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Competitive inland port location and pricing problem: A perspective from the entering seaport

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ABSTRACT

Competition among seaports has been becoming more and more fierce in current times, which has extended to the contest between transportation chains including seaports and their inland ports. Against this background, this paper studies competitive inland port location and pricing problem for an entering seaport under the condition that the incumbent competitive seaport has constructed inland transportation chains inside their overlapping hinterland. Specifically, this paper formulates a mixed-integer nonlinear program for the considered problem, in which we take packaged price and service time as influence factors for the inland transportation chains competition and characterize inland ports choice behaviors for shippers based on logit model. Additionally, this paper designs a hybrid heuristic method by integrating a genetic algorithm and an analytical method to solve location and pricing subproblems, respectively. Based on the computational results and sensitivity analysis, this paper provides some valuable suggestions on how to locate in-land ports and make price decisions for the new entering seaport.

1. Introduction

With the development of international trade, competition between seaports for cargo from the hinterland is becoming more and more fierce, especially between those that are geographically close and have overlapping hinterland. Every competing seaport wants to strive for inland cargo from overlapping hinterland, because cargo is their profit resource, and they must promote their respective competitiveness and survive in the market (Slack, 1985). The fact is inland ports contribute to seaports gaining more inland cargo. When inland cargo is transported from its origination to a seaport through inland ports, an inland transportation chain is formed (Luo et al., 2022). Hence, the battle for inland cargo between two single seaports is gradually extending to the contest of two inland transportation chains with seaports as destinations.

A far-sighted seaport has located inland ports in its hinterland and constructed several inland transportation chains proactively, expanding hinterland and gaining more inland cargo. Qingdao Port, for example, has attracted more cargo by inland ports inside different hinterlands in China. As the competition increasingly intensified, another seaport nearby recognized the importance of inland transportation chains, especially for larger inland cargo volume. This nearby seaport prepares to locate its inland ports to strive for inland cargo from their overlapping hinterland and get competitive advantages. Still take Qingdao port's rivalry, Rizhao Port for example, Rizhao port has located its inland port at Xi'an aiming at more profit through increased inland cargo. Competition by inland transportation chains between the two seaports begins. The latter coming seaport needs not only locate its inland ports, but also price its inland cargo freight service.

As a new inland transportation chains constructor, the entering seaport usually tends to assume that chains will bring more profit, but neglects to analyze the competitive situation before locating its inland ports. The entrant seaport may locate its inland ports by an unscientific method, so that it will not cater shippers' preference well. Moreover, it may be thought that lowering packaged service price or reducing process time is the only way to achieve greater profits. In fact, these two means

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will influence profit from two aspects. They will boost a seaport's market share inside the hinterland but compress its unit profit. Especially reducing time, it will bring extra cost and thus cut profit to various degrees. How much cost it will generate depends on the difficulty to do so.

Building upon the issues, we address the competitive inland port location and pricing problem from the perspective of the entering seaport. We formulate a mixed-integer nonlinear programming model to solve location and pricing subproblems simultaneously. Moreover, we adopt a hybrid method including a genetic algorithm (GA) and an analytical method. Among them, GA is utilized for generating, searching for, and selecting better solutions, while the exact solution method is used to calculate the corresponding optimal price. The main contributions of this paper are as follows.

Contribution 1: We simultaneously consider long-term location and short-term pricing decisions for the studied problem. Specifically, during the initial phase of the location process, we take short-term prices into account. This way, the entrant can choose an inland port location that maximizes profits.

Contribution 2: We design a hybrid method by combining a heuristic and an analytical approach. This hybrid method can solve the location and pricing problems synchronously. In the exact calculation part, we derive an analytical expression of optimal price by Lambert function. Particularly, the optimal price considers different levels of service time. Through profit analysis, it enables decision-making not only on determining the optimal price but also on whether to improve efficiency and establish the optimal price.

Contribution 3: We analyze the influence of related parameters and provide targeted managerial insights. We demonstrate the influence of the number of the incumbent' inland ports on that of the entering seaport and give location suggestions for the entrant. We advise competing seaports to improve competitiveness by improving the ability of saving service time. Moreover, we provide recommendations on how to overcome the impact of price sensitivity of shippers.

The rest of this paper is organized as follows. In section 2, we review related research topics. Section 3 describes the considered problem in detail and constructs the corresponding mathematical model. In section 4, this paper explains the main steps and key points of the hybrid solution method designed in this paper. In section 5, this paper conducts numerical studies and analyses the effects of related parameters. Management discussions and insights are also given in this section. Conclusion is conducted in Section 6.

2. Literature review

In this section, we carry out a literature review about three topics relative to our study: seaports competition, inland port location, hub-and-spoke network.

2.1 Seaport competition

As scholars have long realized that whenever seaports provide similar services for the overlapping hinterland, competition naturally exists （Slack, 1985; Luo *et al*.,2022）. One of the aims of competition is to gain more profit. Cargo from the hinterland is an important profit source, which seaports will strive for with each other. Measure to strive for cargo is an important research direction about seaport competition. Many scholars list important factors influencing seaport competition and conduct corresponding research on how seaports compete.

Ishii *et al*. (2013) examine the effect of inter-port competition by applying a game theoretical approach. They attribute different performance levels to port capacity and thus research some problems of investment to extend capacity. Wan *et al*. (2016) study two seaports competing under the condition that they have a common and respective inland market. They get the conclusion of strategic investment in hinterland accessibility. Balliauw *et al*. (2019) state that port competes with nearby ones to attract cargo, geographical location and differentiated services are important factors influencing competition result. They conduct research on improving capacity by investment. Zheng *et al*. (2020) investigate the effects of demand information sharing during two seaports competitions. Gan *et al*. (2021) conduct research on seaport competition under the competitive condition of carbon emission constraints. There are many other scholars conducting relative research about seaport competition (Kammoun and Abdennadher, 2022; Park, *et al*.,2020; Wiegmans *et al*., 2008; Song *et al*., 2016; Tijan *et al.*, 2022; Lau *et al.*, 2022).

2.2 Inland port construction

With more and more intensified competition and emergency of containerization and commercialization, seaport competition has been changing from competition between individual seaports to a broader scope, for example transport chains, seaport alliances and so on. Therefore, there is an increasing amount of research on inland resources. Álvarez-SanJaime *et al*. (2015) state that inland transport service influences the competitiveness of a seaport deeply. When a seaport wants to achieve competitive advantage, it should consider the integration of seaport and inland transport service. Li *et al*. (2020) research on seaport competition from the perspective of the entire transportation chain. Given the increasing importance of inland resource integration for seaport competition, the significance of inland ports is also becoming increasingly apparent. Inland ports play an important role in terms of integrating inland resources and improving accessibility of inland transportation chains and so on. Many scholars state the significance of inland ports. Roso and Lumsden (2010), Wan *et al.* (2022) hold the opinion that inland ports play a vital role in improving the connectivity between seaports and their hinterland, alleviating various disadvantages that restrict seaports development, coordinating port supply chains, and promoting regional economic development. Jeevan *et al*. (2017) state that inland ports provide economies of scale and scope to their respective clients and enhance the importance of inland networks to improve and consistently elongate the competitiveness of container seaports. In summary, in terms of physical function, inland ports provide cargo freight from hinterland to seaports. And in terms of economic function, it also produces economies of scale and scope. Relying on inland ports, seaport can realize its function in a lower cost and more convenient way. Thus, accessibility between hinterland and seaport gets improved. It is of great importance to conduct research on inland port locations.

Since inland ports are so important, many scholars have conducted research on the construction of inland ports. The common research perspectives include inland port location, scale planning, function of inland port and so on. In location levels, Kurtuluş (2023) conducts research about inland port location and allocation from an environmental perspective. Nguyen *et al*. (2020) study large-scale dry port location. The model they construct is a two-stage model. And they use a hybrid approach of data mining and complex network theory to solve the model. In terms of scale planning, Wei and Li *et al*. (2021) calculate logistics capability coefficient of inland port and rank that when they study alliance systems associated with inland port. Wan *et al.* (2016) construct a competitive model to conduct research about inland port accessibility investment. In the perspective of function, Ma *et al.* (2023) research about the function of different potential inland ports in a certain region. And they use a bilevel programming model to deal with decisions of different makers. In fact, we find that there is relatively limited research on the location and investment of inland ports using mathematical modeling methods. Most studies have approached these topics from a theoretical perspective.

2.3 Hub-and-spoke network

Our research purpose is finding the optimal location of an inland port for entering seaport in a hub-and-spoke network. Usually, inland ports are located by a seaport to supply inland cargo freight for shippers in a wide geographical scope. Inland cargo freight network based on inland port location is a hub-and-spoke network. O'Kelly (1986,2009) describes the structure of hub-and-spoke network in which hubs are central facilities acting as switching points in networks and connecting a set of interacting nodes. His research used to be thought to be the earliest research about hub-and-spoke networks. He classifies hub-and-spoke network as a system with a single hub and two hubs. Hub-and-spoke network is widely used in designing logistics, transportation, express and other networks. Zhou *et al.* (2023) design hub-and-spoke network when they study the container transportation of inland waterway shipping. Yang *et al*. (2023) study optimal scheduling of autonomous vessel trains in a hub-and-spoke network. And there are many other studies associated with hub-and-spoke networks (Zhou *et al*.,2022; Wu *et al*., 2022; Huang *et al*.,2022; Li *et al*., 2023; Karimi-Mamaghan *et al*.,2020).

