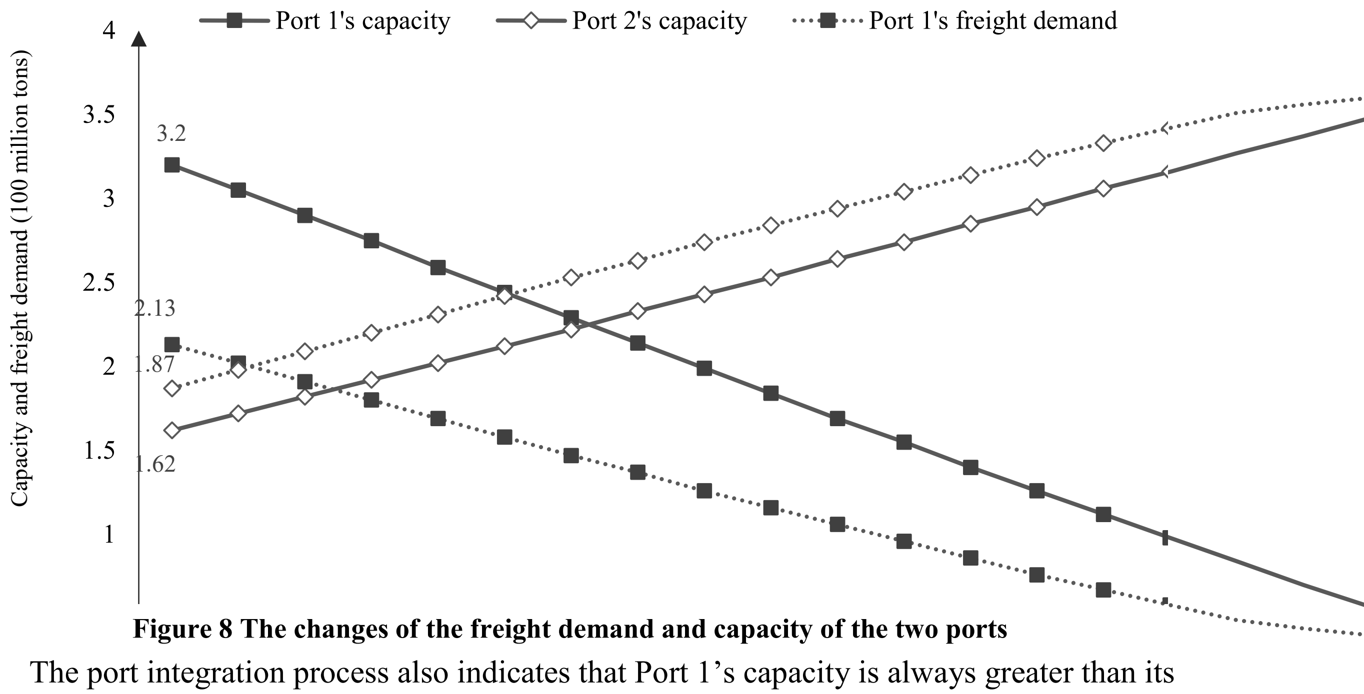


Figure 8 The changes of the freight demand and capacity of the two ports

The port integration process also indicates that Port 1's capacity is always greater than its freight demand and that Port 2's capacity is always less than its freight demand before the end of integration process, whereas the gap between the capacity and the freight demand of the two ports decreases gradually and their capacities both approach their freight demand. Moreover, in the end of period 1, Port 2's available freight demand is already greater than Port 1's available freight demand (exceeding 4 million tons), which indicates that Port 2 has begun to exert the advantage of its proximity to the hinterland. In terms of the relationship between the two ports' capacity, Port 2's capacity is greater than Port 1's capacity at the end of period 7 (greater than 19 million tons). The capacity relationship shows that the port scale pattern in the MPR has begun to change and that Port 2 has attained the role of hub port.

Through the above analysis on the change of the ports' hinterland, capacity, and freight demand, we find that the proposal of a multi-period investment and optimal capacity quit mechanism can effectively stimulate the port integration process and that a port resource integration and cooperative operation plan can be developed based on the integration process.

