International Journal of Industrial Engineering Computations 14 (2023) 483–500

Contents lists available at GrowingScience

International Journal of Industrial Engineering Computations

homepage: www.GrowingScience.com/ijiec

Optimizing inland port scale and function decisions: A bilevel programming approach

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Article history:
Received January 12 2023
Received in Revised Format March 1 2023
Accepted May 14 2023
Available online May, 14 2023
Keywords:
Inland port
Bilevel programming
Hybrid heuristic algorithm
Port planning
Dynamic planning

With the implementation of the Belt and Road Initiative, the inland ports planning is receiving more and more attention. In this work, we aim to determine the scale and function of different potential inland ports in a certain region while considering the cargo flow allocation schemes for the inland ports and seaports in cross-border trade. Unlike previous studies, we consider the dynamic interaction between local government and manufacturing enterprises in the inland port planning process. Based on this, we formulate a bilevel programming model for the considered inland port planning problem, where the upper-level focuses on the local government and the lower-level concentrates on the manufacturing enterprise. To solve the proposed model, we develop a hybrid heuristic algorithm by combining a genetic algorithm and an exact solution method. Furthermore, we conduct a case study of the inland ports planning for the Huaihai Economic Zone in China to verify the applicability of the proposed model and algorithm. The computational results demonstrate that the proposed optimization approach can effectively increase the cross-border transportation market share of inland ports within a limited investment amount and reduce the competition among these inland ports. Our case study also provides valuable management insights on inland port planning in terms of manufacturing enterprises weights, investment limit amount, scale effect, and cargo value weights.

1. Introduction

With the implementation of the Belt and Road Initiative, inland ports are playing an increasingly prominent role in cross-border trade for inland cities in China. Over the past decade, China's inland cities have experienced rapid growth in export-oriented economies. The construction of inland ports also provides the basis for the operation of the China-Europe Railway Express. According to the China Inland Port Development Report, there are over 200 inland ports in China by the end of 2021(Association of Development District in China, 2021). More and more inland cities in China are realizing that the inland ports are no longer just an extension of seaports in the inland areas but have become the new hub for cross-border trade, especially for inland cities. However, issues such as inappropriate distribution of investment in the inland ports and duplication of functional positioning of the inland ports hinder the development of inland ports and waste resources such as land and capital. Zeng *et al*. (2013) made an innovative suggestion, noting that although inland ports can support the increasing volume of inland freight, there is a certain risk in investing in inland ports. Chang *et al*. (2019) pointed out that overinvestment has become a major constraint to the development of inland ports in China. The investment gap between different inland ports in China is large, the investment in 40.39% of inland ports is less than 1 billion yuan, while 13.79% reach more than 10 billion yuan. Ma *et al*. (2023) mentioned that the larger freight volume share of inland ports in the cross-border transportation network

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ISSN 1923-2934 (Online) - ISSN 1923-2926 (Print)
2023 Growing Science Ltd.
doi: 10.5267/j.ijiec.2023.5.001

can help to reduce the total cost of the network. Therefore, how to make a more reasonable plan for inland ports becomes the key issue that needs to be solved for the future development of inland ports. Moreover, inland port investors frequently make decisions on their own regarding the scale and functionality of the inland ports. In China, 78.82% of inland port investors are government or state-owned enterprises (Association of Development District in China, 2021), and in the planning process of inland ports, they prioritize adaptability with national policies and the amount of land resources. However, in practice, investors should not only consider the above-mentioned conditions but also pay more attention to the transportation needs of manufacturing enterprises and the degree of competition among inland ports in the planning region.

By combining these aspects, we develop a bilevel programming model to characterize the dynamic interaction relationship between the local government and the manufacturing companies in the selected region. More specifically, at the upper level, the local government determines the scale and function of different potential inland ports for maximizing the market share. At the lower level, we consider multiple manufacturing companies, which make their respective cargo flow allocation plans for the inland ports and seaports in cross-border trade. By combining the genetic algorithm and the exact solution method, we proposed a hybrid heuristic algorithm to solve the proposed bilevel program and described the key steps of the algorithm. Furthermore, we introduce the planning problem of inland ports for the Huaihai Economic Zone in China as a case study and apply the proposed optimization approach to obtain computational results. Based on the obtained results, the sensitivity analysis is performed, and several planning insights are given.

We summarize the major contributions as follows. The first contribution is to optimize the planning of multiple inland ports in a certain region to increase the cross-border transportation market share of inland ports and reduce the competition among inland ports within a limited investment amount. The second contribution is to develop a bilevel programming model to consider both the local government and manufacturing companies hierarchically throughout the inland port planning process. The third contribution is to identify the impact of different factors related to the planning of inland ports, providing valuable managerial insights based on sensitivity analysis of several factors.

The rest of the paper is structured as follows: Section 2 provides an overview of the current literature on inland port investment problems, cargo flow allocation problems, and the application of bilevel programming. Section 3 develops the up-per-level and lower-level programming models for the mentioned problem. Section 4 designs the algorithm used in this study. Section 5 investigates a case study of the inland ports in Huaihai Economic Zone, analyzes the computational results, and proposes inland port planning strategies. Section 6 gives the main conclusions and makes recommendations for further research.

2. Literature review

In this section, we identify the most relevant attributes that play a role in port planning problems, cargo flow allocation problems, and applications of bilevel programming approach. Additionally, we highlight the characteristics of the primary research and the methods employed to solve the model.

2.1. Research on port planning problems

Port planning problems generally contain the port layout, port investment strategy, port scale, and function decision and other elements (Ho & Ho, 2006). This paper focuses on the strategic decisions of inland port planning regarding inland port investment, scale, and function. Investment in port planning is often large in scale and requires prudent decision-making (Ho and Ho, 2006). Scholars have taken note of this phenomenon and made attempts to optimize the investment of (inland) ports. The contribution of (Koh, 2001) was to develop realistic and relevant investment planning models for inland container transportation systems. Kaysi and Nehme (2016) investigated the optimal strategy for potential investments that port authorities may adopt to attract more carriers. Qu *et al*. (2020) put forward the idea that with the increasing container cargo throughput and the arising port congestion, container ports start to choose the investment expansion strategy to increase port efficiency and then figure out the problem of port congestion. Based on Qu's study, Wang *et al*. (2020) derived the optimal equilibrium outcomes of the investment expansion strategy and investment constant strategy. Moreover, considering the function decisions of ports, Zhang *et al*. (2021) found a cluster of issues in some port functions was continuously neglected following several non-technical reasons since no sufficient approach has been made to present it. Yu *et al.* (2022) show that ports with a developed hinterland economy have obvious advantages in the evolution process, and the reasonable synergistic planning of inland ports and seaports is the key to promote the economic status of the port hinterland. Although some suggestions regarding investment in inland ports have been provided, the actual process of investment in inland ports is more like a game process. Because there remains an information gap between the investment decision-makers and the numerous manufacturing enterprises that the inland ports face. Moreover, studies that consider the planning process from the perspective of an inland port cluster are still lacking. Therefore, in determining the scale and function of inland ports in a certain region, the decision makers need to take into account not only the investors' own investment objectives and investment restrictions but also the varied reactions from the production companies in the hinterland of inland ports.

2.2. Research on cargo flow allocation problems

The topic of liner shipping network design has gained growing attention in recent years, and the cargo flow distribution problem is considered part of it (Brouer *et al*., 2011). Wang *et al*. (2014) developed a mathematical programming model to maximize the carrier's profitability by simultaneously optimizing the ship route scheduling and interrelated cargo allocation scheme. Gasnikov *et al*. (2018) studied dual methods for finding equilibriums in mixed models of flow distribution in large transportation networks. Wang *et al*. (2020) noted that a freight resource sharing platform with accurate and acceptable vehicle-cargo matching results is significant in improving information asymmetry and matching efficiency in cargo allocation problems. Ma (2021) used some relevant literature to explain the key elements of the logistics network flow distribution problem and set up the BP algorithm that will be used to optimize the logistics network flow distribution. While a considerable body of research has been carried out on the cargo flow allocation problems, much less combines the problem with the planning of logistics infrastructures. This research is an attempt to combine the planning of inland ports and the flow allocation of cross-border cargo at the same time, and findings in this work imply that there is a strong relationship between these two problems.

