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A Location Inventory Routing Optimisation Model and Algorithm for a Remote Island Shipping Network considering Emergency Inventory

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Abstract: This paper studies a hub-and-spoke shipping network of remote islands and integrates a maritime location inventory routing problem for a remote island shipping network considering emergency inventory. By determining a series of decisions, including the location of the hub islands, number of shipping routes, schedule of every route, travelling mode of every route, ship size, wharf scale, and inventory capacity, the objective of this study is to minimise the total cost of the remote island shipping network over the operating period. Subsequently, a mixed-integer programming model to minimise the total cost of the system is developed. To solve the model, we present a genetic algorithm based on a stepwise configuration module (SC-GA). Finally, instances are proposed to evaluate the performance of the algorithm. The results of the instance calculation show that the algorithm has good applicability and effectiveness in solving the problem in this paper. Through algorithm comparison, it is found that the performance of SC-GA is better than the algorithms in the relevant literature. This paper provides practical information for the design, optimisation and sustainability of remote island shipping networks considering emergency inventory.

Keywords: remote islands shipping network; sustainability; location; inventory; routing; optimization; emergency inventory

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1. Introduction

Generally, remote islands are groups of islands that are far from the mainland and rely on the mainland for a continuous supply of basic living materials to maintain the long-term residence of residents. This includes, for example, the Da Cunha Islands, the Svalbard Islands, the Kerguelen Islands, the islands in the South China Sea, and the Ogasawara Islands. In reality, the materials transported in such remote islands' shipping networks are primarily basic living materials (mainly including fresh water, food and fuel). Moreover, the number of residents on these remote islands is small and stable, which makes their demand for basic living materials small and stable. At the same time, transport in the remote islands' shipping networks is often disrupted by tropical cyclones. In view of the above situation, in order to ensure the sustainable supply of remote islands, we study the design of a remote island shipping network considering emergency inventory. In such a network, we mainly consider the basic living materials and assume that the demand is deterministic. Additionally, an emergency inventory is maintained on each island to resist the impact of transport disruptions. Cargo is generally transported by sea from the mainland to the hub islands of each archipelago and then from the hub islands to the surrounding islands by sea. Transport ships may have various sizes, such as 100, 500, or 1000 t, or even larger. Routes include the back-and-forth mode (ships load at one hub island and then transport to another island to unload the entire cargo) and cycle mode (ships load at one hub island and then transport to multiple islands in succession to unload the cargo separately). As a result, there is a strong correlation between the location of the hub islands in the remote island shipping network, the number of shipping routes, schedule of every route, travelling mode of every route, size of the ships, wharf scale, and inventory capacity, which must be optimised in an integrated manner. Thus, the question addressed in this article can be considered as the problem of designing a maritime transport network with a single product, deterministic demand, multi-size carrier, and multi-travelling mode. From the above analysis, it can be seen that the research of this article has application value and practical significance in the design of remote islands' shipping networks and the guarantee of continuous supply to remote islands.

The research on the design of remote islands' shipping networks is limited, but the optimisation of maritime transport networks has been extensively studied [1,2]. For example, Santini et al. [3] investigated the problem of designing feeder networks for container liner shipping and observed that the branch-and-price algorithm could solve most instances generated by LinerLib software in less than one hour. Cariou et al. [4] comprehensively considered the selection of visiting ports, order of visiting ports, the volume of cargo between ports, and the number of ships in the route in the liner network design; a mixed-integer linear programming model was developed, and a heuristic algorithm based on a genetic algorithm was designed to solve the problem. Wang et al. [5] developed a mixed-integer linear programming model for container route optimisation for profit maximisation, and it was solved using the branch-and-cut algorithm. Zhen et al. [6] and Wang et al. [7] extended previous research by comprehensively considering sulfur emissions as a limiting factor and investigating operational-level optimisation problems such as ship deployment, speed, schedule, and capacity allocation; they used a three-phase heuristic to solve this problem. Da Costa Fontes and Goncalves [8] proposed a hub-and-spoke network structure with a sub-hub and attempted to apply this network structure in maritime network design. Rahmawan and Angelina [9] developed an all-levels decision-making model for fleet design, ship scheduling, and cargo routing combination problems. The above literature reveals important considerations to focus on for the maritime network design problem and suggests effective solutions which have significant reference value. However, the remote islands' shipping networks are a relatively closed system with a proprietary fleet generally travelling only within the system; therefore, there is a strong correlation between shipping routes, ship size, wharf scale, transport schedule, and warehouse capacities, which significantly differs from the general maritime network design.