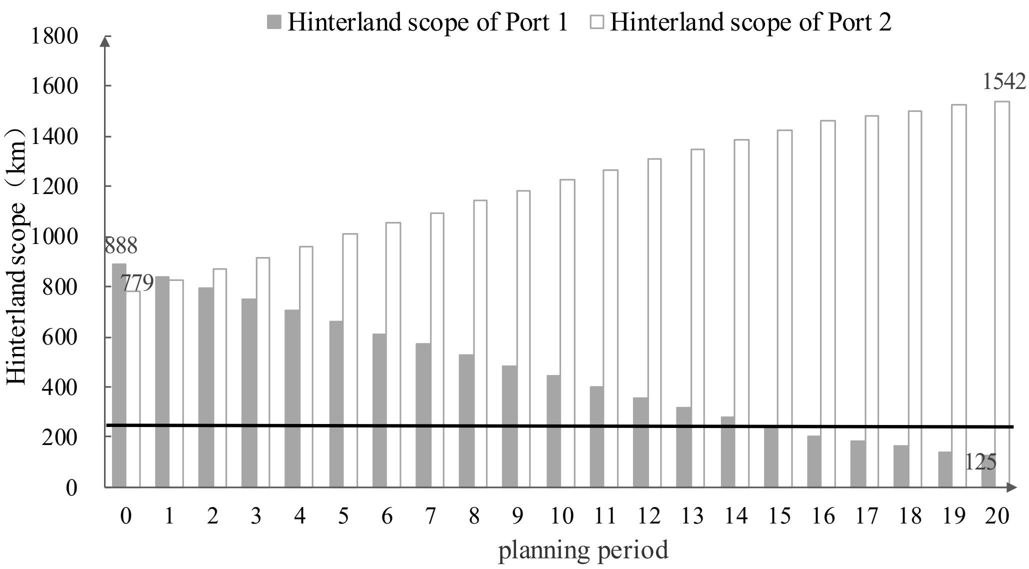


Figure 9 The change of the two ports' hinterland scope

7.3 Sensitivity analysis

Either a fluctuation of the discount rate i in the financial markets or a change of the basic port tariff will affect the process of multi-port integration and cooperative operation. Therefore, we choose these two indicators to implement a sensitivity analysis and discuss the optimal multi-period investment and capacity quit mechanism.

（1） Impact of discount rate on the optimal mechanism

Figure 10 presents the optimal results of the planning integration period, investment volume and scale of asset idling in each period. When i increases from 0.02 to 0.06, Port 2's investment volume and Port 1's idling asset scale both increase gradually (from 2.1 billion RMB to 4.4 billion RMB and from 3.1 billion RMB to 6.4 billion RMB, respectively), whereas the planning integration period decreases gradually (from 29 years to 16 years). The changes occur because in the objective function (Eq. (18)), $P(F,i,n)$ decreases along with increasing discount rate i, which then results in an increase of annual port construction costs in the optimal port layout. To make the objective function approach the minimum, it is necessary to shorten the planning integration period and increase Port 1's annual idling asset scale; however, it is also necessary to enlarge Port 2's annual investment scale. The results also indicate that when both the discount rate and the finance cost for port construction increase, then the decision makers must shorten the planning integration period, increase the asset idling scale for the port that is idle and expand the investment volume for the port that needs expansion to accommodate the changes in the finance market.