2.3. Research on the applications of the bilevel programming approach

Since Vicente and Calamai (1994) made a bibliography review of bilevel programs, the bilevel optimization models exhibit wide applicability in various interdisciplinary research areas, such as biology, economics, engineering, physics, etc. Zhang *et al*. (2012) proposed a high-level programming model by using the methods of scenario analysis and robust optimization. Kalashnikov *et al*. (2015) provided a comprehensive review of some of the above-mentioned new areas including both theoretical and applied results. Sinha *et al*. (2018) provided a comprehensive review of bilevel optimization from the basic principles to solution strategies; both classical and evolutionary. For the application of the bilevel programming approach in (inland) ports, we briefly review closely related studies in Table 1. Even though the bilevel program has been widely utilized in port-related areas, there is a dearth of studies using bilevel models to optimize the planning of inland ports, especially for Chinese inland ports. Based on the actual investment process, this paper applies the bilevel program to characterize the relationship between the upper-level local governments and the lower-level manufacturing enterprises and makes recommendations considering both upper and lower objectives. In addition, this paper develops a hybrid heuristic algorithm by integrating the genetic algorithm with the exact linear programming method.

Table 1
Summary of closely related studies

Publication	Application area	Upper-level objective	Decision variables	Lower-level model	Solution method
Qiu *et al*. (2015)	Storage pricing strategy in ports	Total profit	Storage price	Total cost minimization	Heuristic algorithm
Molavi *et al*. (2020)	Stimulate sustainable energy activities at maritime ports	Multiple objectives related to emissions	Number of components installed	Profit maximization	Heuristic algorithm
Qiu *et al*. (2019)	Service pricing strategy in inland ports	Total profit	Rail transportation charge and rail shuttle service time interval	Total cost minimization	Heuristic algorithm
Lee *et al*. (2013)	Network planning for ports	Equilibrium conditions of SPE	Service charge and routing pattern	Shipment patter decisions	Heuristic algorithm
Jiang *et al*. (2022)	Reorganization of inland river port group	Value contribution and internal competition	Ports layout plan and expansion scale	Port selection and cargo flow allocation	Hybrid heuristic algorithm
This work	Planning of inland port group	Cross-border transport market share	Scale and function of inland ports	Cargo flow allocation	Hybrid heuristic algorithm

3. Problem statement and formulation

In this section, we describe the bilevel planning problem for the inland port in this study. Fig. 1 illustrates the decision makers, decision content, and decision objectives for the upper-level and lower-level models. The dynamic interactions exist between the local government and manufacturing enterprises in inland port hinterland. The government's planning decisions for inland ports will influence the enterprises' cargo flow allocation schemes, while the enterprises' cargo flow allocation schemes will also have an impact on the government's planning goals for inland ports. Fig. 1 also shows the expected effect after optimization, suggesting that we can get a more reasonable investment strategy for inland ports in a certain region, and the competition among inland ports will decrease.

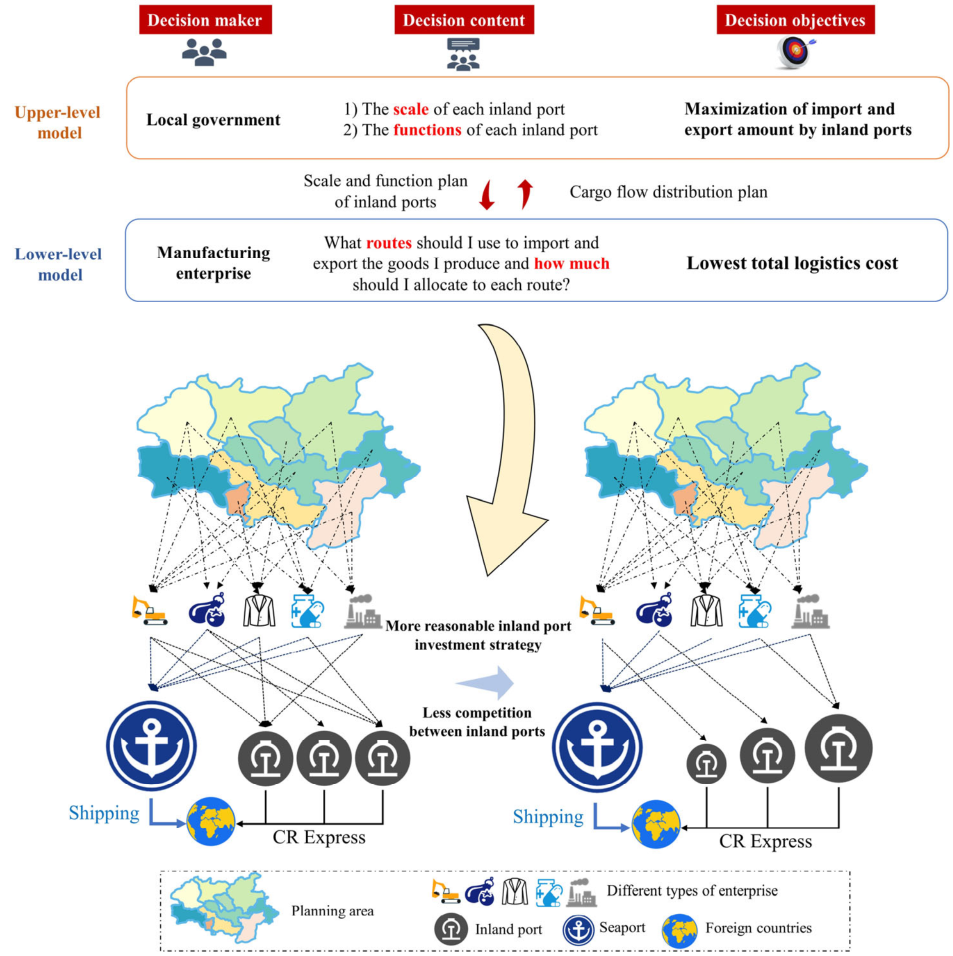

Fig. 1. The framework of the bilevel planning in this study

3.1. Assumptions and definitions

3.1.1 Assumptions

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

Assumption 1. For some economic zones in China, the decisions on the scale and function of inland ports in a certain region are made by the joint committee affiliated with the local government. Considering this situation, we assume that the planning of inland ports is carried out by a single decision-maker in this study.

Assumption 2. The transportation mode in short-distance transport is commonly road. Based on this, we assume that the transportation *cost* from each enterprise in the region to the inland ports or seaports is only related to the transport distance.

Assumption 3. The seaports tend to be larger in scale and more diverse in functionality compared to inland ports. Hence, we suppose that all seaports are integrated ports, that is, each seaport has the function to serve all types of cargo. At the same time, we assume no upper limit for the handling capacity of the seaport.

3.1.2 Definition of sets, parameters, and decision variables

To formally characterize the problem, we first list all sets, parameters, and decision variables used in the problem formulation, as shown in Table 2.

Table 2
Symbols and parameters used in this problem.

Notations	Detailed definitions
Sets	
I	the set of inland ports in the region
J	the set of seaports in the region

M	the set of cities in the region
N	the set of types of import and export cargo
Parameters	
d_{mi}	the transport distance by road between city *m* and inland port *i*
d_{mj}	the transport distance by road between city *m* and seaport *j*
Z	the total investment limit for inland ports in the region
Q_{mn}	the total volume of cargo *n* in city *m* for import and export
R_i	the upper limit of the planning scale of inland port *i*
P_n	the import and export value of unit cargo *n*
c	the unit transport cost by road
U_i	the transport cost from inland port *i* to foreign countries by CRE
V_j	the transport cost from seaport *j* to foreign countries by shipping
λ	the unit construction cost
ρ	the factor of the scale effect for inland port investment
φ_{mn}	the weight of manufacturing company of cargo *n* in city *m* in the cargo allocation optimization
α_n	the functional area required for handling unit cargo *n*
β_i	the proportion of functional area for handling import and export cargo in inland port *i* to total inland port area
Decision variables	
S_i	the planning scale of inland port *i*.
A_{in}	the selection variable for the functions in inland port; takes a value of 1 if inland port *i* has the serving functions required for cargo of type *n* and a value of 0 otherwise.
q_{imn}	the volume of cargo *n* transported from city *m* to inland port *i* for import and export
q_{jmn}	the volume of cargo *n* transported from city *m* to seaport *j* for import and export