This analysis clearly indicates that the design of a remote islands shipping network includes both location, inventory and routing aspects; therefore, the problem in this paper is the maritime location inventory routing problem (MLIRP). Currently, there are few studies on MLIRP, but there are papers that have studied the maritime inventory routing problem (MIRP) and location inventory routing problem (LIRP), and they are summarized in Table 1. In MIRP research, the MIRP and related applications have been adequately surveyed by Papageorgiou et al. [10]. Agra et al. [11] also provided a comprehensive presentation of models. Friske and Buriol [12] modelled the MIRP with a fixed charge network flow and used the relax-and-fix algorithm to solve the MIRP of a single product. Papageorgiou et al. [13] studied deterministic MIRPs with long planning periods and solved them using approximate dynamic programming methods. Rodrigues et al. [14] and Agra et al. [15] studied the MIRP problem by considering stochastic factors such as weather conditions and port waiting times, and they divided the decision into two stages: deciding on the shipping routes and deciding on the visit time and inventory levels at ports. Rusdianto et al. [16] developed a mixed-integer planning model for the MIRP problem of cement transport to minimise transport costs. Dauzere-Peres et al. [17], Christiansen et al. [18] and Yang et al. [19] studied the MIRP using genetic algorithms. Moin et al. [20] solved an IRP with a finite horizon, multiple periods, multiple suppliers, and multiple products using a hybrid genetic algorithm. Papageorgiou et al. [21] performed computational experiments for MIRPLib instances using rolling horizon heuristics, K-opt heuristics, local branching, solution polishing, and hybrids thereof, and they observed that these heuristics outperformed those of CPLEX 12.6.2 and Gurobi 6.5. Friske et al. [22] studied the use of Relax-and-Fix and Fix-and-Optimize matheuristics for solving a specific maritime inventory routing problem. Eide et al. [23] investigated the maritime inventory routing problem taking into account the speed and load of the ship and developed a corresponding new non-linear model. Liu et al. [24] proposed a two-stage distributionally robust optimization (DRO) method to solve the uncertainty of sailing times and port waiting times in the maritime inventory routing problem. Sanghikian et al. [25] designed a hybrid VNS metaheuristic to tackle a real maritime inventory routing problem (MIRP) in a company that explores oil and gas in the Brazilian offshore basin. Misra et al. [26] developed a mixed-integer linear programming framework for a maritime inventory routing problem, which involves multiple refinery liquid products that need to be transported from multiple supply ports to associated consumer ports using ships with undedicated compartments. In addition, Engineer et al. [27], Hewitt et al. [28] and Rakke et al. [29] used the branch-price-and-cut algorithm to solve the MIRP. Song and Furman [30] introduced a flexible modelling framework for MIRP that can be adapted to various practical functions. In LIRP research, Hiassat et al. [31] designed a genetic algorithm to solve the location inventory routing problem of perishable products. Saif-Eddine et al. [32] used an improved genetic algorithm to optimise the total cost of the supply chain in the location inventory routing problem. Kechmane et al. [33] proposed a genetic algorithm combined with local search to solve a multiperiod location lot-sizing routing problem with deterministic demand in a two-echelon network composed of a single factory, a set of potential depots, and a set of customers. Kaya and Ozkok [34] developed a mixed-integer non-linear programming model for the LIRP of a blood distribution network design and solved it using a simulated annealing algorithm. Saragih et al. [35] designed a simulated annealing algorithm for the location inventory routing problem in a three-echelon supply chain system and applied it to a food supply chain system in Jakarta. Guo et al. [36] developed an adaptive genetic algorithm integrating simulated annealing for solving the location inventory routing problem in a closed-loop supply chain. Liu et al. [37] established a location inventory routing optimisation model for a three-stage supply chain distribution system and proposed a pseudo-parallel genetic algorithm integrating simulated annealing to solve it. The literature mentioned above provides an in-depth study of the MIRP and LIRP problems, which has a significant reference value in terms of model construction and algorithm design. However, as can be seen from Table 1, most relevant studies have taken multi-size carriers and transport schedules into consideration, while a few have taken one factor of emergency inventory and multi-travelling mode into consideration. At the same time, there is no paper that has studied the maritime location inventory routing problem considering emergency inventory, multi-size carrier and multi-travelling mode simultaneously.

