An optimization approach to the scale of port cold-chain dedicated terminals considering uncertainties

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\textbf{ABSTRACT}

As an important node of the international cold-chain logistics system, the special terminal for refrigerated ships is the core facility for cargo loading and unloading. To minimize the sum of construction costs and operating costs of dedicated cold-chain terminals, a stochastic programming model is established considering uncertainty of the type and time of arrival of refrigerated vessels and special requirements for cargo handling and storage, and the simulation optimization method based on tabu search is used to determine the optimal scale of cold-chain terminals. A case study on the port cold-chain system of an offshore fishery base is then presented to investigate the specific influence of uncertainties on the scale of cold-chain terminals. This provides a reference for scientific planning of cold-chain facilities and improving the efficiency of cold-chain systems in the sea–land exchange node.

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1. Introduction

Increased levels of consumption associated with the development of the economy and society bring about increased demand for fresh food. As an important part of the cold-chain system, the port provides transportation and storage services for bulk frozen and chilled goods at a global level. The port cold chain mainly involves warehousing, agency, international transit, distribution and trade, pledge supervision, professional inspection, packaging, and finance and other businesses, including domestic sales of foreign aquatic products (Ma \textit{et al.} 2018), fruits and meats. Many ports are actively enhancing the core competitiveness of port cold-chain logistics, making full use of container terminals to transport refrigerated containers, and are actively building specialized refrigerated transfer terminals.

In the case of China (the second largest economy in the world), major coastal ports completed a cargo throughput of 9.188 billion tonnes in 2019, a year-on-year increase of about 4.3%. Major ports increasingly attach importance to the planning and construction of cold-chain infrastructure, as shown in Table 1. As an important type of cold-chain transport infrastructure, the port cold-chain system provides an important guarantee for the efficient operation of international cold-chain transport networks. However, suboptimal port planning not only increases the construction costs of the port, but also affects the production and operation efficiency and the quality of the cargo, thus increasing the carrier’s transportation costs.
This study focuses on the analysis of the composition and characteristics of the port cold-chain system, and puts forward a method for optimizing the scale of the port cold-chain infrastructure under uncertain conditions. It provides a theoretical basis for the port cold-chain system planning, facility construction and coastal port planning adjustment and function expansion, and also solves the problem of how to scientifically control the construction costs of the port side and the transport costs of the carrier.

2. Literature review

The research on cold-chain infrastructure optimization mainly focuses on location, planning and layout, and the configuration of cold-chain supporting equipment. Many researchers consider the capacity of transit warehouses as a known value when studying supply-chain networks for perishable goods (Goli, Tirkolae, and Weber 2020; Tirkolae et al. 2019). However, determining the capacity and configuration of the transit warehouse is also a very important task.

The application of evaluation systems is a traditional topic that has been studied extensively in the field of cold chains, with methods such as grey correlation degree (Zheng and Liu 2009), fuzzy comprehensive evaluation (Xia and Huang 2016) and the analytic hierarchy process (Wang, Ye, and Hu 2007). Based on this research, the most notable factors are chosen to be built into the multi-objective optimization model. Zhu and Da-Wei (2012) established a multi-objective model of cold-chain distribution centre location, taking transportation cost and cold-chain service reliability as the objectives, and took a cold-chain enterprise as an example to conduct numerical analysis. Yuan and Yi (2016) extended the work by taking logistics cost, time window, quality of goods and customer service level into consideration. Storage facilities are the core components of the cold chain, and the scale of storage facilities is directly related to the utilization rate of cold-chain equipment and cold-chain service level (Martinez-Jimenez, Garcia-Salazar, and Mora-Flores 2015; Hwang et al. 1999).

The problem of warehouse scale and storage capacity allocation can be grouped into two types according to the objective: (1) service level and efficiency; and (2) cost and revenue. The factors affecting the storage capacity of warehouses were studied, and the optimal storage scale was determined under a certain service level by simulation methods (Rosenblatt and Roll 1988; Rosenblatt, Roll, and Zyser 1993) or obtained by discussing the loading and unloading efficiency under different stacking rules (Woo and Kim 2011). Based on the economic-order-quantity model, Lee and Elsayed (2005) used a nonlinear optimization method to solve the initial storage capacity problem under specific inventory regulations. In addition, the total capacity of third-party warehouses was to be allocated to provide different service levels under the condition of multi-stage demand uncertainty (Xu, Dong, and Peng 2015). Compared with ordinary warehouses, cold storage has higher standards and requirements for architectural design and supporting equipment, and is generally composed of the main buildings, such as the cold processing room and storage room, and auxiliary buildings (Choi et al. 2006a, 2006b; Gagliardi, Renaud, and Ruiz 2012; Meneghetti and Monti 2015).