3.2. Bilevel programming model formulation

3.2.1 Upper-level programming model

The decision maker of the upper-level planning problem is the local government for maximizing the market share of the cross-border transport value of inland ports in the total network, in other words, maximizing the role of inland ports in promoting the import and export for inland cities. The expression of the upper-level objective function is as in Eq. (1).

$$\max \text{Ratio} = \frac{\sum_{i\in I}\sum_{m\in M}\sum_{n\in N} A_{in} q_{imn} P_n}{\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{n\in N} (q_{imn} + q_{jmn}) P_n} \tag{1}$$

The upper-level programming problem also needs to consider some constraints as discussed below. The investment constraint is expressed by Eq. (2). Zhang *et al*. (2017) proposed the idea that the investment in logistics parks has a certain scale benefit. Hence, we introduced the scale benefit coefficient for inland port investment in this paper. The sum of the investments in each inland port should be less than the government's investment limit.

$$\sum_{i\in I} \lambda (S_i)^{\rho} \le Z \tag{2}$$

The function overlap constraint is expressed by Eq. (3). To realize specialized inland ports and reduce competition among inland ports in a certain region, the functions of each inland port should be different.

$$\sum_{i\in I} A_{in} \le 1, \forall n \in N \tag{3}$$

The expansion scale constraint is expressed by Eq. (4), the scale of each inland port should not exceed its maximum expandable area and should be non-negative.

$$0 \le S_i \le R_i, \forall i \in I \tag{4}$$

The logical constraint on function selection variables is expressed in Eq. (5). That is the function selection variables are 0 or 1.

$$A_{in} \in \{0,1\}, \forall i \in I, \forall n \in N \tag{5}$$

3.2.2 Lower-level programming model

The decision-makers of the lower-level planning problem are manufacturing enterprises from different cities and different types of cargo. Each enterprise's goal is to minimize their logistics costs. The cargo flow allocation plan is related to the inland port function and scale from the upper-level planning also. By introducing the enterprise importance factor φ_{mn}, we derive the following lower-level planning objective in Eq. (6).

$$\min W = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{n\in N}\varphi_{mn}\left[q_{imn}(d_{mi}c+U_i)+q_{jmn}(d_{mj}c+V_j)\right] \tag{6}$$

The inland port service constraint is shown in Eq. (7). Only when an inland port is planned to serve a certain type of cargo *n*, can the enterprises related to cargo *n* choose this inland port to import and export.

$$\operatorname{sign}\left(\sum_{m\in M} q_{imn}\right) \le A_{in}, \forall i \in I, \forall n \in N \tag{7}$$

The inland port capacity constraint. The size of the functional area required for the total amount of import and export cargo allocated to the inland port does not exceed the size of the functional area planned by the inland port to serve the import and export business as in Eq. (8).

$$\sum_{m\in M}\sum_{n\in N} A_{in} q_{imn}\alpha_n \le S_i\beta_i, \forall i \in I \tag{8}$$

The flow balance constraint. The total amount of cargo allocated to each inland port and each seaport by each enterprise is equal to the total amount of import and export cargo actually produced by each enterprise as in Eq. (9).

$$\sum_{i\in I} q_{imn} + \sum_{j\in J} q_{jmn} = Q_{mn}, \forall m \in M, n \in N \tag{9}$$

The non-negative flow constraint. That is, the cargo volume from each enterprise to each inland port or seaport is non-negative as in Eq. (10).

$$q_{imn} \ge 0, q_{jmn} \ge 0, \forall i \in I, j \in J, m \in M, n \in N \tag{10}$$

3.2.3 Model complexity analysis

According to the notations, the bilevel programming model for the considered inland port planning problem can be formulated as:

$$\max \text{Ratio} = \frac{\sum_{i\in I}\sum_{m\in M}\sum_{n\in N} A_{in}q_{imn}P_n}{\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{n\in N}(q_{imn}+q_{jmn})P_n}$$

$$s.t.\begin{cases} \lambda(S_i)^{\rho} \le Z \\ \sum_{i\in I} A_{in} \le 1, \forall n \in N \\ 0 \le S_i \le R_i, \forall i \in I \\ A_{in} \in \{0,1\}, \forall i \in I, \forall n \in N \\ \\ \text{where } q_{imn} \text{ is determined by the following function} \\ \min W = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{n\in N}\varphi_{mn}\left[q_{imn}(d_{mi}c+U_i)+q_{jmn}(d_{mj}c+V_j)\right] \\ s.t.\begin{cases} \operatorname{sign}\left(\sum_{m\in M} q_{imn}\right) \le A_{in}, \forall i \in I, \forall n \in N \\ \sum_{m\in M}\sum_{n\in N} A_{in}q_{imn}\alpha_n \le S_i\beta_i, \forall i \in I \\ \sum_{i\in I} q_{imn} + \sum_{j\in J} q_{jmn} = Q_{mn}, \forall m \in M, n \in N \\ q_{imn} \ge 0, q_{jmn} \ge 0, \forall i \in I, j \in J, m \in M, n \in N \end{cases} \end{cases} \tag{11}$$

In the proposed bilevel model, there are four types of decision variables. In addition, the dynamic interaction between the upper and lower models increases the difficulty to solve the problem. Firstly, we need to decide whether the S_i and A_{in} are satisfied with the constraints in the upper-level model, and can be input into the lower model as parameters for the constraints in the lower model to solve the current optimal cargo allocation plan q_{imn} and q_{jmn} . Secondly, the optimal cargo allocation plan q_{imn} and q_{jmn} is fed back to the upper objective value to obtain the current optimal value. As a result, the proposed model cannot be directly handled by the solvers, e.g., Lingo. Therefore, we designed a hybrid heuristic algorithm in Section 4 to solve the mentioned bilevel programming model.

4. Algorithm design

Due to the hierarchical structure of the proposed bilevel program, the feasible domain is no longer convex and closed, rendering it a non-convex and non-integrable problem, which is typically exceedingly challenging to solve. In this section, we propose a hybrid heuristic algorithm in detail below.

4.1. Core ideas of the algorithm in this problem

Note that the proposed model has a linear programming problem nested inside to solve the minimum logistics cost of each production enterprise. Hence it can be combined with the exact linear programming solution algorithm at the same time under the framework of a heuristic algorithm to improve the solution efficiency and accuracy based on previous studies (Jiang *et al.*, 2022; Chagas *et al.*, 2022; Vega-Mejía et al., 2019). Considering the mentioned situation, a hybrid heuristic algorithm based on an improved genetic algorithm combined with an exact solution algorithm is proposed in this paper with the following core ideas.

Reduce data dimensions

Since the data structure related to the port cargo volume in the proposed model is two-dimensional or even three-dimensional, for instance, q_{mn}、 d_{mi}. In the model, the above expression is easier to understand, but in the actual solving process, the above expression increases the complexity of the solution. Therefore, such data should be reduced in dimensionality before a formal solution.

Combined coding

In this paper, the core variables are the construction scale and functional positioning of each inland port. The scale of inland port construction is real number variables, and the functional positioning of the inland ports are 0-1 variables. Therefore, this paper proposes to combine the two decisions in the form of binary coding, i.e., to reflect both the construction scale of each inland port and the functional position of each inland port in one chromosome, and to cross the scale and function separately in the subsequent crossover process, to improve the efficiency of algorithm optimization.

Algorithm nesting

The genetic algorithm is applied to the solution of the scale and function positioning scheme of the inland port construction; the exact algorithm, as nested in the genetic algorithm, is applied to the solution of the cargo flow allocation scheme in the lower-level model in combination with the strategy of relaxing the constraints. Among them, the exact algorithm can directly use the linprog linear programming solver that comes with MATLAB software. By finding the approximate optimal target value of the upper-level planning through the iterative optimization process of the genetic algorithm, the corresponding construction scale and function positioning scheme of the inland port and the cargo flow allocation scheme of each production enterprise can be found.

Genetic algorithm improvement

The genetic algorithm is improved in two ways by the combined coding of both the scale and function of the inland ports at the same time and by employing the adjustment method to improve the constraint satisfaction of newly generated populations in the genetic algorithm.