One of the main purposes of hub-and-spoke network is to better play the economic benefits of hub density. Gelareh and Nickel (2010) and Gelareh *et al.* (2011) refer to the reason why hub-and-spoke network has attracted wide attention in various fields. They state that hub-and-spoke network offers possibilities of efficient capacity sharing and fleet management on different legs of transport routes. This leads to a better utilization of transporters such as vehicles and vessels, when studying hub location of transportation networks.

It can be concluded that a hub-and-spoke network is a powerful tool to solve location and allocation problems. In view of extensive research and significance of hub-and-spoke network, this paper learns from the design idea of hub-and-spoke network proposed by Tiwari *et al*. (2021), designing a hub-and-spoke network for competitive inland port location. Different from the above studies, destinations of our hub-and-spoke network are fixed seaports. Legs from inland ports as hubs to seaports serve as spokes of our hub-and-spoke network, but they undertake the ultimate consolidation of the entire network's cargo flows.

2.4 Focus of this study

From a related literature review, we find that most studies on seaport competition or competitive location have following characteristics. First, they seldom focus on long- and short-term projects simultaneously. Secondly, when conducting research about seaport competitions, they tend to use game theories and models. Thirdly, the most prevalent solution methods they use are exact or heuristic algorithms, but mixed algorithms are rarely employed. Note that a closely related study was carried out by Lüer-Villagra and Marianov (2013) on the price factor that influences competitiveness. However, they neglected service time or other factors. Conclusion of previous studies about port competition is shown in Table 1.

Table 1
Summary of key previous studies about seaport competition

Publication	Problem researched	Long term decisions	Short term decisions	Model adopted	Solution method
Lüer-Villagra and Marianov (2013)	Hub location planning	Transport hub location	Price	0-1 programming model	A genetic method and an exact method
Ishii *et al.* (2013)	Investment planning	Capacity investment	Price	Multi-period economy model	Exact method
Óscar Álvarez-SanJaime *et al* (2015).	Service providing	×*	Integrated service	Simple competitive model	Exact method
Balliauw *et al.* (2019)	Investment planning	Capacity and its investment time	×	Game-theoretic model	Exact method
Li *et al*. (2020)	Operation planning	×	Subsidy amount	Game model	Exact method
Gan *et al*. (2021)	Operation	×	emission policy	Improved Hotelling model	Exact method
Kammoun and Abdennadher (2022)	Seaport efficiency comparison during competition	×	Efficiency	DEA and Principal Component Analysis	Exact method
This paper	Inland port location and pricing during seaport competition	Inland port location	Price at different time level	Constrained 0-1 programming model	Hybrid solution method

* "×" represents that this publication do not conduct related research

To sum up, this paper studies seaport competition differing from the above research aiming at the location stage. At this stage, we conduct research about seaport competition in terms of both short-term and long-term perspectives. In the short-term, we consider two factors influencing seaport competitiveness. Regarding algorithms, we employ a hybrid heuristic method, including a genetic algorithm and an analytical method.

3. Problem description and formulation

3.1 Problem description

This paper considers a competitive situation, where there have been one or more inland ports by an incumbent seaport (or called the incumbent simply) inside overlapping hinterland. To compete for inland cargo with the incumbent seaport and get more profit, the other later coming seaport nearby (called the entering seaport or the entrant) wants to locate an inland port inside their overlapping hinterland. Each inland transport demand point inside the overlapping hinterland is a candidate node for the entering seaport's inland ports. And they will choose a minimum of one or a maximum of two inland ports of every seaport according to their price and time preference to realize cargo freight to seaports. Inland transportation chains are formed. In this competitive scenario, we conduct relevant research from the perspective of the entrant and provide decision recommendations. Based on it, this paper primarily addresses the following problems:

Optimal inland port location. Among all candidate nodes, which ones should be chosen as the locations for inland ports to attract inland cargo.

Demand points allocation. How will all the demand points be allocated to inland ports to form inland transportation chains of the entering seaport.

Optimal pricing. How to formulate a price that maximizes profit of every inland transportation chain, and further maximize the overall profit of the whole network.

On the basis of solutions to the aforementioned problems, this paper can further provide recommendations for inland port location, demand points allocation, pricing, and the trade-off between service price and time. The studied problems in this paper are illustrated in Fig. 1.

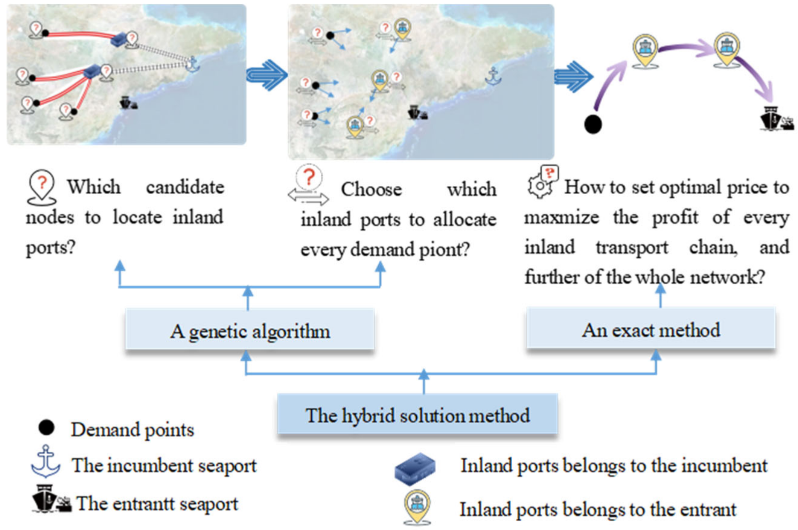


Fig. 1. Problem description

3.2 Competitive inland port location and pricing model

3.2.1 Components of shippers' utility

Demand points are allocated to inland ports based on shippers' utility supplied by seaports' inland transportation chains. During actual competition, the more utility an inland transportation chain provides, the more market share will be allocated to it. In order to express market share of the competing seaports, it is necessary to state the component of shippers' utility in this paper in advance of the competitive model.

Shippers' utility is the "sense of gain" that a seaport supplies by its inland ports. Some scholars accurately interpret this "sense of gain" as "bundle of benefits provided by facilities to customers" (Drezner, 2014), which is one or more factors that constitute the attraction of facilities to shippers (Lančinskas *et al.*, 2015). Scholars quantify shippers' or other service recipients' utility by different factors. Ishii *et al*. (2013) list price as one of the most important factors influencing seaports' performance. Gulhan *et al.* study urban public transportation utility, and they hold accessibility as the fundamental influencing factor. Sakyi *et al.* (2020) adopt price as an important component to characterize shippers' utility.

From most studies about utility in different applied areas, this paper finds that among all the components that make up utility, especially those constituting utility for transportation services, price and time are more studied factors（Jourquin, 2022; Peng *et al*., 2022; Panja & Mondal, 2023; Xiong *et al*., 2023; Haider *et al*., 2021; Krljan *et al.*, 2021）. Even though there are other studied factors, they are often influenced by price or time. The above utility-based discrete choice usually adopts a logit model when it is used to model allocation or choosing process. Based on the above talking about utility, this paper chooses price and time as components of shippers' utility and adopt logit model to express shippers' utility, i.e.

$$u = exp\,[-\gamma p - (1-\gamma)t] \tag{1}$$

where, u is shippers' utility of corresponding inland transportation chain, p is the price of this chain belonging to a seaport, and t is the time. Accordingly, the proportion of providing utility is market share, i.e., x_{ij_2kl} and x_{ij_1st} in our proposed competitive inland port location and pricing model (CLPM).

3.2.2 Assumptions

To construct the model to address the main research questions, we make following necessary assumptions:

- Assumption 1: To benefit from economies of scale by cargo collection via inland port, shippers of every demand point choose at least one and at most two inland ports of every seaport to transport its cargo.
- Assumption 2: When shippers choose inland ports, they only consider the most influencing factors of price and time.
- Assumption 3: The entering seaport can locate an inland port at the same location with the existing seaport but could not share infrastructure of the existing seaport due to their competitive relationship.

- Assumption 4: Only inland ports belonging to the same seaport can be utilized to construct the same inland transportation chain, and an inland port could only be linked with the seaport it belongs to, still due to the competitive relationship between the two seaports.

3.2.3 Notations and parameters

To facilitate model construction, this section describes sets, parameters and decision variables of the CLPM in Table 2.

Table 2
Sets, parameters, and decision variables involved in the formulation.