| Table 1. Scales and situations of the cold storage for coastal seaports of China. |
|-----------------|-----------------|-----------------|
| Port name       | Cold storage scale (10,000 t) | Status quo positioning |
| Dalian Port     | 40              | Fruit, aquatic products and meat import and export base |
| Tianjin Port    | 20.6            | Two-way international transfer and distribution |
| Qingdao Port    | 22.3            | Second largest imported meat refrigerator in China |
| Shanghai Port   | 12.6            | Food import and export transfer base |
| Ningbo Zhoushan Port | 8.5           | Fast passage for customs clearance of imported food |
| Xiamen Port     | 14.3            | Low-temperature logistics transfer base |
| Guangzhou Port  | 11.8            | Largest cold-chain base in South China |
| Other ports     | About 50        | Base of meat, aquatic products, processed food and other goods |

Source: China Cold Chain Logistics Development Report (2019).
Compared with the large amount of port production scheduling and operation strategy research, research on the terminal scale mainly focuses on the berth level and number, and the number of pieces of equipment. Queuing theory, a mathematical method used to study the phenomenon and working process of a system, is a common tool for the study of scale and layout of a terminal (Gokkus and Yildirim 2015; Li, Qiu, and Wu 2010; Noritake and Kimura 1983). Because port production is a complex dynamic and random process, computer simulation has become an effective means by which to study the scale of the terminal. Gambardella et al. (2001) proposed a solution to the problem of loading and unloading resource allocation and scheduling in container terminal systems, and established a simulation model based on discrete events to verify the feasibility of the scheme. Veeke and Ottjes (2002) built a simulation model of a container terminal system to provide technical support for port planning and design, and applied the model to the construction of Maasvlakte 2 in Rotterdam port. Murty et al. (2005) put forward a decision support system in the study of container terminal capacity planning, so as to reduce the waiting time for ships and trucks, solve the congestion problem in the collection and distribution channel and inside the port, and make full use of the port storage space.

The storage yard is the main facility and area for cargo loading and unloading, storage and handover. It has a great impact on the production efficiency of the terminal, and the design of its scale has been widely investigated by many scholars, especially in the area of container terminal capacity (Brinkmann 2005; Chu and Huang 2004; Kim and Kim 1998; Lee, Lee, and Chew 2014; Petering 2011). In the process of operation, the terminal logistics system is faced with a lot of uncertainties, which bring great challenges to the planning and design of the terminal and the determination of its scale. Scholars have analysed these uncertainties in depth to guide port planning (Antonio and Novaes 2012; Martin, Kim, and Marchán 2015), berth allocation (Moorthy and Teo 2006) and fleet transportation schemes (Pujawan et al. 2015).

The above studies mostly focus on the optimization of the scale and resource allocation of port facilities. More and more scholars are beginning to pay attention to the impact of uncertain factors on the scale of port facilities, mostly using simulation methods and mathematical modelling for optimization and analysis. However, few researchers have studied the optimization of the scale of facilities by considering the nature and characteristics of goods and the freight demand in different seasons. It is still necessary to further consider the nature of goods and seasonal uncertainties in demand to study the optimization of the scale of port cold-chain infrastructure. Therefore, finding a way to analyse the uncertainties of the cold-chain system for special goods and plan the scale of the terminal scale is one of the key issues in this study. A stochastic programming model for the scale of dedicated cold-chain terminals considering uncertainty in the type and time of arrival of refrigerated vessels and special requirements for cargo handling and storage is constructed, and the simulation optimization method based on tabu search is used to determine the optimal scale of cold-chain terminals. Suggestions and methods are provided for the scientific planning of the scale of cold-chain facilities and for improving the efficiency of sea–land exchange nodes in cold-chain systems.

3. Problem statement

3.1. Functions and characteristics of special cold-chain terminals

Cold-chain terminals are most often arranged in the form of refrigerated ship berths–leading edge–cold storage. In international trunk lines and long-distance cold-chain transportation, the goods are unloaded through the refrigerated ship berth and then transported horizontally by the port’s tractor–trailer. Upon arrival at the cold storage receiving and unloading area, the goods are placed on shelves in the cold storage by a forklift on a pallet; they can also be transported to the bonded cold storage area for processing and storage, and then transferred to other areas, or transported to the hinterland cold-chain logistics centre and distributed to the target customers through the port collection and distribution system.
The port cold-chain system of the offshore fishery base is taken as an example (Figures 1 and 2). The ocean fishing fleet travels to the fishing ground for production and operation. After harvesting, the deep-sea fishing catch is transported back to the terminal by a refrigerated transport ship from time to time. After customs clearance at the port, the catch is transported by truck to the cold-storage shelf storage or processing area for deep processing. Finally, according to customer demand, the goods are transported out of the port for trade transfer or distribution in the hinterland city. The terminal set-up is similar to a cell formation problem, including the scheduling of parts within cells in a cellular manufacturing system, where several automated guided vehicles are in charge of transferring the exceptional parts (Goli, Tirkolaee, and Aydin 2021).