In reality, the remote island shipping network studied in this paper differs significantly from the general MIRP and LIRP problem, primarily in the following aspects: ① there are multiple travelling modes. In a general MIRP and LIRP, only one type of travelling mode is often considered. However, in remote islands' shipping networks, in addition to routes with full loads and split-delivery (cycle transport routes), some routes may involve a full load and a full discharge between the hub island and several neighbouring islands (back-and-forth transport routes) using smaller ships to reduce ship acquisition costs. ② Ship size varies widely. The capacity of different ships in a remote island shipping network may vary by several times or even tens of times, and the choice of ship size for any particular route will have a direct impact on the upper limit of traffic on that route and hence on the number of islands visited, amount of supply, and supply cycle, which is significantly different from the general LIRP problem. ③ Restrictions exist in the loading and unloading operations. In remote islands' shipping networks, ships of a certain size can only be loaded and unloaded at the wharf corresponding to them, and if larger ships are selected, wharfs must be built to match them. For the general MIRP and LIRP problem, the requirements of the yard station do not vary significantly from one vehicle type to another. ④ Emergency inventory must be considered in the inventory. Sustainability has become a popular concept in the logistics industry [38]. A sustainable supply chain is important, and any disruption in the supply chain could affect the entire logistics network [39,40]. While the general MIRP and LIRP problem frequently does not consider transportation disruptions, the remote island shipping network may cause transportation disruptions owing to external disturbances such as typhoons; therefore, emergency inventory must be set in the inventory of each island, increasing the complexity of the problem. Based on this analysis, we observe that the remote island shipping network studied in this paper differs significantly from the general MIRP and LIRP problem, and the models and algorithms proposed in the abovementioned literature are not fully applicable to the problem in this paper.

Table 1. Comparisons of the research of MIRP and LIRP.

Literature	Location	Inventory	Routing	Emergency Inventory	Multi-Size Carrier	Multi-Travelling Mode	Transport Schedule
Papageorgiou et al. (2014) [10] Agra et al. (2013) [11] Friske and Buriol (2018) [12] Papageorgiou et al. (2015) [13] Rusdianto et al. (2020) [16] Yang et al. (2020) [19] Hewitt et al. (2013) [28] Song and Furman (2013) [30] Friske et al. (2022) [22] Sanghikian et al. (2021) [25] Eide et al. (2020) [23] Liu et al. (2021) [24]		√	√		√		√
Rodrigues et al. (2019) [14] Dauzere-Peres et al. (2007) [17] Christiansen et al. (2011) [18] Engineer et al. (2012) [27]		√	√	√	√		√
Agra et al. (2015) [15] Papageorgiou et al. (2018) [21]		√	√		√	√	√
Moin et al. (2011) [20]		√	√				√
Rakke et al. (2015) [29]		√	√		√		√
Misra et al. (2020) [26]		√	√	√	√		√
Hiassat et al. (2017) [31] Kechmane et al. (2018) [33] Kaya and Ozkok (2020) [34]	√	√	√				√
Saif-Eddine et al. (2019) [32]	√	√	√		√		√
Saragih et al. (2019) [35]	√	√	√			√	√
Guo et al. (2018) [36] Liu et al. (2015) [37]	√	√	√	√			√
This paper	√	√	√	√	√	√	√

Based on the above analysis, this paper studies the remote island shipping network as the research object and considers problems such as hub island location, route setting (selecting the islands to be visited, sequence of island visits, mode of travelling, ship size, wharf scale), and inventory planning (supply cycle, storage capacity of warehouses, emergency inventory). A mixed-integer planning model and a genetic algorithm based on a stepwise configuration module (SC-GA) are developed, and the method is evaluated using computational experiments. The main contributions of this article include: ① in terms of application, based on the material demand characteristics of remote islands, this article comprehensively considers the factors such as emergency inventory to resist the risk of transport disruptions, multi-size carrier and multi-traveling mode, and establishes the location inventory routing optimisation model and algorithm of the remote island shipping network, which can provide a reference for the design of remote islands' (such as the Da Cunha Islands, the Svalbard Islands, the Kerguelen Islands, the islands in the South China Sea, and the Ogasawara Islands) shipping networks. ② In terms of methodology, by comparing the performance of the SC-GA algorithm with other algorithms in the related research of LIRP, it is found that the algorithm in this article is better. Therefore, the algorithm in this article can provide a reference for the design of algorithms for LIRP considering emergency inventory, multi-size carriers, and multi-travelling modes.