4.2. Key steps of the algorithm

The key steps of the proposed hybrid algorithm are shown in Fig. 2, in which there are four key problems to be solved: 1) data dimensionality reduction and parameter preparation; 2) combined coding of the scale and function of inland port; 3) judgment and adjustment of the generated individuals in the initial solution set; 4) selection, crossover, mutation, judgment, adjustment and reorganization operations.

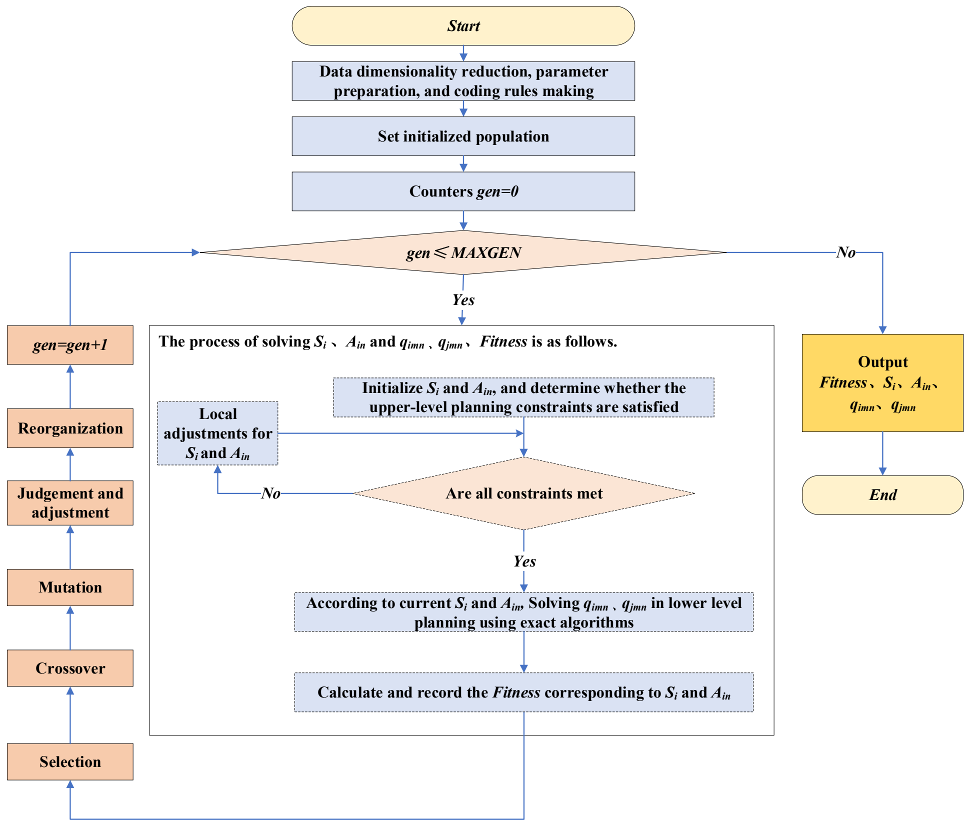

Fig. 2. Flow chart of the hybrid heuristic algorithm.

Data dimensionality reduction, parameter preparation

Multidimensional data are dimensionally reduced in this step. For instance, q_{imn} and q_{jmn} will be reduced to I×M×N and J×M×N variables, and together they form the decision vector in the lower-level planning. This process can also be understood by the following Figure 3.

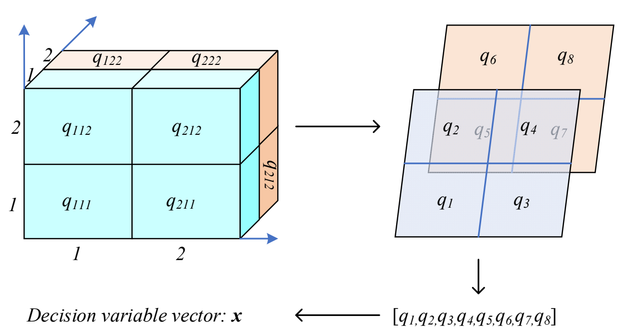

Fig. 3. Data dimensionality reduction process.

Meanwhile, the main parameters in the genetic algorithm need to be set, including population size S_p, selection ratio R_s, crossover probability P_c, variation probability P_m, and the maximum number of iterations gen_{max}.

Combined coding of the size and function of the inland port

In genetic algorithms, the population consists of multiple individuals, and the number of individuals indicates the population size. In this paper, everyone consists of a sequence of 0 and 1, the length of which is determined by the number of inland ports to be decided (I), the function of the inland port (N), and the number of bits used in the coding for the area of the inland port (D). The first I×D codes represent the area of each inland port, e.g., "10101100" when I=2 and D=4 mean that the area of the first inland port is 10 and the area of the second inland port is 12.

The last I×N codes indicate the function of each inland port, 0 means the inland port does not have the function, and 1 means the inland port has the function. For example, when I=2 and N=3, "100001" means that the first inland port has the first function and the second inland port has the third function.

Judgment and adjustment of the generated individuals in the initial solution set

For each randomly generated individual in the initial solution set, the area and function are judged separately to see if the conditions in the upper-level constraint are satisfied. If not, the individuals are adjusted to reduce the area of the inland port or adjust the function of the inland port, so that all the individuals in the initial solution satisfy the upper-level constraints.

Selection, crossover, mutation, judgment, adjustment and reorganization operations

After the initial population generation, genetic operations are needed to generate more excellent and diverse individuals for finding the approximate optimal solution more efficiently and precisely, as shown in Fig. 4.

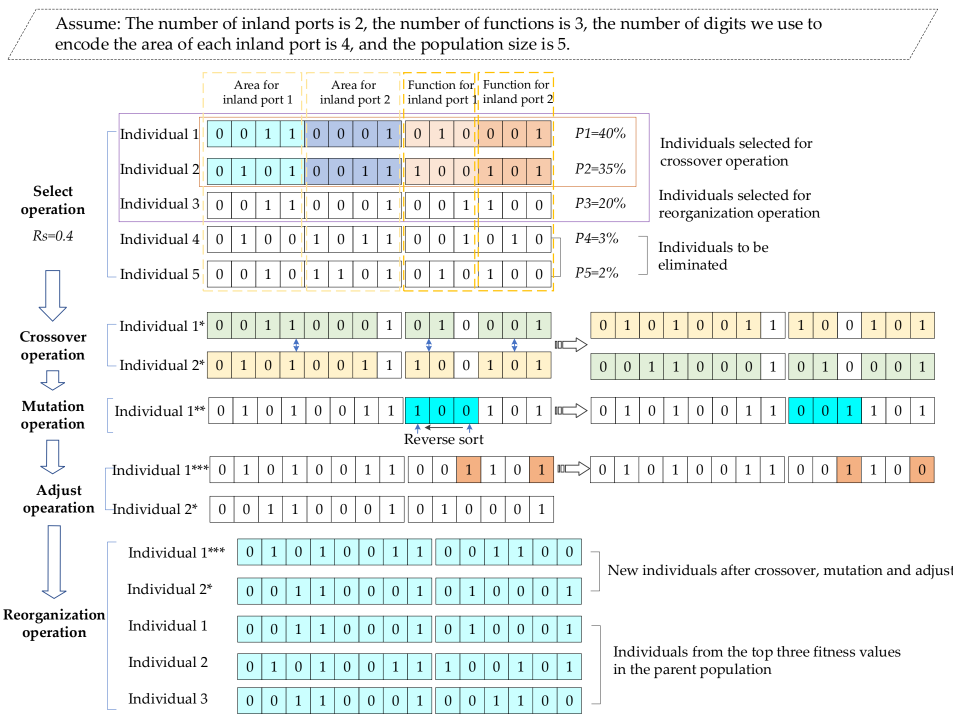

Fig. 4. Genetic operators

Firstly, we select $S_s = S_p \times R_s$ individuals from the S_p individuals of the parent population. The fitness of each individual in the parent population influences its selection probability, which can be expressed by: $P_i = \frac{Fitness_i}{\sum_i^{S_p} Fitness_i}$.

Secondly, the selected individuals are divided into $\frac{S_s}{2}$ groups (if S_s is odd, then divided into $\frac{S_s - 1}{2}$ groups), the probability of crossing two individuals from the same group is P_c. During the crossing, a number less than the number of digits of the code of the group is randomly generated as the intersection position for each group of codes indicating the area of the inland port and each group of codes indicating the function of the inland port, such as 4,3,2,3 for the case, and the segment before the specific position of the code of the group is exchanged.