Examples of common port cold-chain infrastructure planning can be found in the fishing base of Busan Port, Republic of Korea, and the refrigerated terminal in Rotterdam, the Netherlands.
3.2. Analysis of factors influencing the scale of the terminal

The port side aims to have as few berth resources as possible and to load and unload as many goods as possible; while, for the ship side, it is hoped that the berth resources are sufficient, so as to reduce the waiting time of ships at the port. From the perspective of economic benefits, on the one hand, if the number of berths is high, the construction and operation management costs of the terminal will be high, and the coastline resources will be wasted; on the other hand, if the number of berths is low, the waiting time of refrigerated ships will be longer. In addition to the cost of the ship itself, the refrigeration efficiency of the cold-storage equipment in the hold of the ship will decrease, resulting in a loss of quality and overstocking of the cargo. Therefore, based on the comprehensive benefits of various stakeholders, this study considers that the optimal scale of the cold-chain terminal is the one with the minimum total cost of the port and the ship during the period of operation, under the condition of completing the port throughput task.

The total cost of the port and the ship includes, mainly, the construction cost (the infrastructure investment of the terminal is estimated according to the average service life of the facilities and estimated by the average life method), as well as the cost of waiting for berthing for the refrigerated ship in the operation stage, and the cost of loading and unloading the refrigerated ship at the corresponding berth; the uncertain factors in the production and operation of the cold-chain terminal include the throughput; other uncertain factors that have a significant influence on the determination of terminal scale include the rules of arrival of refrigerated vessels and additional losses caused by overstocking of refrigerated ships while waiting to berth.

4. Method

4.1. Stochastic programming model for the scale of the cold-chain terminal

Owing to the long operation period of the cold-chain terminal, it is necessary to make a decision on the berth allocation scheme before the uncertain factors are realized. Determining the scale of the dedicated cold-chain terminal is a problem that should be considered in the planning period, because the berth investment is huge and it is not easy to change after implementation. Therefore, considering the overall economic benefits and logistics efficiency of the port and the ship, the uncertainty of the arriving ship type and the arrival time of the refrigerated ship, the optimal scale of the dedicated cold-chain terminal is determined.

4.1.1. Objective function

To simplify the model reasonably, the following assumptions are made:

- The unloading capacity of a single ship is regarded as having the same uniform distribution as a refrigerated transport ship with the same tonnage.
- The principle of ‘first come, first served’ is adopted for berthing.
- Refrigerated ships need to occupy a berth for replenishment and maintenance, in a certain proportion, after unloading.

The model is established using a scenario set to express uncertain factors. Considering the combined influence of the throughput of the dedicated cold-chain terminal and the extra loss of the cargo owing to the low refrigeration efficiency (when the refrigerated ship arrives at the port and while it is waiting to berth), the waiting time \( w_{β,t}(ω) \) of the refrigerated ship arriving at the port and the cargo handling demand (\( δ_{β,t}(ω) \)) allocated to the corresponding berth constitute the scenario set (ω), which is simulated by the Monte Carlo method.

The objective function is to minimize the total cost of the port and the ship during the operation period. The total cost includes the construction cost of the terminal, the cost of waiting for berthing, and the cost of loading and unloading the refrigerated ship at the corresponding berth, similarly to the composition of the objective function established by Tirkolaee et al. (2020).
The expression for minimizing the total cost is as follows:

$$\min f(x_\alpha) = N \sum_{\alpha=1}^{m} x_\alpha c^b_\alpha + \int_\Omega \rho(\omega) \sum_{t=1}^{N} \sum_{\beta=1}^{n} [\delta_{\beta,t}(\omega) w_{\beta,t}(\omega) c^w_\beta (1 + \eta_d) + \delta_{\beta,t}(\omega) c^s] \, d\omega$$  \hspace{1cm} (1)

where $N$ is the number of days in the operation period; $x_\alpha$ is the number of berths of type $\alpha$, which is the decision variable; $c^b_\alpha$ is the daily average operating cost of a single type $\alpha$ berth; $\rho(\omega)$ is the probability of occurrence of the scenario $\omega$; $\delta_{\beta,t}(\omega)$ represents the local handling capacity of refrigerated vessels of type $\beta$ under the scenario $\omega$ within the time period $t$; $w_{\beta,t}(\omega)$ is the average waiting time of refrigerated ships of type $\beta$ under the scenario $\omega$ within the time period $t$; $c^w_\beta$ is the overstocking loss of unit weight cargo when the ship is waiting to berth; $\eta_d$ is the proportion of additional loss caused by low refrigeration efficiency when the ship is waiting for a berth; and $c^s$ is the handling cost of unit weight cargo after berthing.