The remainder of this paper is organised as follows. In Section 2, a mixed-integer programming model is developed for the problems in this study. Section 3 presents a GA based on a stepwise configuration module to optimise the problem. Section 4 describes the computational experiments used to evaluate the performance of the methodology of this study. Section 5 presents the conclusions. Section 6 presents the difficulties and solutions encountered in this article and provides insights for future research topics.

2. Mathematical Model

2.1. Problem Description

A remote island shipping network frequently consists of the mainland, hub islands, and satellite islands (Figure 1). The hub island is similar to the 'depot' in the classical vehicle routing problem, which is the location at which all ships start and end their routes. In the network, the supplies are transported from the mainland to the hub island via the main network and then distributed from the hub island to its satellite islands via the branch network. In this type of remote island shipping network, the goods transported are primarily basic living materials, which we considered to be a single product with a defined demand. The transport ships in the network may be of multiple sizes, and any of the routes may be under back-and-forth or cycle travelling modes. Thus, the problem in this paper is a single-product, deterministic, finite-horizon, multi-size carrier, multi-travelling mode, full-load and split-delivery problem. This paper seeks to minimize the total cost over the operating period under the precondition of an uninterrupted supply while taking into account the location of hub islands, the number of shipping routes in the main and branch networks, the travelling mode of every route, and ship size and schedule of every route, wharf scale, inventory capacity, emergency inventory and cycle supply of every island. For instance, if we use a large ship on a route and attempt to load it fully, the schedule may be prolonged and the shipping cost reduced, but the wharf and warehouse construction costs will increase, increasing the total cost. Hence, we develop a mixed-integer programming model to optimise a remote island logistics network as a whole. In addition, the approach in this paper is built for a general scenario and can be used to optimise remote island shipping networks with multiple archipelagos.

2.2. Notations

The notations used in this paper are listed as follows, unless otherwise specified (Table 2). Note that the ships in this paper have capacity differences, and we use s to represent ships of different capacities; for example, s may equal 100, 500, 1000 t, etc., while S denotes the set of ships of different capacities, $s \in S$. For ships of different capacities, there are differences in ship purchase, maintenance, shipping costs, and construction costs of the corresponding wharfs, and we assume that the sailing speed of all ships is w.

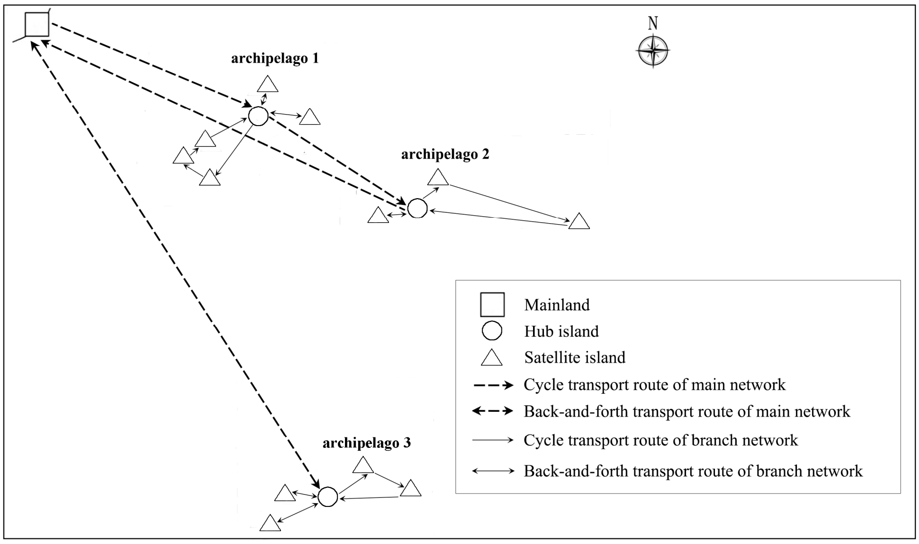

Figure 1. Schematic diagram of the remote island logistics network.

Table 2. List of notations.