Thirdly, the mutation operation is conducted on every individual in the new generation, with a mutation probability of P_m. When two integers less than the total number of coding bits, such as 9 and 11 in the figure, are randomly picked from the mutation population, the 9th through 11th coding sequences are rearranged in reverse order.

Fourthly, each newly generated individual is judged to comply with each constraint in the upper-level planning, and if not, adjusted, such as the 14th coding in the adjust operation in Fig. 5.

Finally, the number of individuals obtained after the preceding procedure is S_s, which is less than the size of the parent population S_p. To solve this problem, we then choose the individuals from the parent population whose fitness ranks in the top S_p-S_s place, and then add them to the next generation population. A new generation of the population is formed at this time.

5. Case study

In this section, we adopt the planning of inland ports in Huaihai Economic Zone as a case study and conduct extensive numerical experiments by using MATLAB r2021a. The experiments were implemented on a Lenovo Thinkpad laptop with an AMD Ryzen 7 6800H with Radeon Graphics @3.2GHz CPU and 16.00 GB RAM using Microsoft Windows 11(64-bit).

5.1. Case data and algorithm parameter setting

5.1.1 Case data

To test the proposed model, we introduce the planning problem of inland ports in Huaihai Economic Zone in this section. According to a previous study (Ma *et al*., 2023), there are three important inland ports in this Economic Zone, Xuzhou inland port, Zaozhuang inland port, and Yanzhou inland port, and the seaport in this region is Rizhao port. The number of cities in this region is 10, including Xuzhou, Lianyungang, Suqian, Suzhou, Huaibei, Shangqiu, Zaozhuang, Jining, Linyi, and Heze. And the number of types of cargo related to foreign trade is five, including Advanced equipment, Agricultural products, Textiles, Biomedical products, and Coal & Chemicals. These are also five types of cargo with the best cross-border trade performance in the Huaihai Economic Zone (Tao *et al*., 2022 and National Bureau of Statistics of China, 2003).

Table 3 shows some basic data (P_n and α_n) related to the type of cargo. Data related to the inland ports is set as in Table 4, we use mu as the unit to describe the area of an inland port (1 mu = 666.67 m^2). Table 5 shows some input parameters of the model. Table 6 shows the assumed output of different import and export cargo by enterprises in each city. The transportation distances are based on Ma *et al*. (2023). The investment limit Z is set to be 8 billion yuan. The weight of manufacturing companies is set to be the same in the original scheme.

Table 3
Basic data related to the type of cargo

Type of cargo	P_n	α_n
Advanced equipment	1.5	5
Agricultural products	0.7	3
Textiles	0.8	4
Biomedical products	0.7	3
Coal & Chemicals	1.2	5

Table 4
Basic data related to the inland ports

Name of inland port	R_i (mu)	β_i
Xuzhou inland port	6000	0.2
Zaozhuang inland port	5000	0.1
Yanzhou inland port	2000	0.15

Table 5
Input parameters for the model

Parameter	Baseline value	Data source
c	10 (yuan/TEU·km)	Ma *et al*. (2023)
λ	190 (10000yuan/mu)	CFLP (2022)
ρ	0.9	Zhang *et al*. (2017)

Table 6
The assumed output (unit: 10000t) of different cargo in different cities

City	Advanced equipment	Agricultural products	Textiles	Biomedical products	Coal & Chemicals
Xuzhou	75	25	25	50	25
Lianyungang	0	12.5	0	37.5	25
Suqian	25	0	37.5	50	12.5
Suzhou	25	0	12.5	25	12.5
Huaibei	50	25	0	12.5	0
Shangqiu	37.5	25	25	0	0
Zaozhuang	25	0	12.5	12.5	25
Jining	50	12.5	25	0	0
Linyi	25	37.5	25	0	50
Heze	25	0	12.5	12.5	25

5.1.2 Algorithm parameters

We change various values of the algorithm parameters in the numerical experiments, as can be seen in Figure 5. According to the performance of the factors and in combination with the calculation time, we selected the following parameters for subsequent calculations: S_p=120*,* R_s=0.4, P_c=0.4, P_m=0.12.

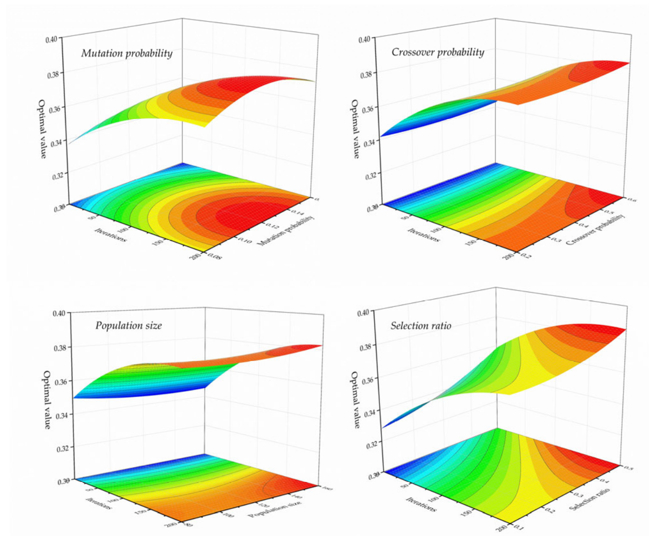

Fig. 5. Test results of the genetic algorithm with different parameters.

With the above algorithm parameters, bring in the actual data of the case and perform 20 Bernoulli tests. The statistical results of the optimal values are shown in Table 7. The optimal values under the selected algorithm parameters differ from 0.3523 to 0.3892. The variance and the standard deviation of the optimal value is relatively small, indicating that our experimental results are concentrated, and the results obtained with the same parameters are acceptable. In order to simplify the content in the charts, in the rest of this paper, S1 represents the planned area of Xuzhou inland port, S2 represents the planned area of Zaozhuang inland port, and S3 represents the planned area of Yanzhou inland port. Fig. 6 shows us the distribution of the scale of each inland port in the Bernoulli test. The experimental group corresponding to the nearest optimal value to the median (0.3734) is used as the basis for subsequent analyses.

Table 7
Descriptive statistics of the optimal value

	Min	Max	Mean value	Median value	Variance	Standard deviation
Optimal value	0.3523	0.3892	0.3728	0.3733	0.000117	0.010816

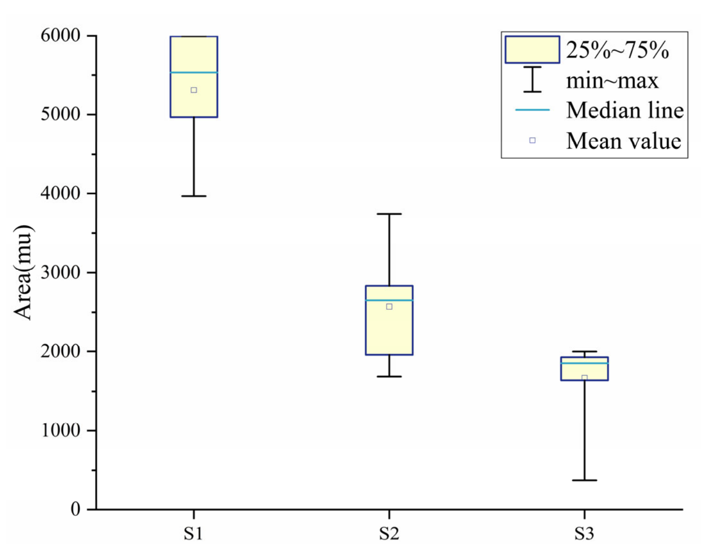

Fig. 6. The distribution of the scale of each inland port

5.2. Computational results and analysis

The optimization process of this case is shown in Fig. 7. As the number of iterations increases, the planning area of Xuzhou inland port and Yanzhou inland port keeps increasing and the planning area of Zaozhuang inland port keeps decreasing, until it reaches stability at about 100 iterations. For the objective value, during the first few iterations, faster growth is achieved and eventually, stabilization is also reached, proving that the hybrid heuristic algorithm proposed in this paper is effective in searching for the optimal solution.