- **Determination of terminal construction cost**

  The construction cost of the cold-chain terminal includes the sum of the berth construction cost and the amount of investment in the terminal facilities allocated to the berths. When calculating the terminal construction cost, according to the average service life of the facilities, a depreciation estimation is made on the terminal infrastructure investment according to the average service life method, which is converted into the daily average operating cost $c^b_\alpha$. According to the number $x_\alpha$ of berths of various types $\alpha$ in the planning scheme, the number of days $N$ of the terminal operation period is investigated and the terminal construction cost $N \sum_{\alpha=1}^{m} x_\alpha c^b_\alpha$ is obtained.

- **Determination of overstocking cost of a refrigerated ship waiting to berth**

  When a ship of type $\beta$ is waiting for a berthing space, the shipowner will lose $c^w_\beta$ owing to the overstocking of cargo. However, compared with the loss caused by the backlog of general cargo, the backlog cost of frozen and chilled cargo waiting for berthing in the port may be higher than that of ordinary cargo, which is recorded as $\eta_d$. Therefore, the overstocking cost of the goods waiting for a berth is $c^w_\beta (1 + \eta_d)$. According to the statistics of the average waiting time $w_{\beta,t}(\omega)$ for refrigerated ships of type $\beta$ under the scenario $\omega$ in the time period $t$, and local loading and unloading capacity $\delta_{\beta,t}(\omega)$, the total backlog cost $\int_\Omega \rho(\omega) \sum_{t=1}^{N} \sum_{\beta=1}^{n} \delta_{\beta,t}(\omega) w_{\beta,t}(\omega) c^w_\beta (1 + \eta_d) \, d\omega$ of refrigerated ships is obtained.

- **Determination of cargo handling cost**

  The handling cost $c^s$ per unit weight of cargo after berthing is investigated, and the total cost $\int_\Omega \rho(\omega) \sum_{t=1}^{N} \sum_{\beta=1}^{n} \delta_{\beta,t}(\omega) c^s \, d\omega$ of cargo handling is obtained.

### 4.1.2. Restraint condition and functional relationships among variables

To ensure that the length of shoreline $\sum_{\alpha}^{m} \theta_\alpha x_\alpha$ occupied by berths does not exceed the length of the planned port shoreline $L_\alpha$, and to maintain the ecological and environmental benefits of terminal construction, the following constraints are stipulated:

$$\sum_{\alpha}^{m} \theta_\alpha x_\alpha \leq L_\alpha$$  \hspace{1cm} (2)
The model is established on the premise that there is a demand for new or expanded terminals in the port area, so the number of terminals $\sum_{\alpha} x_{\alpha}$ must be a non-negative integer. To ensure that the berth combination in the model is not empty, the constraints are as follows:

$$\sum_{\alpha} x_{\alpha} \geq 1 \quad \forall \alpha \in m$$  \hspace{1cm} (3)

With the help of the simulation model of the port cold-chain system and the terminal operation system, through simulation and quantification, the relationship between $w_{\beta,t}(\omega)$ and $x_1, \ldots, x_m, n, \delta_{\beta,t}(\omega)$ is as follows:

$$w_{\beta,t}(\omega) = u(x_1, \ldots, x_m, n, \delta_{\beta,t}(\omega)) \quad \forall t \in T, \forall \omega \in \Omega$$  \hspace{1cm} (4)

where $\delta_{\beta,t}(\omega)$ is the length of the $\delta_{\beta,t}(\omega)$ tonne berth, $\delta_{\beta,t}(\omega)$ is the upper limit of shoreline length occupied by berths, $u(x)$ is the calculation method of the average waiting time, and $n$ is as described in Equation (1). In the cold-chain transportation network model, $\delta_{\beta,t}(\omega)$ is the cargo flow allocated to the current terminal when the freight demand changes in the scenario $\omega$.