Acronyms	
BFRG	Back-and-forth routing group
CR	Cycle routing
inv	Inventory
wc	Warehouse construction
Sets	
K	A set of archipelagos (i.e., islands groups), $k \in K$
P^k	A set of islands in archipelago k, $p^k \in P^k$
S	A set of alternative ship size, $s \in S$.
M	A set of BFRG in the branch network, $m \in M$
N	A set of CR in the branch network, $n \in N$
U	A set of BFRG in the main network, $u \in U$
V	A set of CR in the main network, $v \in V$
Parameters	
o	The mainland port
Z	The number of the archipelago
g^k	The number of islands in the archipelago k.
C_{BFRG}, C_{CR}	The total shipping costs of the BFRG and the CR in the branch network, respectively
C_{MBFRG}, C_{MCR}	The total shipping costs of the BFRG and CR in the main network, respectively MBFRG means the back-and-forth routing group in the main network; MCR means the cycle routing in the main network
C_{ship}	The ship usage cost
C_{wharf}	The wharf construction cost
C_{inv}, C_{wc}	The inventory cost and warehouse construction cost, respectively
$l_{i,j}$	The distance between island i and island j
w	Sailing speed of a ship
t_{all}	The total time of system operation (days)

Table 2. *Cont.*

Discrete decision variables	
h^k	The hub island in archipelago k, where $h^k = \sum_{p^k \in P^k} a_{p^k}^{\text{hub}} p^k$, e.g., if island $3^{\#}$ is the hub island of archipelago k, then $h^k = 3^{\#}$.
e_n	The number of islands visited by the CR n in the branch network, e.g., if the CR 3 in the branch network is $2^{\#} \to 3^{\#} \to 7^{\#} \to 1^{\#} \to 2^{\#}$, then $e_3 = 5$.
f_v	The number of islands visited by CR v in the main network.
d_x^n	The xth island of CR n in the branch network, e.g., if CR 3 in the branch network is $2^{\#} \to 3^{\#} \to 7^{\#} \to 1^{\#} \to 2^{\#}$, then $d_2^3 = 3^{\#}$
r_y^v	The yth island of CR v in the main network, e.g., if CR 2 in the main network is $o \to 2^{\#} \to 15^{\#} \to 22^{\#} \to o$, then $r_1^2 = 2^{\#}$.
Continuous decision variables	
$t_m,\ t_n$	The shipping schedule of the BFRG m and the CR n in the branch network, respectively
$t_u,\ t_v$	The shipping schedule of the BFRG u and the CR v in the main network, respectively
τ	Any moment in a transport schedule
Binary decision variables	
$a_{p^k}^{\text{hub}}$	If island p^k is the hub island of an archipelago, $a_{p^k}^{\text{hub}} = 1$; otherwise, $a_{p^k}^{\text{hub}} = 0$
$a_{p^k}^m$	If BFRG m in the branch network transports for island p^k, $a_{p^k}^m = 1$; otherwise, $a_{p^k}^m = 0$
$a_{p^k}^n$	If CR n in the branch network transports for island p^k, $a_{p^k}^n = 1$; otherwise, $a_{p^k}^n = 0$
$a_{h^k}^u$	If the hub island h^k of the archipelago k is transported by the main network in the back − and − forth route group u, $a_{h^k}^u = 1$; otherwise, $a_{h^k}^u = 0$
$a_{h^k}^v$	If the hub island h^k of the archipelago k is transported by the main network in the cycle route, v, $a_{h^k}^v = 1$; otherwise, $a_{h^k}^v = 0$
b_s^m	If the ship size of BFRG m , $b_s^m = 1$; otherwise, $b_s^m = 0$
b_s^n	If the ship size of CR n is s, $b_s^n = 1$; otherwise, $b_s^n = 0$
b_s^u	If the ship size of BFRG u , $b_s^u = 1$; otherwise, $b_s^u = 0$
b_s^v	If the ship size of CR v , $b_s^v = 1$; otherwise, $b_s^v = 0$
b_s^k	If ship type s occurs in the branch network of archipelago k, $b_s^k = 1$; otherwise, $b_s^k = 0$

2.3. Model Formulation

In this study, we develop a cost optimization model that takes into account emergency inventory with the basic objective of a continuous supply of living materials over an operating period. While most papers on the MIRP [13–16] primarily consider transport costs as minimal, this paper considers wharf construction, ship usage, inventory, and warehouse construction costs in addition to transport costs.