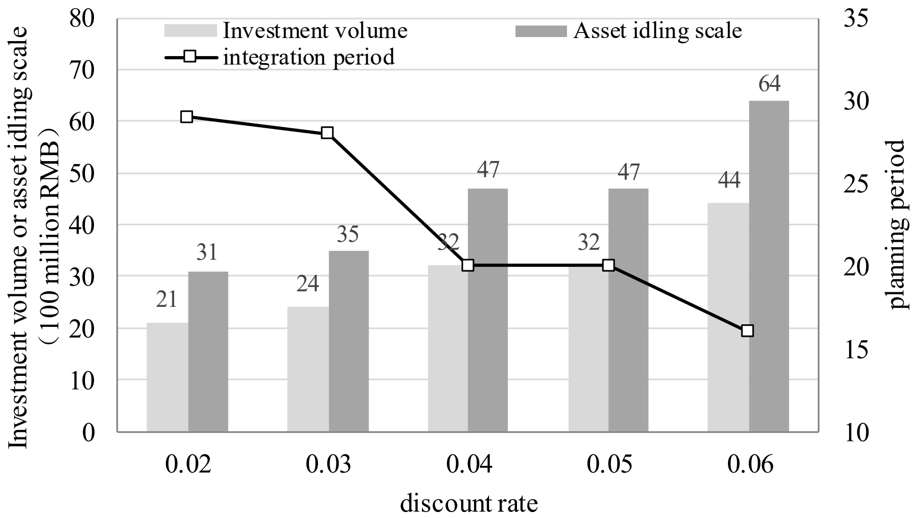


Figure 10 Optimal integration mechanism under different discount rates

(2) Impact of the basic port tariff on the optimal mechanism

Assume that the two ports have the same basic port tariff. Figure 11 presents the optimal planning integration period, the investment volume and the asset idling scale under different basic tariffs. When the tariff increases from 50 RMB/ton to 300 RMB/ton, Port 2's investment volume, Port 1's asset idling scale in each period, and the planning period all remain essentially unchanged (i.e., the optimal investment volume for Port 2 is 4.5-5.1 billion RMB, the optimal asset idling scale for Port 1 is 3.1-3.5 billion RMB, and the optimal integration period is 19-21 years). This trend indicates that the integration plan is not sensitive to the basic tariff and that the basic port tariff only minimally influences the integration of port resources in the MPR.

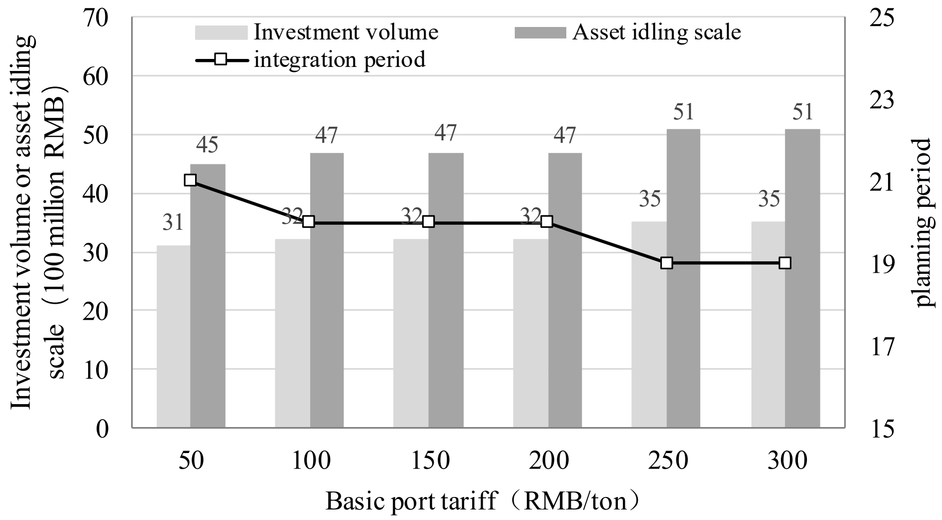


Figure 11 Optimal integration mechanism under different basic tariffs

8. Discussion and Policy Implications

The above sections have presented a method for determining the optimal layout of the port group with maximizing the social welfare in a MPR, designed the multi-period investment and quit mechanism for port resources integration. To realize a successful port integration, the following problems also should be paid attention.

First, the key to port integration is to design an incentive mechanism to make the ports with surplus resources willing to leave the market and the ports with insufficient capacity willing to invest in additional capacity. According to our analysis, a three-step incentive mechanism can be designed to realize port integration. The first step is that of top-level design, i.e., a port group should be founded under the direct leadership of the provincial government to govern all the ports in the region to realize unified planning and operation. This measure has already been undertaken in the ZheJiang, Guangxi, Jiangsu, and Hebei Provinces; the four provinces have enacted the concept of “one province, one port” using the administration, commands and the assets of the State-owned Assets Supervision and Administration Commission (SASAC). Specifically, the ZheJiang seaport Investment & Operation Group Co. Ltd. was founded in 21 August 2015. this group integrates five port companies, namely, Ningbo Port, Zhoushan Port, Jiaxing Port, Taizhou Port, and Wenzhou Port in Zhejiang Province, to realize unified operation. In this typical case of provincial government integration, the administration power and assets of SASAC are used to implement provincial port resource integration. This approach can achieve a synergistic effect using port assets and avoid the disordered of port competition in the region.