Notations	Description
Sets and elements	
N	Set of candidate nodes in the overlapping hinterland， $N = \{1,2 \ldots n\}$. $i \in N$.
Q_1，Q_2，	Sets of inland port location of the incumbent and the entering seaport.
j_1, j_2	The incumbent and the entering seaport.
Decision variables	
Y_k	0-1 variables, indicating whether candidate node k is selected as an inland port location by the later coming seaport, whereby 1 means selected, and 0 otherwise.
H_{ik}	0-1 variables, indicating whether demand point i is allocated to the inland port k, whereby 1 means allocated, and 0 otherwise.
P_{ij_2kl}	Unit weight cargo optimal price of the inland transportation chain $i \to k \to l \to j_2$ for the entrant seaport, $(k, l) \in Q_2$.
Parameters	
x_{ij_1st}	Market share of the incumbent in i using chain $i \to s \to t \to j_1$, $(s,t) \in Q_1$.
x_{ij_2kl}	Market share of the entrant in i using chain $i \to k \to l \to j_2$, $(k,l) \in Q_2$.
c_{ij_1st}	Per unit of weight cost of the incumbent seaport via $i \to s \to t \to j_1$.
c_{ij_2kl}	Per unit of weight cost of the entering seaport via $i \to k \to l \to j_2$
α, β, χ	Coefficient of scale economies of legs from demand points to inland ports, between inland ports, from inland ports to seaports.
P_{ij_1st}	Unit weight cargo price via $i \to s \to t \to j_1$ charged by j_1.
p_{ij_1st}, p_{ij_2kl}	The dimensionless P_{ij_1st}， P_{ij_2kl}.
T_{ij_1st}, T_{ij_2kl}	Actual service process time of j_1 via $i \to s \to t \to j_1$, and that of j_2 via $i \to k \to l \to j_2$.
t_{ij_1st}， t_{ij_2kl}	The dimensionless T_{ij_1st}, T_{ij_2kl}.
$\varDelta_1$	Price margin charged by j_1 over its cost, $\varDelta_1 \geq 0$.
$\varDelta_2$， δ_2	Service process time level of j_1 and j_2 relative to average, expressed as a percentage.
λ	Difficulty of saving time coefficient, $\lambda < 0$.
γ	Shippers' price-time preference coefficient, $0 < \gamma < 1$.
W_i	Inelastic cargo freight volume of i that need transported to seaports.
F_k	Fixed cost of building an inland port at candidate node k per year.

3.2.4 Mathematical formulation

By integrating the logit model, we establish the following mixed-integer nonlinear programming model for the considered problem:

$$Z = max \sum_{i \in N} \sum_{k,l \in Q_2} W_i \left(P_{ij_2kl} - c_{ij_2kl}(1+\delta_2)^{\lambda}\right) x_{ij_2kl} - \sum_{k \in N} F_k Y_k \tag{2}$$

$$Y_k \in \{0,1\}, \forall k \in N \tag{3}$$

$$H_{ik} \in \{0,1\}, \forall i \in N, k \in Q_2 \tag{4}$$

$$\sum_{k.l\in N} x_{ij_2kl} + \sum_{s,t\in Q_1} x_{ij_1st} = 1,\ \ i\forall\in N \tag{5}$$

$$x_{ij_2kl} = \frac{Y_kY_lH_{ik}H_{kl}H_{lj_2}\, exp\left[-\gamma\bar{p}_{ij_2kl} - (1-\gamma)t_{ij_2kl}\right]}{\sum_{k,l\in N} Y_kY_lH_{ik}H_{kl}H_{lj_2}\, exp\left[-\gamma\bar{p}_{ij_2kl} - (1-\gamma)t_{ij_2kl}\right] + \eta_{ij_1}},\quad \forall i,k,l\in N \tag{6}$$

$$x_{ij_1st} = \frac{exp\left[-\gamma p_{ij_1st} - (1-\gamma)t_{ij_1st}\right]}{\sum_{k,l\in N} Y_kY_lH_{ik}H_{kl}H_{lj_2}\, exp\left[-\gamma\bar{p}_{ij_2kl} - (1-\gamma)t_{ij_2kl}\right] + \eta_{ij_1}},\qquad \forall i,k,l\in N \tag{7}$$

$$\eta_{ij_1} = \sum_{s,t\in Q_1} exp\left[-\gamma p_{ij_1st} - (1-\gamma)t_{ij_1st}\right]\ ,\ \ \forall i\in N \tag{8}$$

$$\sum_{k\in N} Y_k = q \tag{9}$$

$$H_{ik} \le Y_k,\ \ \forall i,k\in N \tag{10}$$

$$H_{kl} = Y_kY_l,\ \ \forall k,l\in N \tag{11}$$

$$H_{kj_2} = Y_k,\ \ \forall k\in N \tag{12}$$

$$H_{kk} = 1,\ \ \forall k\in Q_2 \tag{13}$$

The objective function (2) maximizes the entrant's profit, i.e., the total revenue minus the fixed and variable cost. Eq. (3) and (4) constrain the value scope of decision variables of location and allocation. Eq. (5) ensures that inland cargo transportation to seaport for all demand points inside overlapping hinterland could be realized by either the incumbent's or the entrant's inland ports. Eq. (6) and (7) define market share of the incumbent and the entrant at a demand point i. Eq. (8) represents utility that the incumbent provides to shippers of a demand point i. Condition (9) inputs the number of inland ports that the later coming seaport plans to locate. Constraint (10) states that only a candidate node is chosen as an inland port location that a demand point can be allocated to. Constraint (11) indicates that any two inland ports belonging to the entrant are connected. Eq. (12) requests only the inland port belonging to the entrant is connected directly to the seaport it belongs to. Eq. (13) requests if a candidate node is chosen by the entering seaport to locate an inland port, it must be allocated to itself.

Next, we further explain the calculation of the relevant parameters in the proposed model. Eq. (14) and (15) show how to calculate packaged service price and service process time of an inland transportation chain for the incumbent. Eq. (16) shows the calculation method of newcomer's service process time. Eq. (17) shows how to calculate the entering seaport's service process cost without considering its difficulty of saving service time.

$$P_{ij_1st} = \left(\alpha c_{is} + \beta c_{st} + \chi c_{tj_1}\right)(1+\Delta_1) \tag{14}$$

$$T_{ij_1st} = \left(T_{is} + T_{st} + T_{tj_1}\right)(1+\Delta_2) \tag{15}$$

$$T_{ij_2kl} = \left(T_{ik} + T_{kl} + T_{lj_2}\right)(1+\delta_2) \tag{16}$$

$$c_{ij_2kl} = \left(\alpha c_{ik} + \beta c_{kl} + \chi c_{lj_2}\right) \tag{17}$$

The following formulas (18-21) imply the method of dimensionless processing for the packaged service price and service process time of both the later coming and the incumbent seaport. We implement dimensionless scaling using the Min-Max normalization method. p_{ij_1st} and $t_{ij_1st}$are the dimensionless values of P_{ij_1st} and T_{ij_1st}. Meanwhile, p_{ij_2kl} and t_{ij_2kl} are that of P_{ij_2kl} and T_{ij_2kl}. Furthermore, p_m and p_c are minimum value and the range of service price of the incumbent. The same as t_m and t_c .

$$p_{ij_1st} = \frac{P_{ij_1st} - p_m}{p_c} \tag{18}$$

$$t_{ij_1st} = \frac{T_{ij_1st} - t_m}{t_c} \tag{19}$$

$$p_{ij_2kl} = \frac{P_{ij_2kl} - p_m}{p_c} \tag{20}$$

$$t_{ij_2kl} = \frac{T_{ij_2kl} - t_m}{t_c} \tag{21}$$

4. Solution method

In this section, we first conduct a simple review on solution method for competitive location, and then we describe our hybrid solution method.

4.1 Algorithm overview

Ernst *et al.* (2009) research on hub location problems and state that in hub location problem either single allocation or multiple problem is proved to be NP-hard. So, it is quite necessary to design a personalized heuristic algorithm for solving hub location and allocation problems in the network. Fernández *et al.* (2021) use heuristic algorithms to study the problem of competitive location. They designed several sorting based discrete selection algorithms and solved the competitive location model based on Pareto- Huff customer choice principle. Some others use genetic algorithms with different improvements (Lančinskas *et al*., 2015; Bozkaya *et al*. 2010). What they used is not simple basic heuristic. Heuristics must be improved to adapt to specific real-world problems. As we show in Table 1, when it refers to the competitive location problems, most scholars utilize a heuristic or exact algorithm.

If the search space of problem solutions only contains binary variables, any meta-heuristic algorithm that can solve combinatorial problems can be used (Lüer-Villagra & Marianov, 2013). In our paper, a genetic algorithm is adopted to solve the location and allocation problem, mainly based on the following considerations: 0-1 decision variables are easier to encode, expression of solutions is easier and more intuitive. Therefore, genetic algorithms have a good performance in solving similar problems. But in fact, our problem encompasses more than just location and allocation. Besides heuristic algorithms, we turn to an exact method to solve pricing problems.