2.3.1. Shipping Cost Model

This paper divides the travelling mode of the route into two types: back-and-forth routing (BFR), which transports between a hub island and a satellite island, and cycle routing (CR), which transports between a hub island and several satellite islands. Because one ship may serve two or more BFRs, we define the scenario as a back-and-forth routing group (BFRG). For example, three routes between a hub island and satellite islands $1^{\#}$, $5^{\#}$, and $4^{\#}$ are served by one ship; thus, the three routes are a BFRG. In terms of calculating the shipping cost, this paper uses the distance between islands multiplied by the unit freight rate of the ship to calculate the shipping cost [8]. The unit freight rate varies between ship types [16,41]. Thus, the shipping cost model can be stated as follows:

$$C_{\text{BFRG}} = \sum_{k \in K} \sum_{p^k \in P^k} \sum_{m \in M} \sum_{s \in S} 2 l_{h^k, p^k} a_{p^k}^m b_s^m c_s^{\text{tr}} \frac{t_{\text{all}}}{t_m} \tag{1}$$

$$C_{\text{CR}} = \sum_{n \in N} \sum_{x=1}^{e_n - 1} \sum_{s \in S} l_{d_x^n, d_{x+1}^n} b_s^n c_s^{\text{tr}} \frac{t_{\text{all}}}{t_n} \tag{2}$$

$$C_{\text{MBFRG}} = \sum_{k \in K} \sum_{u \in U} \sum_{s \in S} 2 l_{o, h^k} a_{h^k}^u b_s^u c_s^{\text{tr}} \frac{t_{\text{all}}}{t_u} \tag{3}$$

$$C_{\text{MCR}} = \sum_{v \in V} \sum_{y=1}^{f_v - 1} \sum_{s \in S} l_{r_y^v, r_{y+1}^v} b_s^v c_s^{\text{tr}} \frac{t_{\text{all}}}{t_v} \tag{4}$$

where c_s^{tr} is the shipping cost per nautical mile of the s-type ship. Equations (1) and (2) are the sum of the shipping costs of all the BFRGs and CRs in the branch network during the total operation time. Equations (3) and (4) are the sum of the shipping costs of all the BFRGs and CRs in the main network during the total operation time.

Thus, the ship usage cost can be stated as follows:

$$\begin{aligned} C_{\text{ship}} = & \sum_{m \in M} \sum_{s \in S} b_s^m c_s^{\text{pur}} + \sum_{n \in N} \sum_{s \in S} b_s^n c_s^{\text{pur}} + \sum_{u \in U} \sum_{s \in S} b_s^u c_s^{\text{pur}} + \sum_{v \in V} \sum_{s \in S} b_s^v c_s^{\text{pur}} \\ & + \left(\sum_{m \in M} \sum_{s \in S} b_s^m c_s^{\text{mai}} + \sum_{n \in N} \sum_{s \in S} b_s^n c_s^{\text{mai}} + \sum_{u \in U} \sum_{s \in S} b_s^u c_s^{\text{mai}} + \sum_{v \in V} \sum_{s \in S} b_s^v c_s^{\text{mai}} \right) \cdot t_{\text{all}} \end{aligned} \tag{5}$$

where c_s^{pur} and c_s^{mai} are the purchase and daily maintenance costs of the s-type ship, respectively. Equation (5) is the sum of the ship purchase and maintenance costs during the total operation time of all the BFRGs and CRs in the branch and main networks.

2.3.2. Wharf Construction Cost Model

The wharf construction cost model can be stated as follows:

$$\begin{aligned} C_{\text{wharf}} = & \sum_{k \in K} \sum_{p^k \in P^k} \sum_{m \in M} \sum_{s \in S} a_{p^k}^m b_s^m c_s^{\text{wharf}} + \sum_{n \in N} \sum_{s \in S} (e_n - 2) b_s^n c_s^{\text{wharf}} \\ & + \sum_{k \in K} \sum_{u \in U} \sum_{s \in S} a_{h^k}^u b_s^u c_s^{\text{wharf}} + \sum_{k \in K} \sum_{v \in V} \sum_{s \in S} a_{h^k}^v b_s^v c_s^{\text{wharf}} + \sum_{k \in K} \sum_{s \in S} b_s^k c_s^{\text{wharf}} \end{aligned} \tag{6}$$

where c_s^{wharf} is the construction cost of a wharf at which the s-type ship can berth. In Equation (6), the first and second items are the sums of the wharf construction costs of all the satellite islands visited by BFRGs and CRs in the branch network; the third and fourth items are the sums of the wharf construction costs of all hub islands visited by BFRGs and CRs in the main network, and the fifth item is the sum of the construction costs of all hub island wharfs corresponding to ship size appearing in the branch network of every island.

2.3.3. Inventory Cost Model

In the remote island shipping network, all shipping is disrupted when a tropical cyclone comes; therefore, the daily consumption of each island will be supplied by its inventory until the tropical cyclone is over. Thus, similar to the stock buffer (safety stock) set up by [14] to prevent stock shortages in the event of delays, the emergency inventory (Q_{risk}) is proposed to resist the risk of disruption of shipping logistics due to tropical cyclones, and it can be expressed as:

$$Q_{\text{risk}} = \Delta t \cdot q \tag{7}$$

where Δt is the number of days that the emergency inventory of every island can supply its daily consumption, and q is the average daily consumption.