Second, the integrated ports should set a reasonable port tariff rate and implement a expense collection mechanism The primary aim of the mechanism is to prevent a monopoly based on pricing. This application of “one province, one port” will weaken port competition, decreasing the port choice available to shippers. Moreover, it will be more convenient for the port group to monopolize price and then trigger a scenario involving high prices with low service quality. To overcome these drawbacks, the administration should formulate guidance on pricing and limit prices based on historical data, market demand, and the price of the other ports in adjacent provinces to guarantee benefits to shippers. Another aim of the mechanism is to convert the savings on land transport expenses into government income. To realize the maximal social welfare, the government can create a large fund (which is often invested by the companies in the SASAC) to integrate the port resources. The funds originate from taxes (which are the assets of citizens); thus, the benefits of port investment should revert to the government on behalf of the citizens.

Third, a transfer payment policy should be established so that the higher-up government can subsidize the port cities with asset idling through transfer payments. This policy will encourage the ports to use the subsidies to invest in more potential industries that will earn profits exceeding the revenue from port operation. Only by formulating and implementing such a policy will the integration of port resources succeed and the regional development and upgrading of industries in port cities be realized. The transfer payment policy will be helpful to all the ports in the region, particularly those ports needing to have their assets idled. On the one hand, the transfer payments can avoid the freight revenue loss from idle capacity. On the other hand, these ports can use the funds made available through transfer payments to invest in industries with high potential. For the ports with insufficient capacity, the transfer payment can improve the state of disordered port competition. Cities that are more suitable to developing the port industry will more actively invest in capacity expansion.

The context of our research is excess supply and resource idling in Chinese ports. Given this background, the implementation of cooperative operation through port resources integration will avoid creating a port monopoly and disrupting the benefits to shippers. In the case of excess port capacity, port integration will only minimally change the situation of supply exceeding demand, and the shippers' market will remain unchanged. Moreover, many ports exist in adjacent regions, and any port monopoly or decrease in port service quality will result in the departure of shippers and shipping companies to the other ports. Therefore, in the context of excess port capacity, the operational doctrine of "one province, one port" will maintain a balance between the market mechanism and the administration mechanism. This guideline also provides the most effective way to use resources.

9. Conclusions

In this paper, we studied the port group optimization problem for a funnel-type MPR with the objective of maximizing the social welfare of the external transport system where the ports are regarded as hubs. Based on an optimal port group plan, we proposed a method for port resource integration and cooperative operation in a closed region. An empirical study was performed using a funnel-type MPR formed by 41 cities along the coastline in the Liaoning Province of northeast China.

The results indicated that the proposed method, which determined the optimal scale of the port group with maximizing social welfare and the multi-period investment and quit integration mechanism, can optimize the port layout pattern in an MPR and effectively stimulate the port resource integration process. A sensitivity analysis showed that when the discount rate increases, decision makers can consider shortening the integration planning period by increasing the investment volume and the scale of asset idling at each period. The sensitivity analysis also indicated that the basic port tariff only minimally influences the investment and quit mechanism for port integration. Several notable problems that arise when port integration and cooperation are conducted are also addressed. The research results provide an important theoretical reference and practical framework for local governments and decision makers in the port corporation to conduct the integration of port resources and cooperative operation in MPRs.

Additionally, when analyzing the port investment for capacity expansion, we considered the effect of the economies of scale for port construction. However, in actual port expansion process, when the port scale exceeds a certain extent, it will led to serious congestion, safety and environmental problems, increase the extra social cost, and then occur diseconomies of scale (Teye, Bell, and Bliemer, 2017). Thus, when we determine the optimal scale of port group, the critical point of the economies of scale for the ports should be determined firstly, and then relationship between the critical point and the port scale after the investment can be discussed. If the port scale exceeds the critical point, we need to add the extra cost owing to the diseconomies of scale for port construction when we calculate the annual construction cost or fixed cost.

The authors recognize that there is still space to further study this topic. Potential directions include, but are not limited to: firstly, the port resources integration and cooperative operation optimization model for section-type MPR should be taken into consideration in future study. Secondly, the limitation of linearly distributed hinterland should be overcome, and the internal transport cost in closed region should be accurately calculated based on the actual hinterland spatial pattern. Lastly, the impact of the regional shipping accessibility on the hinterland freight demand should be investigated after port resources are integrated, and the dynamic relationship between regional accessibility and the hinterland freight demand should embed into our proposed theoretical model.

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