4.2 Hybrid solution method

Our hybrid heuristic method includes two parts: a genetic algorithm (GA) and an exact method. Among the whole hybrid solution method, GA is executed to generate, search for, compare and select better solutions. The exact process is implemented after each iteration of GA to calculate the optimal price and generate maximum profit. When GA generates a feasible solution, the entire competitive location and pricing problem is divided into n different subproblems based on demand points. Each subproblem achieves profit maximization, and the current feasible solution also achieves that. Then, based on the maximization of profit, different feasible solutions and solution sets are compared and iterated to ultimately obtain the corresponding solution with maximum profit. The whole dividing and calculation logic is shown in the Fig. 2.

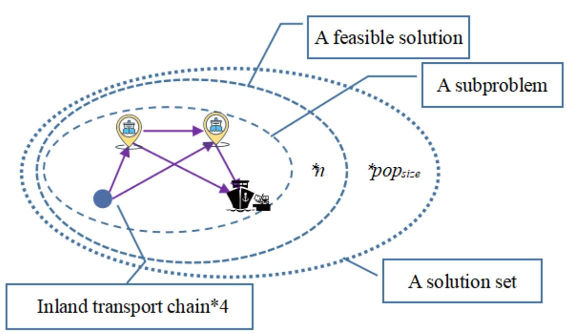


Fig. 2. Problem dividing and calculation logic

4.2.1 Genetic algorithm (GA)

At the beginning of the whole calculation process, GA generates initial feasible solutions through an initialization procedure. Then, it continuously generates feasible solutions through the iteration process. Additionally, GA compares feasible solutions and select better ones using its roulette wheel selection technique. In summary, GA is used to solve the location and allocation problem in this study.

The main steps of GA proposed in this paper are as follows: Firstly, an initialization process is used to generate the initial population, whose size is pop_{size}. Then we get pop_{size} feasible solutions. Save all feasible solutions in the feasible solution setS_0. Secondly, calculate the fitness of all the feasible solutions in S_0. In the fitness calculation process, optimal price at a certain efficiency level needs to be calculated. Subsequent iteration includes crossover and mutation operations. Solution set for every iteration is composed by 80% selected from last iteration's solution set by roulette method. 20% solutions with the highest fitness values of the last iteration come into this iteration. The framework of our GA is shown in Fig. 3.

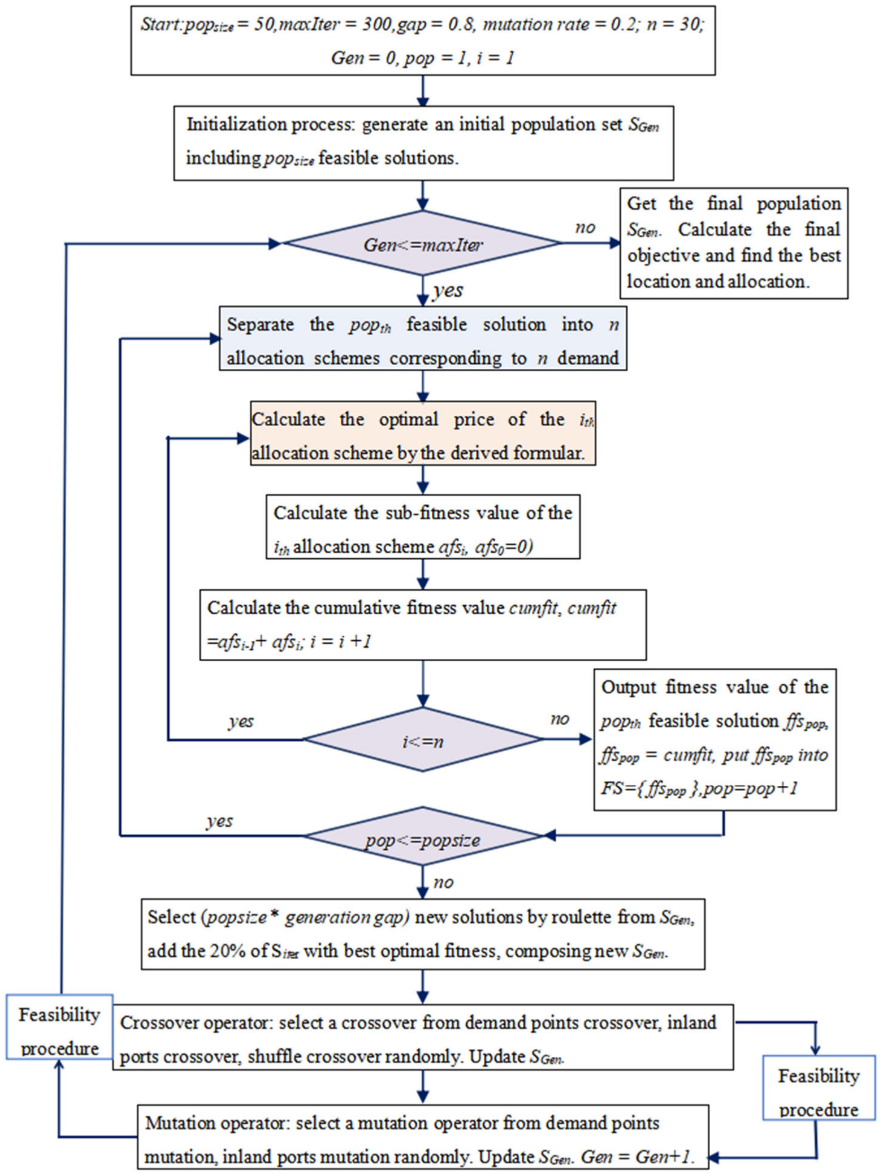


Fig. 3. Framework of GA proposed in this paper

The proposed GA adapts to the problem of this paper from the following four aspects: Firstly, simpler solution presentation. Our proposed GA presents solution by an array instead of a one-dimensional location vector adding a 2- dimensional allocation array. And the following iteration, we need operate only on the whole array, instead of operating on the vector representing location and array representing allocation respectively. Secondly, more operators. We expanded number of crossover and mutation operators to 3 and 2 respectively. Thirdly, more intuitive operation process. Practical meaning is given to crossover and mutation operators. They are named by actual operations intuitively. When operating crossover and mutation, choose one kind of operator randomly. By the process of crossover and mutation operators, we can watch the optimization process more clearly and intuitively, and we can get the whole specific process of optimization. Fourthly, unique feasibility procedure, which maintains solutions feasible consistently after every iteration.

- **Presentation of GA's solution**

A solution array of our GA implies two parts. i.e., inland port location and demand points allocation to inland port. We need to select inland port location from all candidate points, and then allocate all the other demand points to inland port. A solution of our GA is expressed by an $n * n$ two-dimensional array, implying location and allocation simultaneous. In the solution presentation array, every column where '1' occurs represents that this candidate node is inland port location of the entering seaport, and the positions of '1' in each row represents the allocations of each demand point. Fig. 4 sets $n = 6$ as an example to show that candidate nodes $2, 4, 5$ are inland port locations. A usual demand point 1 is allocated to 4 and 5. Demand point 5, selected as an inland port location, is allocated to 2 and 5. And so on to other demand points.

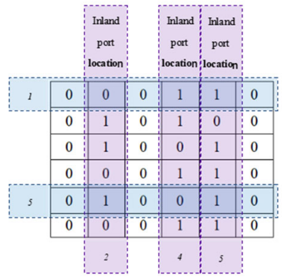


Fig. 4. Location solution of CLPM presentation

- **Crossover operator**

Crossover operators of GA in this article include demand point allocation, inland ports and shuffle crossover operators as shown in Fig. 5. **(a)** shows demand point allocation crossover operator, where the inland port location of the two parent solutions maintains an allocation of some demand points (set 1 as example) cross. Excellent inland port location genes can be inherited. Inland port crossover operator is shown in **(b)**. The two parent solutions each choose some inland ports (sets 4 of parent 1, and 3 of parent 2 as an example) to cross, and the demand point allocation is maintained. By Inland port crossover operator, excellent demand point allocation genes can be inherited. The shuffle crossover operator is shown in **(c)**, carrying out an inland port crossover operator and demand point allocation crossover operator synchronously. By shuffle crossover operator, the location and allocation dimensions of solution space can be exploited simultaneously. Through the above three crossover operators, GA exploits the solution space from different dimensions with different intensities.