### 4.2. Solution of stochastic programming model for the scale of the special cold-chain terminal

Considering the uncertain factors, the objective function contains many variables which cannot be converted into accurate values or explicit expressions, which means that the model cannot be processed by common operational research methods. Therefore, in this study, the stochastic parameters and related function information in the model are obtained through simulation, and a simulation optimization method based on tabu search is designed to solve the stochastic planning model. A description of the simulation model is provided in the Supplementary Material.

The tabu search algorithm is a heuristic search method that has been widely applied in the field of optimization (Alinaghian et al. 2021; Yang, Kuo, and Chang 2004), especially in simulation optimization models (Choi, Rehn, and Erikstad 2018; Koulouriotis, Xanthopoulos, and Tourassis 2010). The algorithm flowchart is shown in Figure 3. Tabu search is widely used in production scheduling, layout design, circuit design and combinatorial optimization.

According to the analysis of decision variables involved in Section 4.1, the solution of the model includes two parts: the berth level type $m$ and the number of each type of berth $x_{\alpha}$. This study applies a double iteration cycle model; the first layer circulation is calculated by enumeration to determine berth type set $m$, while the second cycle uses the tabu-based simulation optimization method for decision variables $x_{\alpha}$ value.

With regard to the variables involved in the two-layer cycle, the length of the shoreline, port layout and road network structure in the auxiliary program of the simulation model of the cold-chain system remain unchanged, and the number of each berth type in the main program of the simulation model and berth tonnage in the auxiliary program need to be updated.

In the second cycle, in the case of berth-type determination, the tabu-based simulation optimization framework is integrated:

1. **Step 0**: Combine the plane constraint and the initial attributes of resources to determine the initial value setting of $x_{\alpha}$ in the feasible domain $FR$, and record it as $u^0$, so that $u^{\text{now}} = u^{\text{best}} = u^0$;
2. **Step 1**: If the number of simulations experienced in the search exceeds the maximum number of simulations allowed in the search, go to **Step 5**; otherwise go to **Step 2**;
3. **Step 2**: Collect samples in the neighbourhood $N(u^{\text{now}})$ of the current solution $u^{\text{now}}$, and select a subset $S(u^{\text{now}})$;
4. **Step 3**: Input the elements in $S(u^{\text{now}})$ into the simulation model for simulation, and select the $u^{\text{best}}$ solution with the minimum objective function value according to the simulation results;
5. **Step 4**: Update the search memory;
Step 5: Let $u_{\text{now}} = u_{\text{nest}}$. If $u_{\text{nest}}$ is better than $u_{\text{best}}$, let $u_{\text{best}} = u_{\text{nest}}$.

Step 6: If the simulation time is used up, stop the whole search process.

To run the above tabu-based simulation optimization process, the key contents to be determined are as follows: initialization; setting of decision variables; rules for collecting neighbourhood samples; search for memory and aspiration criterion.

1. Initialization of decision variables

Because the coastline length of berth is less than the range of planning port coastline (i.e. to meet $\sum_{\alpha} \theta_{\alpha} x_{\alpha} \leq L_s$), and because the cold storage tanker ship type has discrete finite characteristics, the cold-chain dedicated terminal berth level is limited and scattered. The initialization process of the decision variables is as follows:

Step 1: Randomly select the value of component $u_j (j = 1, \ldots, m)$ of $u^0$ with uniform probability within the berth resource type range;

Step 2: Judge whether the constraint condition $\sum_{\alpha} \theta_{\alpha} x_{\alpha} \leq L_s$ is established; if yes, the operation will end; if not, repeat Step 1 until the constraint condition is satisfied.

2. Rules for collecting neighbourhood samples

For the berth resource allocation problem, the generation rules of neighbourhood $N(u)$ of the current solution $u$ are as follows:

$$N(u) = N_{ad}(u) \cup N_{st}(u)$$

(5)

$$N_{ad}(u) = \{ v \in FR|u, \exists j(1 \leq j \leq \alpha \wedge v_k = u_k + 1) \}$$

(6)
\[ N_{ad}(u) = v \in FR \mid u, \exists j (1 \leq j \leq \alpha \land v_k = u_k - 1) \]  

\[ N_{st}(u) = v \in FR \mid u, \exists j (1 \leq j \leq \alpha \land v_k = u_k + 1) \]

\( N_{ad}(u) \) shows that the number of berths \( \alpha \) increases by one; \( N_{st}(u) \) shows that the number of berths \( \alpha \) decreases by one. At the same time as determining the neighbourhood structure, a suitable sampling rule should be made, i.e., a subset \( S(u_{\text{now}}) \) conforming to the rule should be selected from the neighbourhood \( N(u_{\text{now}}) \) of the current solution \( u_{\text{now}} \). For the cold-chain berths in the port area, which are generally affected by the freight demand and the coastline range, the number of solutions in the neighbourhood \( N(u_{\text{now}}) \) is limited, so the solution that is not subject to taboos can be taken as the candidate solution.