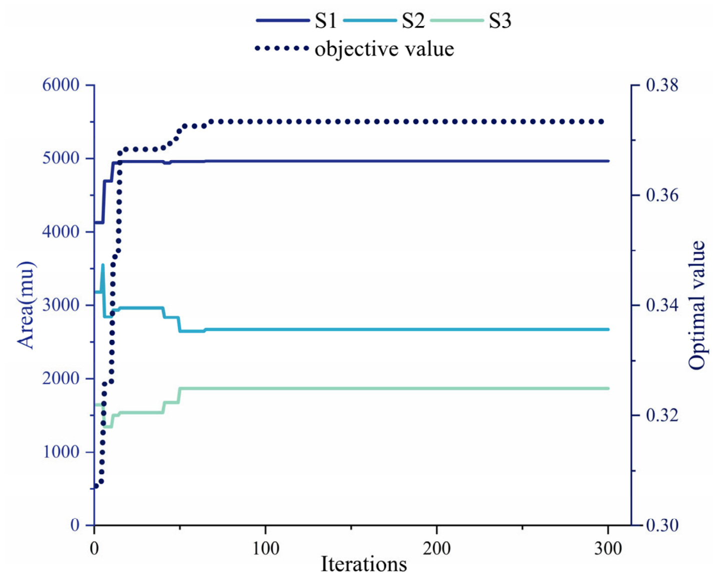

Fig. 7. Iterative optimization search process.

Comparing the objective value of solutions between traditional investment strategy (allocate investments based on land resources) and the optimal plan we proposed in this study, we can get the following results as in Table 8. The results report that the optimal plan significantly outperforms the traditional plan, with a rise of 14.68% in the objective value while the total land use decreased by 1.6%. The results prove to us that our optimized planning will save land resources while increasing the inland ports' market share in overall cross-border trade.

Table 8
Comparison of the traditional plan and the optimal plan

Objective value and solutions	Traditional plan	Optimal plan
Objective value	Ratio=0.3256	Ratio=0.3734 (14.68%↑)
Total land use (mu)	9646.8	9498.1 (1.6%↓)
Inland port area S_i	$S1$=4644.5, $S2$=3684.5, $S3$=1317.8	$S1$=4962.9, $S2$=2671.9, $S3$=1863.3
Inland port function A_{in}	A_{in}=1 for any i and n	A_{11}=1, A_{15}=1, A_{24}=1, A_{32}=1, other A_{in}=0

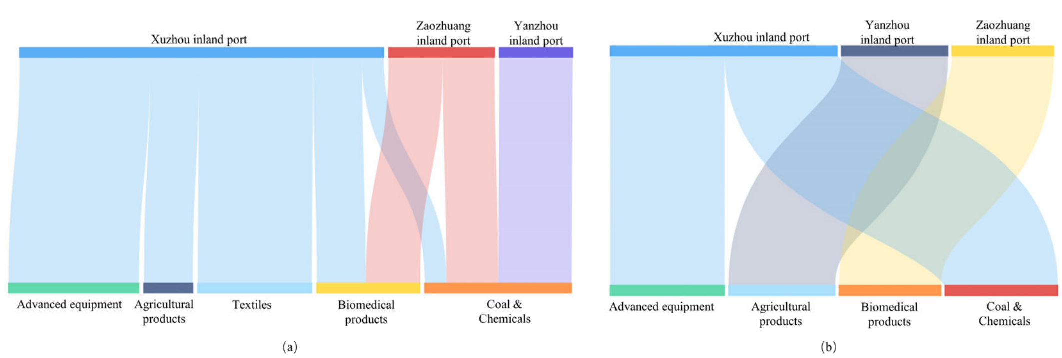

Fig. 8. (a) Competition for different types of cargo before optimization and (b) after optimization.

Moreover, Fig. 8 illustrates the competition for different types of cargo before and after optimization. It can be observed from Fig. 8(a) that before the optimization, the inland ports will compete for the same type of cargo in Huaihai Economy Zone, for example, all three inland ports serve for coal and chemicals. However, after optimization, there remains no competition for the same type of cargo as in Fig. 8(b).

The cargo flow of the optimal plan is shown in Fig. 9. We use two Sankey diagrams to indicate the cargo flow allocation for different types of cargo and different cities. More agricultural products choose inland port as a hub to import and export, and for textiles, all textiles will choose seaport to import and export in this case. And all cities except for Lianyungang will use both inland port and seaport for cross-border transportation, indicating that the cities do not have a strong preference for the type of hub they use regarding cross-border transport.

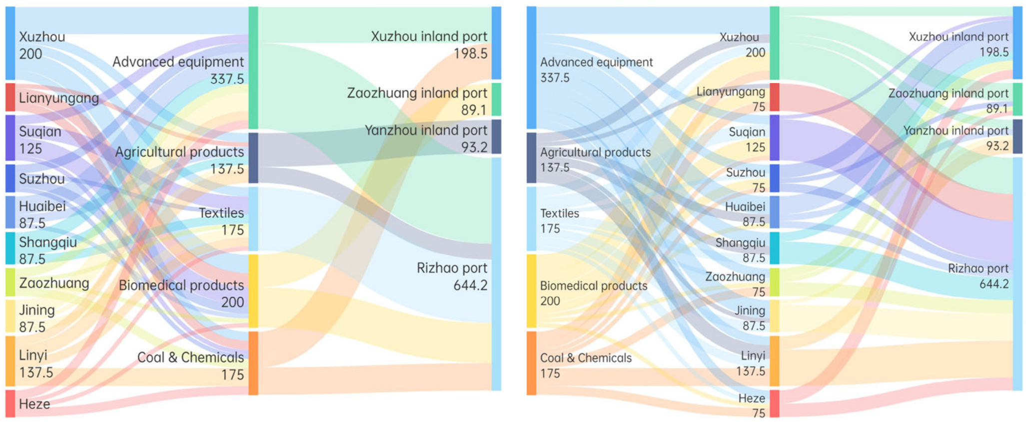

Fig. 9. Sankey diagrams for cargo flow allocation.

5.3. Sensitivity analysis

Sensitivity analysis is conducted with respect to the manufacturing enterprises weights, the investment limit, the effects of the investment scale, and the cargo value weights to demonstrate their impacts on the optimal plan for inland port scale and function.

5.3.1 Impact of manufacturing enterprises weights

To demonstrate the impact of manufacturing enterprises weights, we assume the following four scenarios:

- Scenario 1: The weight of each manufacturing enterprise is consistent (the original scheme),
- Scenario 2: Higher weighting for enterprises located in cities with inland ports,
- Scenario 3: The weights are assigned according to the output volume of each manufacturing enterprise,
- Scenario 4: Allocate weights according to the average GDP in the last three years of the cities where each manufacturing enterprise is located in.

The comparison results are shown in Fig. 9. From the figure, different weights of manufacturing enterprises will have some influence on the optimal target value and the size of each inland port. The difference between scenario 1, scenario 2, and scenario 4 is not significant. However, in scenario 3, the optimal target value is significantly improved, and the differences of the inland port scale plan is also significant. It can be inferred that using the output volume of each manufacturing enterprise as its weight will effectively improve the applicability of the planning and help the inland port system to behave better in the cross-border trade process.

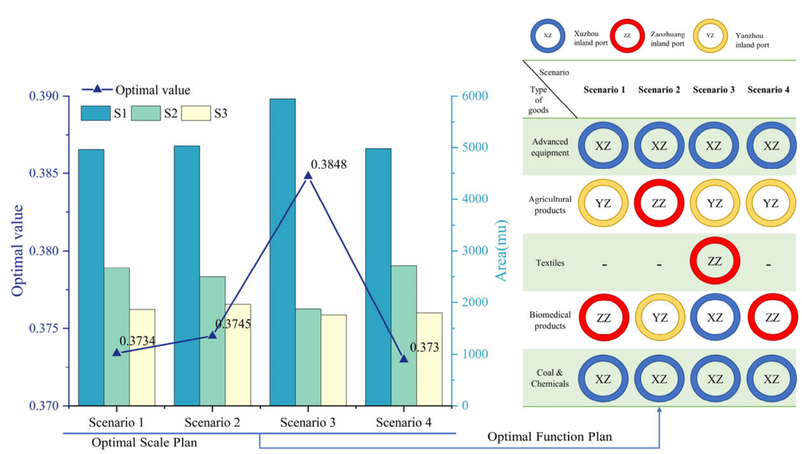

Fig. 10. Impact of manufacturing enterprises weights on optimal plan

In the meantime, Fig. 10 also shows the optimal inland port function scheme under different scenarios. In this case, Xuzhou inland Port will have the function of serving advanced equipment and coal & chemicals, regardless of the weight of each manufacturing enterprise.