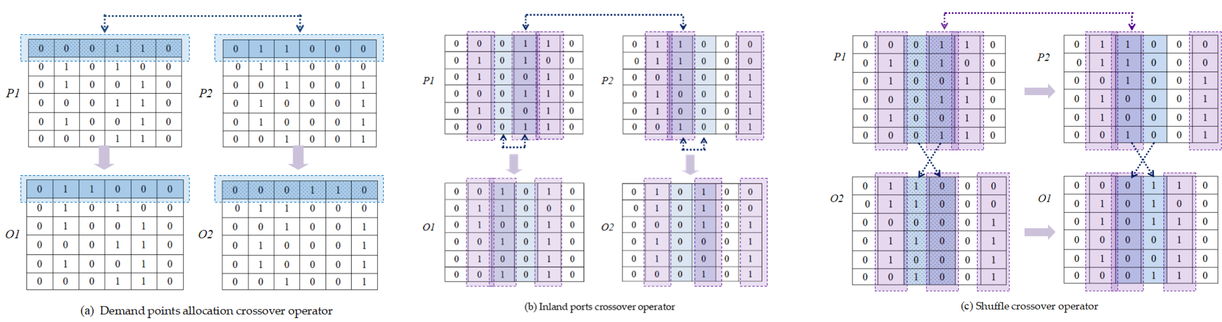
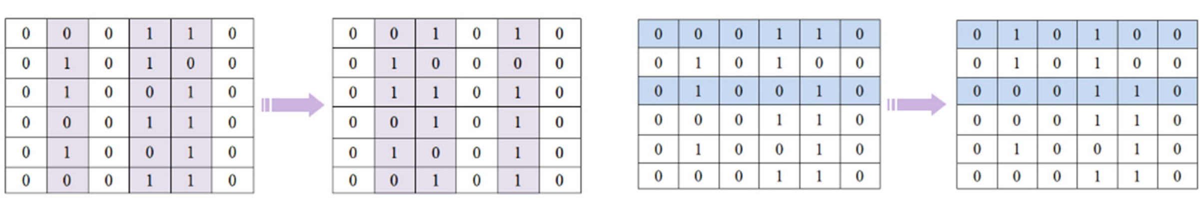


Fig. 5. Crossover operators

- **Mutation operator**

This paper proposes two kinds of mutation crossover by improving and extension, i.e., inland port mutation operator and demand point allocation mutation operator, each of which is shown in Fig. 6. In (a), the original inland port location mutates from $(1, 4, 5)$ to $(2, 3, 5)$. In (b), allocation of demand point 1 and 3 mutates. Before mutation, demand point 1 is allocated to inland ports 4 and 5, but to 2 and 4 after mutation.



(a). Inland ports mutation operator **(b).** Demand point allocation mutation operator

Fig. 6. Mutation operators

- **Solution feasibility procedure**

The above crossover and mutation operators will inevitably produce infeasible solutions. There are several possibilities of infeasible solutions. **Firstly**, some inland ports are not allocated to themselves. **Secondly**, some demand points are allocated to non-inland ports. **Thirdly**, a demand point is allocated to less or more than two inland ports. We use solution feasibility procedures to transform infeasible solutions into feasible. Firstly, ensure every inland port is allocated to itself. Secondly, cut off the allocation linkages from demand points to non-inland ports. **Fourthly**, cut off redundant linkages from every demand point randomly by only maintaining two linkages. **Finally**, for every inland port who is only allocated to itself, choose one more inland port to allocate it to. Through the above procedures, solutions got from crossover and mutation operators of each iteration always stay feasible. Fitness computation procedures could be implemented after each iteration.

4.2.2 Optimal price calculation

Based on the problem dividing and calculation logic above, it is necessary to calculate the optimal price that maximizes the profit of a specific inland transportation chain after GA finds a feasible solution. To solve this problem, considering the dimensionless calculation of shippers' utility, we derive the optimal price expression through the first-order condition of the objective function.

The Separate pricing problem has been incorporated in the competitive location problem by many scholars (Lüer-Villagra & Marianov, 2013; Kononov et al., 2019; Kress & Pesch, 2015; Zhang et al., 2015). They hold the same opinion that pricing mechanism is an important tactical means to obtain competitive advantage. But the price-time combined problem has never been taken into consideration synchronously in various competitive location research. In a practical scenario, price and time are often taken into consideration by shippers when they choose transportation service. So, we study price and time simultaneously in our competitive inland port location and pricing model (CLPM). Due to the adoption of the logit model to represent the utility of shippers, the calculation of the optimal price involves solving the argument of an exponential function. Considering the complexity and difficulty of this task, we employ the Lambert function to construct the formula for calculating the optimal price.

Once GA finds a feasible solution including location$\{\hat{Y}_k\}$ and allocation$\{\hat{H}_{ik}\}$, the whole CLPM can be separated into special problem corresponding to every demand point. Let S_{ij_2} is the set of feasible pairs of inland ports that supply inland cargo freight from the demand point i to the entering seaport, that is:

$$S_{ij_2} = \{(k,l) \in N^2, \hat{Y}_k = \hat{Y}_l = \hat{H}_{ik} = \hat{H}_{kl} = \hat{H}_{lj_2}\}, \quad \forall i \in N \tag{22}$$

Replacing (4) in objective function (2), and using Eq. (22), the objective function of the CLPM is:

$$\hat{Z} = max \sum_{i=n} W_i \frac{\sum_{(k,l)\in S_{ij_2}} \left(P_{ij_2kl} - c_{ij_2kl}(1+\delta_2)^{\lambda}\right) exp\,[-\gamma p_{ij_2kl} - (1-\gamma) t_{ij_2kl}]}{\sum_{(k,l)\in S_{ij_2}} exp\,[-\gamma p_{ij_2kl} - (1-\gamma) t_{ij_2kl}] + \eta_{ij_1}} - \tau \tag{23}$$

with:

$$\tau = \sum_{k\in N} F_k \hat{Y}_k\,, \qquad \eta_{ij_1} = \sum_{s,t\in Q_1} exp\left[-\gamma p_{ij_1st} - (1-\gamma) t_{ij_1st}\right]$$

Optimal price of a route at certain time level can be derived from the first order condition of the objective function and expressed in the following formula:

Formular 1:

$$P^*_{ij_2kl} = c_{ij_2kl}(1+\delta_2)^{\lambda} + \frac{p_c}{\gamma}\left[1 + W\left(\frac{exp\left(\frac{p_m\gamma}{p_c} - 1\right)}{\eta_{ij_1}} \sum_{(k,l)\in S_{ij_2}} \frac{exp\,(-\frac{\gamma c_{ij_2kl}(1+\delta_2)^{\lambda}}{p_c})}{exp\left[(1-\gamma) t_{ij_2kl}\right]}\right)\right] \tag{24}$$

where, $W(.)$ is the Lambert function, the inverse function of complex function $f(W) = W.exp(W)$. For the detailed derivation process, please refer to **Appendix A**.

5. Numerical experiments and analysis

In this section, we conduct extensive numerical experiments on the basis of a case study. The proposed hybrid method is programmed using Python 3.11. The numerical experiments are implemented on a personal computer (Honor magic book with an AMD Ryzen 5 3500U with Radeon Vega Mobile @ 2.10 GHz CPU and 8GB RAM) with the Microsoft Windows 10(64-bit).

5.1 Case data and parameter setting

Our proposed model and hybrid solution method are tested by data of 28 chosen prefecture-level cities of Shandong, Henan and Shanxi Province. In addition, we take Rizhao Port and Qingdao Port as the entering and the incumbent seaport, respectively. The selected prefecture-level cities are inside the overlapping hinterland. Inland cargo freight volume (W_i) of each demand point i is forecasted based on their last year's freight weight. Distance data required are obtained by Place API and Direction API of Baidu Map. The unit cargo rate is set to 0.2 $yuan\ per\ ton - kilometer$. The average speed, taking operating time at inland ports into consideration, is set to 18 km/h. The fixed cost to construct an inland port is set to 2 $billion$, which is depreciated at a constant rate in five years. So, the annual average fixed cost (F_k) is 400 $million$. The final profits shown in the figures of this paper are all measured in million. We display the incumbent seaport's income (and not the profit), because the incumbent seaport is supposed to have been in the market for a while. Considering that economies of scale mainly apply between inland ports and between the inland port and the seaport, we set $\alpha = 1$, $\beta = \{0.6, 0.9\}$, $\chi = \{0.6,0.9\}$.In order to reflect the competition in our model, we assume that the existing seaport has already located 2 inland ports by P-center method (Eiselt and Marianov, 2009). The other parameters and variables are set as follows: $\lambda = \{-3, -1, -0.3\}$; $\Delta_1 = \{0.05, 0.1, 0.2, 0.3, 0.4\}$;

$\Delta_2 = \{-0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3\}$; $\delta_2 = \{-0.4, -0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3, 0.4\}$;

$\gamma \in [0, 1]$, and we discretized it as $\gamma = \{0.2, 0.5, 0.8\}$.

5.2 Computational results

We calculate the optimal location and price scheme under conditions when the incumbent seaport has located varying quantities of inland ports. We observe from Fig. 7 that the number of incumbent's inland ports deeply influence the number of the entrant's, which depicts a competitive relationship of reciprocal growth and decline. When the incumbent has located relatively fewer inland ports, then the entrant could locate more inland ports to gain more profit. On the contrary, if the incumbent has located more, the entrant should reduce the number of its pending inland ports. In Fig. 7, the incumbent seaport has located 3, 2 and 1 inland port, then the optimal number of the entrant's inland port can be seen in (a), (b) and (c).