3. Memory search and aspiration criterion

In the tabu search process, search memory is reflected in the tabu table, which is usually composed of a ternary array \((\text{index, berth\_num, count})\), representing, respectively, the berth type number, the number of berths of the current berth type and the length of time remaining in the tabu table. If \( v \in N_{ad}(u) \land v_k = u_k + 1 \) or \( v \in N_{st}(u) \land v_k = u_k - 1 \), then \((k, u_{\text{now}}, \text{count})\) is entered in the tabu table.

5. Tests and results

Taking the minimum sum of terminal construction cost and operation cost as the optimization objective, and using the cold-chain operation system of a deep-sea fishery base as an example, the production law of the cargo supply side and the operation process of the cold-chain system is simulated. Considering the uncertain factors such as the composition of goods and the random arrival of refrigerated ships, the simulation optimization method based on tabu search is used to solve the special cold-chain terminal regulations. The model is used to obtain the optimal berth allocation scheme of the port cold-chain system.

The test runs were performed on a 3.50 GHz Xeon personal computer with 32.0 GB RAM. The model resulted in a problem instance with thousands of constraints and a few tens of thousands of variables (around 1500 integers) and was solvable well within the acceptable limits for decision support in industrial practice.

5.1. Input data for the optimization model

5.1.1. Refrigerated ship to/from port and truck transport mode

Referring to the statistical data of an offshore fishery base, the daily catch data of three main species in the base for three consecutive years (to reduce the freight imbalance for two consecutive years) are obtained, as shown in Figure 4. The arrival mode of refrigerated vessels in the base is closely related to the species of the pelagic catch, showing obvious seasonal fluctuations. According to the historical statistics and empirical values, the discharge volume of a single ship is randomly generated by a uniform distribution within a given range, as shown in Table 2. Some of the catches on shore are directly transported by truck to the cold storage outside the port area for storage, and some are transported to the cold storage in the harbour for transfer or processing.

5.1.2. Cost parameters

According to the investigation on the offshore fishing base and the general setting of a real cold-chain seaport, the daily average operating costs of 10,000 dead weight tonnage (DWT) berths and 5000 DWT berths are 21,200 and 15,500 yuan, respectively; the unloading cost of a single tonne of cargo at the berth is 20 yuan/t; and the ratios of the waiting expenses of various ship types and the extra loss of cargo due to low refrigeration efficiency on such ships and the backlog loss of ordinary cargo are shown in Table 3. The length of the planned shoreline shall not exceed 350 m and the time horizon is more than 1 year because of obvious seasonal fluctuations and annual periodicity. Other main parameters, including cold storage handling technology and operation parameters, are shown...
Table 2. Information about reefer ships.

| DWT (t) | Average discharge (t) | Number of gantry cranes equipped | Waiting expenses (10,000 yuan/ship/day) | Relative cost apportioned per tonne | Additional loss ratio |
|---------|-----------------------|----------------------------------|----------------------------------------|-------------------------------------|----------------------|
| > 5000  | 6500                  | 1                                | 5.2                                    | 0.48                                | 0.1                  |
| 5000    | 2800                  | 1                                | 3                                      | 0.64                                |                      |
| 2000    | 1200                  | 1                                | 2                                      | 1                                   |                      |

Note: DWT = dead weight tonnage.

in Table 3. Most of the parameters with average values are subject to an exponential distribution or Poisson distribution.

Based on the theory of uncertainty and the uncertainty analysis of cold-chain systems in the offshore fishery base, the operation simulation model is used to simulate the random arrival of refrigerated ships and the process of truck loading and unloading. The Monte Carlo sequences of waiting for berthing, auxiliary operation, and loading and unloading of refrigerated ships are obtained as the basic input of the stochastic planning model of the terminal scale.