In this paper, we make the following assumptions. (1) The daily consumption of each island is continuous and deterministic (because the goods transported by the remote island shipping network in this paper are primarily basic living materials and the population and living space within the archipelago is relatively stable [12]). (2) The transport speed is the same for all vessels.

(3) The inventory time is at the beginning of each period, and Q_{sup} denotes the supply. Therefore, the inventory state function is as follows: $I(\tau) = Q_{\mathrm{all}} - q\tau, \tau \in [0,t]$, where Q_{all} denotes the inventory capacity, and t is the shipping schedule of the route (supply cycle of the island). The supply should be replenished to Q_{all} when the inventory state $I(\tau) = Q_{\mathrm{all}} - qt$; therefore, $Q_{\mathrm{sup}} = qt$ and $Q_{\mathrm{all}} = Q_{\mathrm{sup}} + Q_{\mathrm{risk}}$. According to the inventory state (Figure 2), the supply in the period $[0,t]$ can be expressed as:

$$\int_0^t I(\tau)d\tau = \int_0^t (Q_{\mathrm{all}} - qt)d\tau = (Q_{\mathrm{sup}} + Q_{\mathrm{risk}})t - \frac{1}{2}qt^2 = \Delta tqt + \frac{1}{2}qt^2 \quad (8)$$

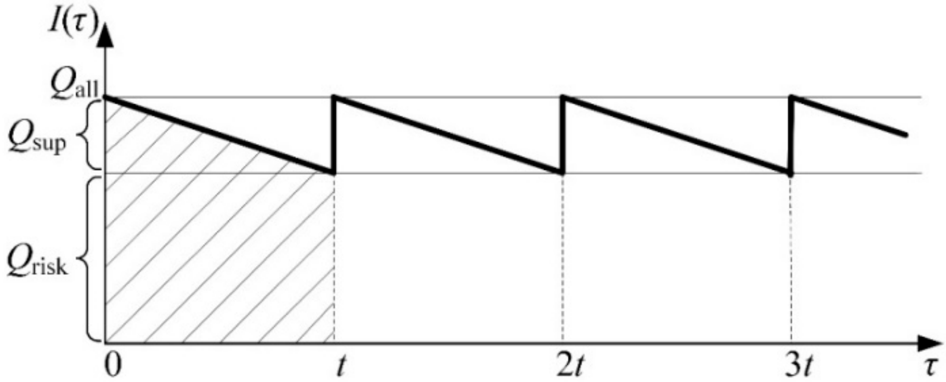

Figure 2. Inventory state.

According to Equation (8), q_{h^k} is the average daily consumption of the hub island k; q_{p^k} is the average daily consumption of the satellite island p^k visited by a BFR; and a_n^k is the binary decision variable such that if CR n of the branch network is travelling on an island k, $a_n^k = 1$. Then, the inventory cost model and warehouse construction cost model can be stated as follows:

$$\begin{aligned} C_{\mathrm{inv}} = & \sum_{k\in K}\sum_{p^k\in P^k}\sum_{m\in M} a_{p^k}^m\left(\tfrac{1}{2}q_{p^k}t_m^2 + \Delta t q_{p^k}t_m\right)\tfrac{t_{\mathrm{all}}}{t_m} + \sum_{n\in N}\sum_{x=2}^{e_n-1}\left(\tfrac{1}{2}q_{d_x^n}t_m^2 + \Delta t q_{d_x^n}t_m\right)\tfrac{t_{\mathrm{all}}}{t_n} \\ & + \sum_{k\in K}\sum_{u\in U} a_{h^k}^u\left[\frac{1}{2}\begin{pmatrix}\sum\limits_{p^k\in P^k}\sum\limits_{m\in M} a_{p^k}^m q_{p^k} \\ +\sum\limits_{n\in N}\sum\limits_{x=2}^{e_n-1} a_n^k q_{d_x^n} + q_{h^k}\end{pmatrix}t_u^2 + \Delta t q_{h^k}t_u\right]\frac{t_{\mathrm{all}}}{t_u} \\ & + \sum_{k\in K}\sum_{v\in V} a_{h^k}^v\left[\frac{1}{2}\begin{pmatrix}\sum\limits_{p^k\in P^k}\sum\limits_{m\in M} a_{p^k}^m q_{p^k} \\ +\sum\limits_{n\in N}\sum\limits_{x=2}^{e_n-1} a_n^k q_{d_x^n} + q_{h^k}\end{pmatrix}t_v^2 + \Delta t q_{h^k}t_v\right]\frac{t_{\mathrm{all}}}{t_v} \end{aligned} \quad (9)$$