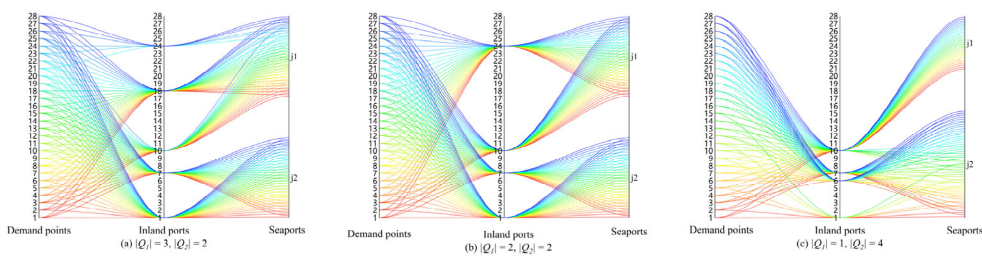


Fig. 7. Influence of $|Q_1|$ on the number of the entrant's inland ports

Additionally, Fig. 8 shows the situation when the entering seaport locates two inland ports on the premise that the incumbent has located two inland ports at demand points 10 (Liaocheng) and 24 (Anyang). The incumbent (j_1) has located its two inland ports at candidate point 10 (Liaocheng) and 24 (Anyang). The entrant (j_2) locates its two inland ports at points 1(Jinan) and 7(Taian). The total profit is 5710 million RNY. We take demand point 3 as an example to show the optimal price for it in Table 3.

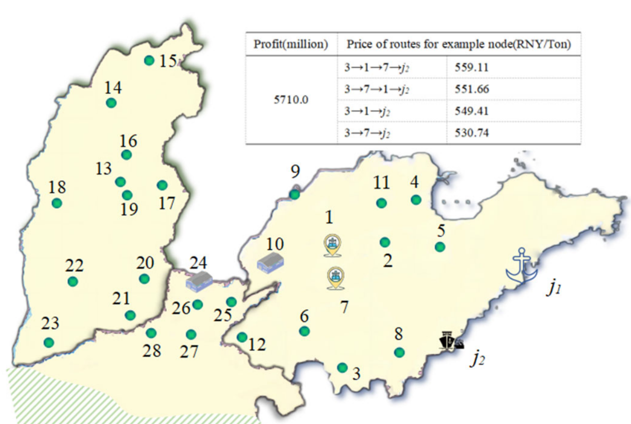


Fig. 8. The entering seaport locates 2 inland ports at 1 and 7($\Delta_1 = 0.2$; $\Delta_2 = \delta_2 = 0$; $\gamma = 0.5, \lambda = -0.3$)

Table 3
The optimal price for every demand point ($\Delta_1 = 0.2$; $\Delta_2 = \delta_2 = 0$; $\gamma = 0.5, \lambda = -0.3$)

Demand point	Optimal price *	Demand point	Optimal price *	Demand point	Optimal price *	Demand point	Optimal price *
1 **	515.3 536.23 505.6	8	562.68 559.27 552.98 538.35	15	613.94 630.21 604.25 609.28	22	588.69 594.22 578.99 573.29
2	538.44 551.07 528.75 530.14	9	529.17 545.43 519.47 524.51	16	591.71 607.97 582.01 587.05	23	614.2 618.24 604.5 597.31
3	559.11 551.66 549.41 530.74	10	516.79 523.81 507.09 502.89	17	563.1 579.36 553.4 558.44	24	534.77 538.01 525.07 517.09
4	550.77 568.85 541.07 547.92	11	542.46 561.21 532.76 540.29	18	599.64 614.03 589.94 593.11	25	536.27 538.15 526.57 517.22
5	554.01 570.03 544.31 549.11	12	541.24 541.46 531.54 520.54	19	579.02 593.42 569.33 572.49	26	539.92 543.16 530.22 522.24
6	542.83 537.75 533.13 516.82	13	581.58 597.85 571.89 576.92	20	561.49 565.55 551.79 544.62	27	552.69 555.89 542.99 534.96
7 **	530.45 520.75 499.83	14	616.61 632.87 606.91 611.95	21	574.79 578.03 565.09 557.11	28	566.06 569.28 556.36 548.36

* The optimal price of every inland transportation chain for every demand point i, $i \to 1 \to 7 \to j_2$, $i \to 7 \to 1 \to j_2$, $i \to 1 \to j_2$, $i \to 7 \to j_2$ in respective order.
** These two demand points are selected as inland port location. There are three chains for them to the entering seaport.

5.3 Sensitivity analysis and discussions

To recognize the most significant parameters of the proposed model, this section conducts sensitivity analysis from aspects of the incumbent (Δ_1 and Δ_2), the entrant itself (λ), and the competing environment (γ and β) respectively.

5.3.1 Influence of the incumbent's time ($\boldsymbol{\Delta_1}$) and price ($\boldsymbol{\Delta_2}$)

When the entering seaport begins to set a price, the incumbent seaport could be offering service with different prices and time. Then it could have different impacts on the entering seaport's pricing and profit.

Influence on the entrant's optimal price

The influence on optimal price is shown in Fig. 9. In (a), the incumbent provides faster service at a higher price. While in (b), it is the opposite. In the former scenario, the entering seaport could set a higher service price than in the latter. When shippers are sensitive to service time, the entering seaport's optimal price follows the same pattern as shippers are efficiency sensitive in Fig. 9. In addition, we find that, influence of related parameters on the optimal price of a representative chain shows almost the same level and trend as that on all chain's wholes.

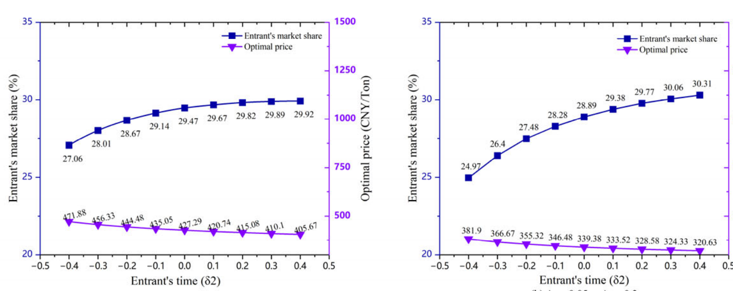


Fig. 9. Influence of Δ_1 and Δ_2 on the entering seaport's optimal price ($\gamma = 0.8$)

- **Influence on the entering seaport's profit**

Based on the above impact of Δ_1 and Δ_2 on the optimal price of the entrant, how the two parameters influence its profit can be concluded from Fig. 10. Compared to low-price and inefficient services, if the incumbent offers faster services at a lower price, the entering seaport can achieve higher profits when they follow the competition. We tested the situation when shippers are time sensitive, it shows the same rule.

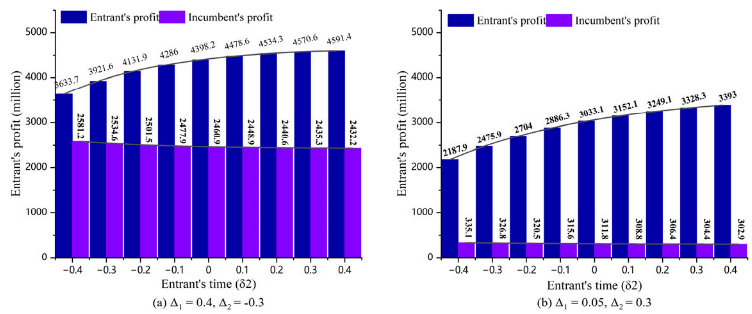


Fig. 10. Influence of Δ_1 and Δ_2 on the entering seaport's profit ($\gamma = 0.8$)

Based on the above analysis about the influence of the incumbent's current service time and price, it is not difficult to find that when the competitor has provided quicker service with higher price, the entering seaport achieves higher profits given fixed shippers' sensitivity. Therefore, the incumbent is often referred to as leader. But when the newly coming seaport gets involved in competition, a rational pricing strategy is the follow strategy. Either the leader sets a high or low price, following it.

*5.3.2 Influence of time saving difficulty coefficient (**λ**)*

During competition, the competitive ability of the entrant influences its own competition performance. We model the competition ability of the entering seaport by time saving difficulty coefficient (λ). λ is represented by cost when the entering seaport tries to save its service process time. When the seaport tries to do that, the more cost paid means the more difficulty. We remind readers again that λ is negative.

- **Influence of λ on the optimal price**

As shown in Fig. 11, the optimal price of all chains for 28 nodes at different service time levels changes as λ. It can be observed that as λ increases, the optimal price exhibits a smaller variation with changes in service time. Conversely, when λ decreases, the optimal price becomes more unstable. If the entering seaport faces a significant challenge in saving service time, it should set higher prices when providing faster service. It is also important to adjust service pricing according to changes in service time. On the contrary, lower prices can be maintained when there is no difficulty in saving service time.