5.3.2 Impact of investment limit

Fig. 11 shows that the increase in investment limit in inland ports will enhance the role of inland ports in the whole network. Meanwhile, the growth is not linear, and the growth is faster when the total investment scale in inland ports is less than 6 billion yuan. On the other hand, when the investment limit is less than 5 billion yuan, nearly all investments will be applied to the construction of Xuzhou inland port. And only when the investment limit is higher than 7 billion yuan will the construction of Zaozhuang inland port be considered. Moreover, when the investment limit is less than 6 billion yuan, Xuzhou inland port will serve three to four types of goods because most of the investment will be used to build Xuzhou inland port. And when the investment limit is more than 7 billion yuan, the scale and function of Xuzhou inland port and Yanzhou inland port will not change significantly, while the Zaozhuang inland port will realize services for one to two types of cargo as the investment increases.

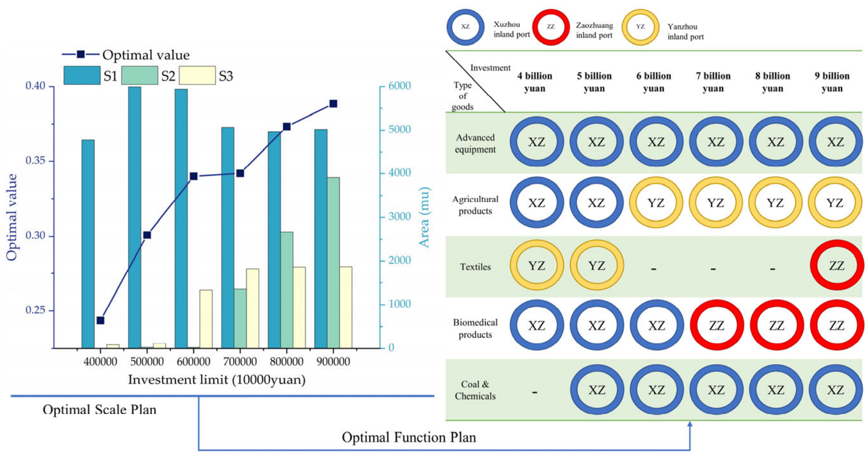

Fig. 11. Impact of investment limit on optimal plan

5.3.3 Impact of the scale effect on inland port investment

Fig. 12 depicts the impact of the effects of the economies of scale. The current study found that the optimal value will decrease as the scale effect of inland port investment becomes smaller. When the scale effect factor ρ is 1, in other words, there are no scale effects in the investment process, the optimal value is only 0.2133. The results once again demonstrate to us the importance of scale effects in a large-scale investment process such as inland port investment. Additionally, different scale effect factors will also have an impact on the optimal inland port scale and function scheme, but in spite of these factors, Xuzhou inland port has unique advantages of consolidation and distribution of advanced equipment.

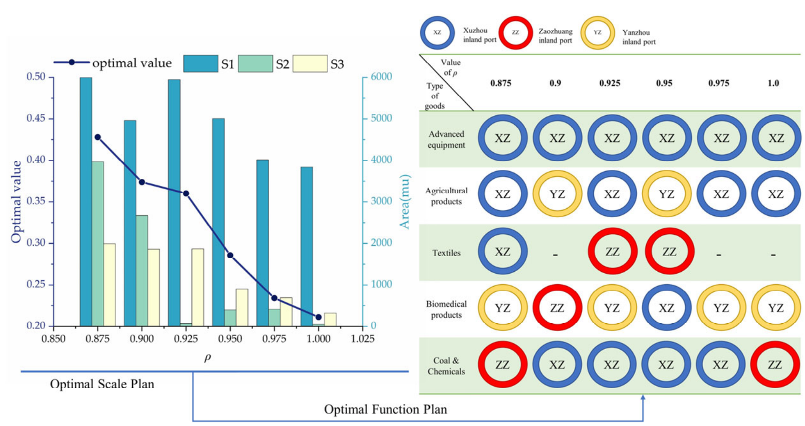

Fig. 12. Impact of scale effects on optimal plan.

5.3.4 Impact of cargo value weights

To illustrate the impact of cargo value weights, we suppose the following four scenarios:

- Scenario 1: Original plan,
- Scenario 2: All cargo has the same value,
- Scenario 3: Advanced equipment has the outstanding weights,
- Scenario 4: Agricultural products have outstanding weights.

And the comparison is displayed in Fig. 13. The value weights of the cargo will largely affect the proportion of cargo transported by inland ports. When not considering the difference in value between types of cargo (as in Scenario 2), the volume of different types of cargo transported by inland ports will be relatively balanced.

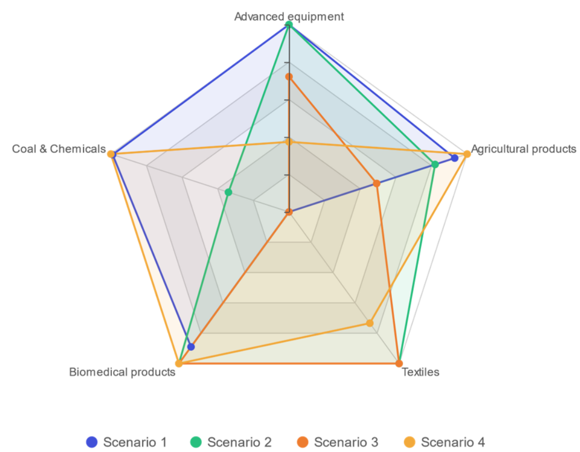

Fig. 13. Comparison of the cargo transported by inland ports in different scenarios.

5.4 Managerial insights

Based on our computational results, we provide the following managerial insights for inland port planning. The current study demonstrates that the bilevel programming model and the hybrid heuristic algorithm proposed in this research are useful tools for the planning optimization of inland ports in a certain region. The optimization results are significantly better than the results under traditional investment. Meantime, the competition between inland ports is narrowed as can be seen in Figure 8. The above results demonstrate that our optimal plans have practical implications. Determine the weight of each enterprise according to its output volume. By comparing the optimal inland port scale and function scheme and optimal target values under different scenarios, we find that using the manufacturing enterprise output volume as the weight of each manufacturing enterprise in the lower-level planning will effectively improve the overall planning objective compared to other weighting schemes. The proper investment limit for inland ports should be determined. When the investment limit is too low, only one inland port will be constructed to achieve the scale investment effect. However, when the investment limit for inland ports is too high, the marginal advantage to the objective value is not readily apparent. The scale effect of the investment in inland ports will largely affect the market share of inland ports in cross-border transport in the whole network. Therefore, we need to improve the investment scale effect of inland ports by methods regarding optimizing the investment mode, resource utilization, etc. Prior to planning the inland port, it is important to define the value weights for each import and export cargo category in the region, as the value weights have a significant impact on the objective values and the cargo flow allocation plan. For instance, in some regions, they will pay more attention to the development of certain categories of special cargo, which may be small in volume at present. However, considering future development, it should be given sufficient value weighting in the actual planning.

6. Conclusions

In this paper, we focused on the inland planning problem by considering the objective of maximizing the cross-border transportation market share of inland ports within a limited investment amount. Noting that the manufacturing companies are often ignored in the planning of inland ports, we innovatively proposed a bilevel programming model to include both local government and manufacturing companies in the planning process. Furthermore, we developed a hybrid heuristic algorithm to solve the proposed model. Additionally, extensive numerical experiments were carried out on a real-world case study of the Huaihai Economic Zone to verify the applicability and efficacy of the proposed model and algorithm. Finally, valuable managerial insights are proposed.

The major limitation of the present study is that we only considered the cargo related to foreign trade, although the role in domestic logistics is also important when planning inland ports. In addition, this study only considered the problem of planning multiple inland ports by a single decision-maker. Future research should be undertaken to explore the issues regarding multi-investors planning multiple inland ports.

Declaration of competing interest

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

Acknowledgement

This research was funded by the National Natural Science Foundation of China, grant number 71890972/71890970.

Data availability statement

All data generated or analyzed during this study are included in this article.