5.2. Analysis of the optimization results of terminal scale

To verify the effectiveness of the simulation optimization algorithm based on tabu search, the constraints on the coastline length range are now extended to 800 m, and solutions are found through stochastic programming and deterministic programming, to compare the advantages and disadvantages of the two methods. The optimal berth allocation schemes obtained by stochastic planning and deterministic planning based on simulation are listed. Assuming that uncertain freight demand can be foreseen and corresponding decisions made, the solution in the determined freight scenario is called the deterministic scene (DS). Similarly, a solution in an uncertain freight scenario is called the stochastic scene (SS), and it is the simulation optimization method proposed in this study. The results in Table 4 show that under the same total freight demand conditions, it is more reasonable to optimize the terminal scale using stochastic planning, and its total cost is significantly lower than the
Table 3. Main input data of the proposed optimization for the size and scale of the berth.

| Parameter                              | Unit | Data              |
|----------------------------------------|------|-------------------|
| Simulation time                        | h    | $3 \times 365 \times 24$ |
| Terminal throughput                    | t    | See Figure 4      |
| Layout of port and cold storage        |      |                   |
| Maximum length of berth shoreline      | m    | 320               |
| Lower limit of berth utilization       | %    | 0.35              |
| Access road and road width             | m    | 20                |
| Number of truck loading and unloading positions in port cold storage | |
| Port and cold storage operation        |      |                   |
| Average berthing time of refrigerated ship | h    | 0.75             |
| Average departure time of refrigerated ship | h    | 0.35             |
| Time required for single gantry crane to unload unit cargo | h | 0.1 |
| Time required for truck to travel unit distance | h | 1/30 |
| Time required for truck to unload unit load | h | 0.1 |
| Average pretreatment and inspection time of a single tonne of cargo | h | 1/60 |
| Time required for unit distance of horizontal transportation | h | 1/15 |
| Average storage life of goods           | d    | 30                |
| Proportion of direct shipment of goods |      | 0.2; 0.5; 0.3     |

Table 4. Comparative analysis of stochastic and deterministic solutions.

| Freight demand scenario | Optimal berth allocation schemes | Total cost (10,000 yuan/month) |
|-------------------------|---------------------------------|--------------------------------|
|                         | 10,000 t berth | 5000 t berth |                                  |
| SS                      | 4               | 0             | 279.4                            |
| DS (−30%)               | 4               | 0             | 271.6                            |
| DS (−15%)               | 4               | 1             | 323.9                            |
| DS (0)                  | 3               | 2             | 305.8                            |
| DS (15%)                | 3               | 2             | 309.1                            |
| DS (30%)                | 3               | 2             | 313.7                            |

Note: SS = stochastic scene; DS = deterministic scene.

3.058 million yuan/month obtained by determined planning, which is the same as the optimal berth allocation scheme of the determined scenario (−30%). Thus, the superiority of this solution with the tabu search algorithm is shown, even though there is no significant difference in the computation time between DS and SS. Therefore, the superiority of the stochastic programming model is that it can generate an optimal solution with lower cost, even though it takes longer to compute and run to obtain the final results.

Based on main parameters of the examples of cold-chain terminals and sequence sets of the pelagic fishery production supply fluctuations, the calculation result is: one 10,000 t berth. The corresponding port construction and operation costs are 864,000 yuan/month.

The results were considered for the case where the overstocking cost of the catch for a berth is the same as the overstocking cost of general cargo when the reeler is waiting. However, the backlog costs of frozen and chilled goods may be higher than those of ordinary goods while they are waiting at the port, compared with the losses caused to shipowners by the backlog of ordinary goods. Therefore, the sensitivity analysis of the model should be carried out for the extra part of the overstocking loss caused by the low refrigeration efficiency of the cargo when the ship is waiting for a berth, which exceeds the backlog loss caused by the ordinary cargo when the ship is waiting for a berth. In addition to the property and added value of the goods, the overstocking cost is directly related to the waiting time of the refrigerated ship. Thus, under the constraints of the planned shoreline length, the characteristics of berth waiting times for refrigerated ships under various berth allocation scenarios were analysed.
5.3. Analysis of influence of terminal scale on waiting time of refrigerated ship

As noted in the analysis of factors influencing the scale of the terminal, the waiting time has a significant impact on the results. In the case where the planned shoreline length range is known, the simulation results of time spent waiting to berth for refrigerated ships with limited berths within this range are compared. For convenience, three berth combinations are numbered: berth combination I (C1) is for one 10,000 t berth, berth combination II (C2) is for one 10,000 t berth and one 5000 t berth, and berth combination III (C3) is for two 10,000 t berths.

The algorithm in Section 4.2 is used to solve the optimization model with uncertainties, and the time series of refrigerated ships waiting for berthing in the scenario of a limited number of berth combinations is obtained. After arranging them in descending order according to the berthing duration, the statistical results shown in Figure 5 are obtained. In scenarios I, II and III, the average waiting time of the refrigerated vessel arriving at the port is 751.8, 393.5 and 89.4 min, respectively, and the average waiting time of a single tonne of cargo arriving at the port is 768.8, 437.5 and 84.1 min, respectively (Table 5).