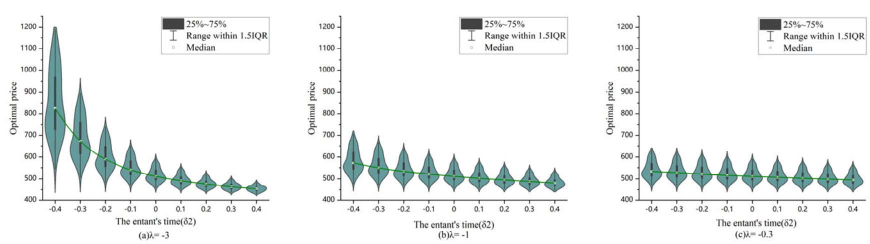


Fig. 11. Influence of λ on optimal price ($\Delta_2 = 0$)

- **Influence of λ on the entrant's profit**

Fig. 12 (a) illustrates the variation of entering seaport's total profit with respect to service time for different values of λ. **(b)** and **(c)** choose one chain for demand point 3 as an example to present the corresponding variations in optimal price and market share. The rate of profit changing with service time extends as λ decreases. When $\lambda = -3$, this rate reaches its maximum. So, in the scope of our study on service time, when $\lambda = -3$ and $\lambda = -1$, the entering seaport's profit shows an initial increase followed by a decrease as the service time is extended. However, when $\lambda = -0.3$, the ability to save service time has not yet resulted in a decrease in profit. This is because the greater the difficulty in saving service time, the significant cost increases are associated with that. Consequently, this leads to a faster increase of optimal prices (shown in **(b)**) and ultimately results in a rapid decline in market share (shown in **(c)**). Also, we observe that, if λ is relatively larger, quicker service than average can achieve maximum profit, whereas the opposite is true if λ is smaller.

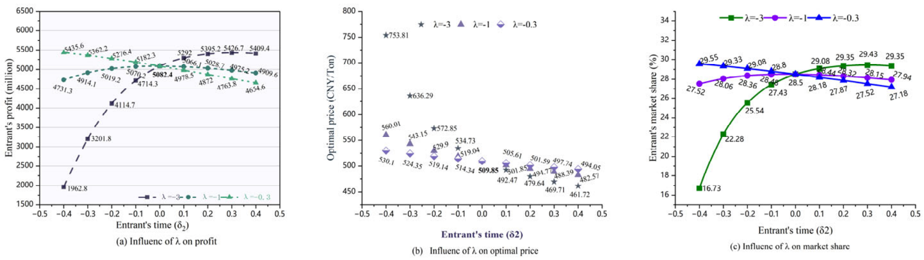


Fig. 12. Influence of λ on profit of the entering seaport ($\Delta_2 = 0$)

Only by improving the ability to compress service time can the newcomer continuously gain more profit in a stable price level through reducing service time. If this ability is weak, the entering seaport only has a narrow range of relatively high profits. Both increasing and decreasing efficiency will finally result in a decrease in profit. Worse, if this ability can't be enhanced temporarily, the entering seaport could only make price and time decisions based on the incumbent seaport's decision. As shown in the Fig. 13, Δ_2 influences the position of the seaport's profit peak when it is not easy to provide quick service. The slower the leader's service, the entrant's profit peaks will occur at its own slower service time level.

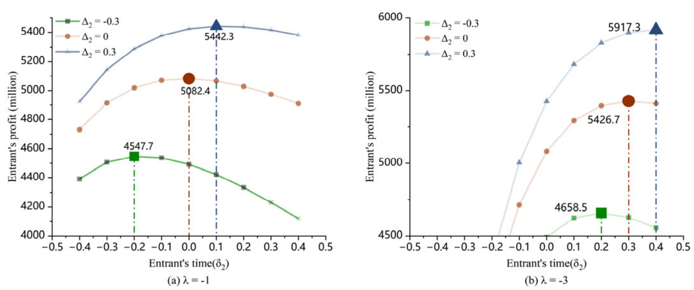


Fig. 13. Influence of Δ_2 on the entrant's profit peak ($\gamma = 0.5$)

As the follower, when it cannot supply quick service with low cost, the entering seaport should follow the incumbent's service time strategy. Either the leader set a relatively slower or quicker service strategy, the entering seaport should hold the same.

5.3.3 Influence from the competition environment

Factors from the environment that influence competition mainly include shippers' preference (γ) and scale economies (β). Preference parameter (γ) represents shippers' choice preference for inland cargo freight service considering price and time of an inland transportation chain. The bigger γ, the more price sensitive shippers are, and the less willing they are to choose service with a high price. Otherwise, the opposite relation.

- **Influence of shippers' preference on optimal price**

How shippers' preference affects the entering seaport's price decision is shown in Fig. 14. This figure shows the optimal price level and changing trends for all 28 demand points under the influence of γ. When shippers are time sensitive, the entering seaport could set a relatively high price. On the contrary, it should lower its price to get a maximizing profit. Due to the inverse relationship between service time and utility, regardless of whether shippers are time or price sensitive, prolonging service time will inevitably require a downward adjustment of the optimal price to some extent.

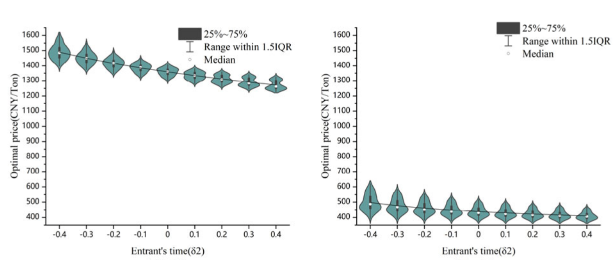


Fig. 14. Influence of γ on the entering seaport's optimal price ($\Delta_1 = 0.4$, $\Delta_2 = -0.3$)

- **Influence of shippers' preference on profit**

Influence of γ on profit can be seen in Fig. 15. Firstly, γ influences the level of the entering seaport's profit. When shippers are sensitive to service time, the entering seaport can obtain high profits. Conversely, it can only generate minimal profits. Secondly, γ also influences changing direction of the entrant's profit as it adjusts service time. When shippers are time sensitive, reducing service time can increase profits within the scope of service time levels we research on. Conversely, extending service time is necessary to achieve higher profits.

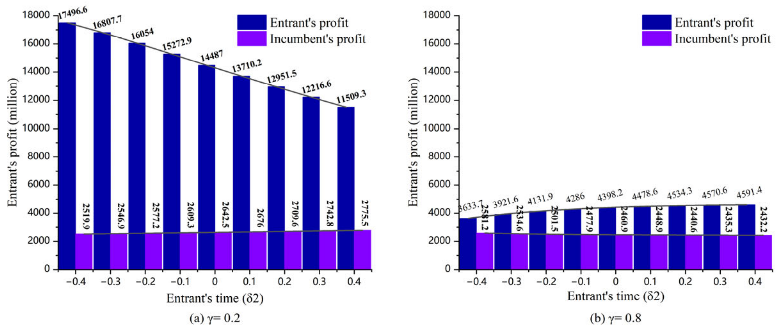


Fig. 15. Influence of γ on both seaports' profit ($\Delta_1 = 0.4$, $\Delta_2 = -0.3$)

After that, we test the situation when the incumbent seaport provides slow service at low price ($\Delta_1 = 0.05, \Delta_2 = 0.3$), the entering seaport should also hold the same strategy according to shippers' sensitivity as current situation ($\Delta_1 = 0.4$, $\Delta_2 = -0.3$). In summary, if shippers are sensitive to efficiency, improve efficiency. We turn to Fig. 16 to analyze the mechanism of how γ impacts profit. Fig. 16 illustrates that if the shippers are time sensitive, extending the service time will result in a decrease in market share, whereas it will be the opposite if they are price sensitive. Combining Fig. 14, we can explain influence of γ on profit.

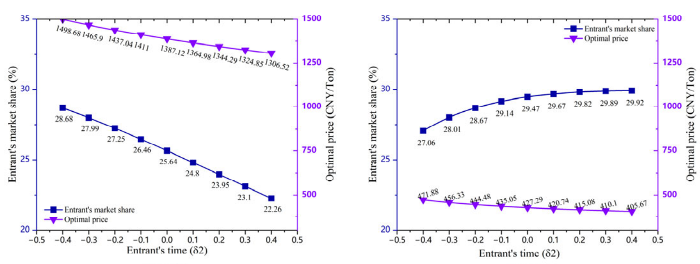


Fig. 16. Influence mechanism of γ on the entering seaport's profit (set node 3 as example

- **Impact of scale economies**

The economies of scale coefficient (β) mainly affect the distance between the entrant's inland port. Because the role of scale economies is to discount the cost of cargo transportation at corresponding legs. So, when the economies of scale coefficients are smaller, the corresponding legs will be extended to obtain more cost discount to construct inland transportation chains with more cost advantage. As shown in Fig. 17, when β reduces from 0.9 to 0.6, the distance between inland ports extends from that in (a) to (b).