References

Association of Development District in China (2021). China Inland Port Development Report; China Fortune Press: Beijing, BJ. ISBN 9787504775092.

Brouer, B.D., Pisinger, D., & Spoorendonk, S. (2011). Liner Shipping Cargo Allocation with Repositioning of Empty Containers. *INFOR: Information Systems and Operational Research*, *49*(2), pp.109–124. https://doi.org/10.3138/infor.49.2.109.

CFLP (2022). Sixth National Logistics Park (Base) Survey Report. [online] Available at: http://www.chinawuliu.com.cn/lhhzq/202212/16/595027.shtml [Accessed 6 Apr. 2023].

Chagas, G.C., Lorena, L. and Santos R. (2022). A hybrid heuristic for overlapping community detection through the conductance minimization. *Physica A: Statistical Mechanics and its Applications*, 592, pp.126887–126887. https://doi.org/10.1016/j.physa.2022.126887.

Chang, Z., Yang, D., Wan, Y. and Han, T. (2019). Analysis on the features of Chinese dry ports: Ownership, customs service, rail service and regional competition. *Transport Policy*, 82(1), pp.107–116. https://doi.org/10.1016/j.tranpol.2018.06.008.

Gasnikov, A.V., Gasnikova, E.V., & Nesterov, Y.E. (2018). Dual Methods for Finding Equilibriums in Mixed Models of Flow Distribution in Large Transportation Networks. *Computational Mathematics and Mathematical Physics*, 58(9), pp.1395–1403. https://doi.org/10.1134/s0965542518090075.

Ho, M.W., & Ho, K.H. (2006). Risk Management in Large Physical Infrastructure Investments: The Context of Seaport Infrastructure Development and Investment. *Maritime Economics & Logistics*, 8(2), pp.140–168. https://doi.org/10.1057/palgrave.mel.9100153.

Jiang, L., Wang, X., Yang, K., & Gao, Y. (2022). Bilevel optimization for the reorganization of inland river ports: A niche perspective. *Socio-Economic Planning Sciences*, *86*, p.101466. https://doi.org/10.1016/j.seps.2022.101466.

Kalashnikov, V.V., Dempe, S., Pérez-Valdés, G.A., Kalashnykova, N.I., & Camacho-Vallejo, J.-F. (2015). Bilevel Programming and Applications. *Mathematical Problems in Engineering*, 2015, pp.1–16. https://doi.org/10.1155/2015/310301.

Kaysi, I., & Nehme, N. (2016). Optimal investment strategy in a container terminal: A game theoretic approach. *Maritime Economics & Logistics*, *18*, 250-26. https://doi.org/10.1057/mel.2015.7.

Koh, Y.-K. (2001). Optimal investment priority in container port development. *Maritime Policy & Management*, *28*(2), pp.109–123. https://doi.org/10.1080/03088830117187.

Lee, H., Song, Y., Choo, S., Chung, K.-Y., & Lee, K.-D. (2013). Bi-level optimization programming for the shipper-carrier network problem. *Cluster Computing*, *17*(3), pp.805–816. https://doi.org/10.1007/s10586-013-0311-6.

Ma, J., Wang, X., Yang, K., & Jiang, L. (2023). Uncertain Programming Model for the Cross-Border Multimodal Container Transport System Based on Inland Ports. *Axioms*, *12*(2), 132. https://doi.org/10.3390/axioms12020132.

Ma, L. (2021). Analysis on the Application of BP Algorithm in the Optimization Model of Logistics Network Flow Distribution. *Lecture Notes on Data Engineering and Communications Technologies*, *84*(1), 67–74. https://doi.org/10.1007/978-981-16-5857-0_9.

Molavi, A., Lim, G. J., & Shi, J. (2020). Stimulating sustainable energy at maritime ports by hybrid economic incentives: A bilevel optimization approach. *Applied Energy*, *272*, 115188. https://doi.org/10.1016/j.apenergy.2020.115188.

National Bureau of Statistics of China (2003). *Comparative Analysis of the Development Status of Huaihai Economic Zone.* [online] Available at: http://www.stats.gov.cn/ztjc/ztfx/dfxx/200305/t20030512_31192.html.

Qiu, X., & Xu, G. (2019). Optimizing Rail Transport Service in a Dry Port System. *IEEE Transactions on Engineering Management*, *69*(6), 1–15. https://doi.org/10.1109/TEM.2019.2951915.

Qiu, X., Lam, J.S.L., & Huang, G.Q. (2015). A bilevel storage pricing model for outbound containers in a dry port system. *Transportation Research Part E: Logistics and Transportation Review*, *73*, 65–83. https://doi.org/10.1016/j.tre.2014.10.009.

Qu, C., Zeng, Q., Li, K.X., & Lin, K.-C. (2020). Modeling incentive strategies for landside integration in multimodal transport chains. *Transportation Research Part A: Policy and Practice*, *137*, 47–64. https://doi.org/10.1016/j.tra.2020.04.012.

Sinha, A., Malo, P., & Deb, K. (2018). A Review on Bilevel Optimization: From Classical to Evolutionary Approaches and Applications. *IEEE Transactions on Evolutionary Computation*, *22*(2), 276–295. https://doi.org/10.1109/tevc.2017.2712906.

Tao, J., Lu, Y., Ge, D., Dong, P., Gong, X., & Ma, X. (2022). The spatial pattern of agricultural ecosystem services from the production-living-ecology perspective: A case study of the Huaihai Economic Zone, China. *Land Use Policy*, *122*, 106355. https://doi.org/10.1016/j.landusepol.2022.106355.

Vega-Mejía, C., González-Neira, E., Montoya-Torres, J., & Islam, S. (2020). Using a hybrid heuristic to solve the balanced vehicle routing problem with loading constraints. *International Journal of Industrial Engineering Computations*, *11*(2), 255-280.

Vicente, L.N., & Calamai, P.H. (1994). Bilevel and multilevel programming: A bibliography review. *Journal of Global Optimization*, *5*(3), 291–306. https://doi.org/10.1007/bf01096458.

Wang, C., Xie, F., & Xu, L. (2020). Which terminals should expand investment: a perspective of internal non-cooperative competition in a port?. *Maritime Policy & Management*, *47*(6), 718-735. https://doi.org/10.1080/03088839.2020.1725674.

Wang, H., Wang, S., & Meng, Q. (2014). Simultaneous optimization of schedule coordination and cargo allocation for liner container shipping networks. *Transportation Research Part E: Logistics and Transportation Review*, *70*(07), pp.261–273. https://doi.org/10.1016/j.tre.2014.07.005.

Wang, Z., Li, Y., Gu, F., Guo, J., & Wu, X. (2020). Two-sided matching and strategic selection on freight resource sharing platforms. *Physica A: Statistical Mechanics and its Applications*, [online] *559*, p.125014. https://doi.org/10.1016/j.physa.2020.125014.

Yu, P., Wang, Z., Yin, H., Wang, J., & Xu, Z. (2022). Dynamic evolution of shipping network based on hypergraph. *Physica A: Statistical Mechanics and its Applications*, *598*, 127247–127247. https://doi.org/10.1016/j.physa.2022.127247.

Zeng, Q., Maloni, M.J., Paul, J.A., & Zhongzhen Yang, Z. (2013). Dry Port Development in China: *Transportation Journal*, *52*(2), p.234. https://doi.org/10.5325/transportationj.52.2.0234.

Zhang, D., Jiang, J., Li, S., Li, X., & Zhan, Q. (2017). Optimal Investment Timing and Size of a Logistics Park: A Real Options Perspective. *Complexity*, 2017(1), 1–12. https://doi.org/10.1155/2017/2813816.

Zhang, M., Huang, J., & Zhu, J. (2012). Reliable facility location problem considering facility failure scenarios. *Kybernetes*, *41*(10), pp.1440–1461. https://doi.org/10.1108/03684921211276666.

Zhang, Y., Wu, Y., Wang, W., Yang, Y., & Ma, L. (2021). Novel Multifunctional Dual-Band Coupled-Line Coupler with Reuse of Low-Frequency Trans-Directional and High-Frequency Contra-Directional Functions. *IEEE Transactions on Circuits and Systems II: Express Briefs*, *68*(6), pp.1917–1921. https://doi.org/10.1109/tcsii.2020.3042503.