From the perspective of the service level of a port cold-chain system, the following results can be drawn:

(1) In the cold-chain production and operation system of ports, the level and quantity of berths will have a significant impact on the waiting time for refrigerated ships. For example, both berth scenario III and scenario I have a tonnage of 10,000, but these combinations are equipped with two berths and one berth, respectively. The model operation results show that the average waiting time for refrigerated ships is significantly reduced, being more than eight times greater in scenario I than in scenario III. Comparing berth combinations III and II, the number of berths is two in both scenarios, but there are differences in berth level.
(2) There is little difference between the average waiting time of the refrigerated vessel and the average waiting time for loading and unloading of a single tonne of goods. By comparing berth combinations I, II and III, it can be seen that the difference in average waiting time for refrigerated ships and the average waiting time of a single tonne of cargo is 2%, 11% and 5%, respectively.

5.4. Sensitivity analysis of extra loss ratio

It is difficult to estimate fluctuations in the refrigeration efficiency of refrigerating equipment when the refrigerating vessel is waiting for berthing, and the quality loss of the catch may differ significantly. Compared with the loss caused by the overstocking of ordinary goods, the overstocking cost of frozen and chilled goods at the port is usually higher than that of ordinary goods. Therefore, sensitivity analysis should be carried out on the comparison model between the excess loss caused by low refrigeration efficiency and the backlog loss caused by ordinary cargo waiting to berth, to explore the extent of its influence on the solution result of the model. Monthly berthing charges and monthly total charges under different scenarios were calculated, and sensitivity analysis was conducted, as shown in Figure 6.

The results show that, as the average waiting time of scenario III is relatively short, it has little impact on the cost generated by the backlog of goods in the port. When the extra loss ratio is greater than 4, the optimal berth allocation scheme is changed from berth combination I to berth combination III, as shown in Table 6. It can be seen that the overstocking loss due to the cargo carried by the refrigerated transport vessel when the vessel is waiting to berth (which refers mainly to the quality

Table 6. Main results of the proposed optimization for different additional loss ratio.

| $1 + \alpha_d$% | 1 | 2 | 3 | 5 | 10 |
|-----------------|---|---|---|---|----|
| Optimization results | I | I | I | III | III |
| Monthly total charges (10,000 yuan) | 86.4 | 105.8 | 125.2 | 142.6 | 154.6 |

Figure 6. Average monthly cost statistics. Scene = scenario.
loss caused by the change in environmental temperature of the cargo and the duration of the refrigerated vessel waiting to berth) has an impact on the berth allocation of the cold chain of the port which cannot be ignored.

6. Conclusion and implications

The results of this study show that, within a certain range, regardless of the cost factor, the improvement in berth quantity and level is conducive to ensuring the efficient and smooth sea and land refitting of cold-chain cargo. The model goal is to achieve the shortest average waiting and unloading time per unit weight of goods. Therefore, within a certain range, the average waiting and unloading times of refrigerated ships can be substituted for the average waiting and loading time of goods per unit weight to optimize the allocation of terminal berth resources.

The backlog costs of frozen and chilled goods may be higher than those of ordinary goods while they are waiting at the port, compared with the losses caused to shippers by the backlog of ordinary goods. Sensitivity analysis of the extra loss ratio shows that compared with conventional industrial port area planning, the scale of the cold-chain terminal is not only determined by the annual amount of cargo handling, but also related to the seasonal fluctuation and the nature of cargo itself. Therefore, when planning a special cold-chain terminal, it is necessary to investigate and analyse the arrival rules, attributes and storage requirements of the main cargo types, and determine the appropriate terminal size and passing capacity using a scientific optimization model.

This model provides suggestions and methods for the scientific planning of the scale of cold-chain facilities and for improving the efficiency of cold-chain systems in the sea–land exchange node. It focuses on the analysis of the composition and characteristics of the port cold-chain system, in contrast to traditional terminals in a port, and puts forward an optimization method for cold-chain infrastructure scale under uncertain conditions. It provides a theoretical basis for the planning of the port cold-chain system, facility construction, and coastal port planning adjustment and function expansion; and it also solves the problem of how to scientifically control the construction costs on the port side and the transport costs of the carrier from a fresh perspective.

The stochastic programming model is limited to the original layout of the terminal, for which it is capable of producing definite results. The influences of port planning and initial layout on the optimization results cannot be ignored. In addition, because the simulation model is embedded in the algorithm, the whole solution process is time consuming, but it would be of great help to engineering cost control and in saving resources. In the future, the influence of wharf type on the model should be considered to optimize the compatibility between the simulation model and the mathematical model to improve the efficiency of the solutions.

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