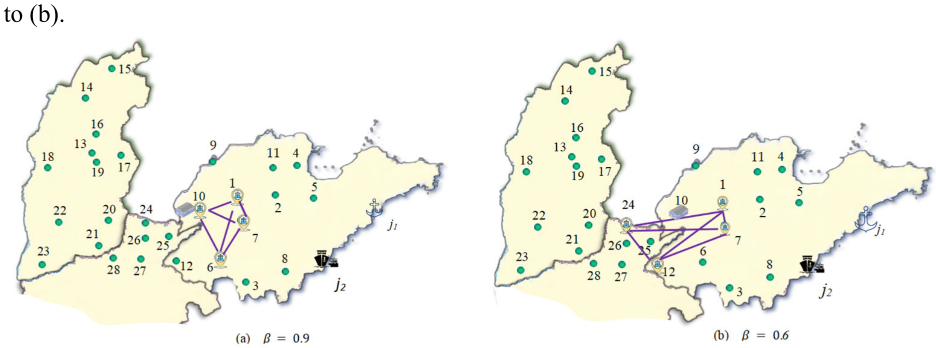


Fig. 17. Influence of economies of scale ($|Q_1| = 1, |Q_2| = 4$)

5.4 Managerial insight

According to the results of the numerical experiments, we provide the following managerial insights:

Enhance ability to improve service efficiency. This ability is the most fundamental competitiveness that will enable the newcomer to break away from the situation of following the competition and achieve higher profits by continuously reducing service time. Higher information technology level, more advanced operational equipment, and more scientific operation organization mode can be adopted to enhance this ability.
Strive to overcome the influence of shippers' sensitivity. If shippers are price sensitive, the competitor can't obtain more profit anyway, which usually indicates a sluggish inland transportation market or fierce homogeneous competition, and inland port location for entering seaport also faces more uncertainties. The entering seaport should prompt shippers to pay more attention to service quality by various measures, rather than solely focus on price. For example, differential service, extended service, value-added service and so on. In a word, give more compelling reasons to persuade shippers to ignore service price.
Seek cooperation and potential complementarity. If seaports are geographically close and have overlapping hinterland, and they provide similar service, competition between them is inevitable. Our experiment shows that, in a competitive situation, where the individual seaport aims to maximize its profit, Pareto optimality does not exist. Especially when the decision maker is weak in its service efficiency, it can only gain low profit by following the leader's strategy. Cooperation, instead of competition, for example undertaking different functions, carrying distinct types of goods and so on, will reduce homogeneous competition, benefiting the two competitors.
Expand cargo resources. Only with more resources of cargo can more profit be generated. Besides constructing inland ports, improving accessibility between seaport and its hinterland, targeted and scientific subsidies and so on will collect more cargo from wider hinterland.

6. Conclusion

In this paper, we studied the competitive inland port location and pricing problem in the perspective of the later coming seaport, when an incumbent seaport has located a certain number of inland ports inside overlapping hinterland. We established a mixed-integer nonlinear programming model, and then proposed a hybrid solution method to solve it. We also derived the closed optimal price expression under different service time levels. Followed by basic computation, we analyzed the influence of pertinent parameters. Finally, we put forward a series of management suggestions for the entering seaport.

Author Contributions

Conceptualization, methodology, software, validation, formal analysis, investigation: Yurong Wang, Xifu Wang, Kai Yang. Writing—original draft preparation: Yurong Wang. Resources, data curation, writing—review and editing: Xifu Wang, Kai Yang, Junchi Ma: visualization-- Yurong Wang, Junchi Ma. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The datasets generated during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix A: The derivation of the optimal prices

The objective function is:

$$\hat{Z} = max \sum_{i=n} W_i \frac{\sum_{(k,l)\in S_{ij_2}} \left(P_{ij_2kl} - c_{ij_2kl}(1+\delta_2)^{\lambda}\right) exp\,[-\gamma p_{ij_2kl} - (1-\gamma)t_{ij_2kl}]}{\sum_{(k,l)\in S_{ij_2}} exp\,[-\gamma p_{ij_2kl} - (1-\gamma)t_{ij_2kl}] + \eta_{ij_1}}$$

where:

$$p_{ij_2kl} = \frac{P_{ij_2kl} - p_m}{p_c}$$

$$t_{ij_2kl} = \frac{T_{ij_2kl} - t_m}{t_c}$$

When GA has found a feasible solution including location <$\widehat{Y_k}$> solution and allocation<$\widehat{H_{ik}}$> solution, the whole problem is divided into n subproblems. The first derivative of the objective function with respect to t_{ij_2kl} for each subproblem is:

$$\left\{exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right]\right\}\left[1-\frac{\gamma}{p_c}\left(P_{ij_2kl}-c_{ij_2kl}(1+\delta_2)^{\lambda}\right)\right]\left\{\sum_{(k,l)\in S_{ij_2}} exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right] + \eta_{ij_1}\right\}+$$

$$\frac{\gamma}{p_c}\left\{\sum_{(k,l)\in S_{ij_2}}(P_{ij_2kl}-c_{ij_2kl}(1 + \delta_2)^{\lambda})\,exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right]\right\}\left\{exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right]\right\}=0$$

Extract common factors and cancel out, and we can get:

$$\left[1-\frac{\gamma}{p_c}\left(P_{ij_2kl}-c_{ij_2kl}(1+\delta_2)^{\lambda}\right)\right]\left\{\sum_{(k,l)\in S_{ij_2}} exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right]+\eta_{ij_1}\right\} + \frac{\gamma}{p_c}\left\{\sum_{(k,l)\in S_{ij_2}}(P_{ij_2kl}-c_{ij_2kl}(1+\delta_2)^{\lambda})\,exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right]\right\}=0$$

Let $r_{ij}=P_{ij_2kl}-c_{ij_2kl}.(1+\delta_2)^{\lambda}$, then $r_{ij}+c_{ij_2kl}(1+\delta_2)^{\lambda}=P_{ij_2kl}$, Substitute these two equations into the above equation:

$$\left[1-\frac{\gamma}{p_c}r_{ij_2}\right]\left\{\sum_{(k,l)\in S_{ij_2}} exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right]+\eta_{ij_1}\right\}+\frac{\gamma}{p_c}r_{ij_2}\sum_{(k,l)\in S_{ij_2}} exp\left[-\gamma\frac{P_{ij_2kl}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right] = 0$$

After further manipulation:

$$\left[-1+\frac{\gamma}{p_c}r_{ij_2}\right]=\frac{\left\{\sum_{(k,l)\in S_{ij_2}} exp\left[-\gamma\,\frac{r_{ij}+c_{ij_2kl}(1+\delta_2)^{\lambda}-p_m}{p_c}-(1-\gamma)t_{ij_2kl}\right]\right\}}{\eta_{ij_1}}$$

$$\left[-1+\frac{\gamma}{p_c}r_{ij_2}\right]=exp\left(-\frac{\gamma r_{ij}}{p_c}\right)exp\left(\frac{p_m\gamma}{p_c}\right)\sum_{(k,l)\in S_{ij_2}}\frac{exp\left(-\frac{\gamma c_{ij_2kl}(1+\delta_2)^{\lambda}}{p_c}\right)}{\{exp[(1-\gamma)t_{ij_2kl}]\}\eta_{ij_1}}$$

Let： $\displaystyle\sum_{(k,l)\in S_{ij_2}}\frac{exp\left(-\frac{\gamma c_{ij_2kl}(1+\delta_2)^{\lambda}}{p_c}\right)}{\{exp[(1-\gamma)t_{ij_2kl}]\}\eta_{ij_1}}= Q_{ij_2}$

then: $\left[-1+\frac{\gamma}{p_c}r_{ij_2}\right]exp\left[-1+\frac{\gamma}{p_c}r_{ij_2}\right]= exp\left[-1+\frac{\gamma}{p_c}r_{ij_2}\right]exp\left(-\frac{\gamma r_{ij}}{p_c}\right)exp\left(\frac{p_m\gamma}{p_c}\right)\frac{Q_{ij_2}}{\eta_{ij_1}}=exp\left(\frac{p_m\gamma}{p_c}-1\right)\frac{Q_{ij_2}}{\eta_{ij_1}}$

According to the form of the Lambert function: $z=W(z)\,exp[W(z)]$,

Then above equation can be transformed into:

$$r_{ij_2}=\frac{p_c}{\gamma}\left[1+W\left(\left[exp\left(\frac{p_m\gamma}{p_c}-1\right)\right]\frac{Q_{ij_2}}{\eta_{ij_1}}\right)\right]$$

Substitute $r_{ij} = \bar{P}_{ij_2kl} - c_{ij_2kl}(1+\delta_2)^{\lambda}$ and $\sum_{(k,l)\in S_{ij_2}} \frac{exp\,(-\frac{\gamma c_{ij_2kl}(1+\delta_2)^{\lambda}}{p_c})}{\{exp[(1-\gamma)t_{ij_2kl}]\}\eta_{ij_1}} = Q_{ij_2}$ back into the above equation, and we can get:

$$P^*_{ij_2kl} = c_{ij_2kl}(1+\delta_2)^{\lambda} + \frac{p_c}{\gamma}\left[1 + W\left(\frac{exp\left(\frac{p_m\gamma}{p_c} - 1\right)}{\eta_{ij_1}} \sum_{(k,l)\in S_{ij_2}} \frac{exp\,(-\frac{\gamma c_{ij_2kl}(1+\delta_2)^{\lambda}}{p_c})}{exp\left[(1-\gamma)t_{ij_2kl}\right]}\right)\right]$$

where $W(.)$ is Lambert function, inverse function of $y = xexp(x)$