$$C_{\mathrm{wc}} = \left\{\begin{array}{l} \sum\limits_{k\in K}\sum\limits_{p^k\in P^k}\sum\limits_{m\in M} a_{p^k}^m q_{p^k}(\Delta t + t_m) + \sum\limits_{n\in N}\sum\limits_{x=2}^{e_n-1} q_{d_x^n}(\Delta t + t_n) \\ + \sum\limits_{k\in K}\sum\limits_{u\in U} a_{h^k}^u\left[\begin{pmatrix}\sum\limits_{p^k\in P^k}\sum\limits_{m\in M} a_{p^k}^m q_{p^k} \\ +\sum\limits_{n\in N}\sum\limits_{x=2}^{e_n-1} a_n^k q_{d_x^n} + q_{h^k}\end{pmatrix}t_u + q_{h^k}\Delta t\right] \\ + \sum\limits_{k\in K}\sum\limits_{v\in V} a_{h^k}^v\left[\begin{pmatrix}\sum\limits_{p^k\in P^k}\sum\limits_{m\in M} a_{p^k}^m q_{p^k} \\ +\sum\limits_{n\in N}\sum\limits_{x=2}^{e_n-1} a_n^k q_{d_x^n} + q_{h^k}\end{pmatrix}t_v + q_{h^k}\Delta t\right] \end{array}\right\} C_{\mathrm{build}} \quad (10)$$

where Equation (9) is the sum of the inventory costs of all the islands visited by the BFRGs and CRs in the branch and main networks. Equation (10) is the sum of the warehouse construction costs of all islands visited by the BFRGs and CRs in the branch and main networks.

2.3.4. Formulation

The integrated model can be described using the following formulations:

$$\text{Minimise } C_{\mathrm{total}} = C_{\mathrm{BFRG}} + C_{\mathrm{CR}} + C_{\mathrm{MBFRG}} + C_{\mathrm{MCR}} + C_{\mathrm{ship}} + C_{\mathrm{wharf}} + C_{\mathrm{inv}} + C_{\mathrm{wc}} \quad (11)$$

$$\text{s.t.} \sum_{m \in M} a_{p^k}^m + \sum_{n \in N} a_{p^k}^n \leq 1, k \in K; p^k \in P^k \tag{12}$$

$$\sum_{p^k \in P^k} \left(\sum_{m \in M} a_{p^k}^m + \sum_{n \in N} a_{p^k}^n \right) = g^k - 1, k \in K \tag{13}$$

$$\sum_{u \in U} a_{h^k}^u + \sum_{v \in V} a_{h^k}^v \leq 1, k \in K \tag{14}$$

$$\sum_{k \in K} \left(\sum_{u \in U} a_{h^k}^u + \sum_{v \in V} a_{h^k}^v \right) = Z \tag{15}$$

$$a_{p^k}^m q_{p^k} t_m \leq \sum_{s \in S} b_s^m s, k \in K; p^k \in P^k; m \in M \tag{16}$$

$$\sum_{x=2}^{e_n - 1} q_{d_x^n} t_n \leq \sum_{s \in S} b_s^n s, n \in N \tag{17}$$

$$a_{h^k}^u \left(\sum_{p^k \in P^k} \sum_{m \in M} a_{p^k}^m q_{p^k} + \sum_{n \in N} \sum_{x=2}^{e_n - 1} a_n^k q_{d_x^n} + q_{h^k} \right) t_u \leq \sum_{s \in S} b_s^u s, k \in K; u \in U \tag{18}$$

$$\sum_{k \in K} a_{h^k}^v \left(\sum_{p^k \in P^k} \sum_{m \in M} a_{p^k}^m q_{p^k} + \sum_{n \in N} \sum_{x=2}^{e_n - 1} a_n^k q_{d_x^n} + q_{h^k} \right) t_v \leq \sum_{s \in S} b_s^v s, k \in K; v \in V \tag{19}$$

$$\sum_{p^k \in P^k} a_{p^k}^m + \frac{2 \sum_{p^k \in P^k} l_{h^k, p^k} a_{p^k}^m}{w} \leq t_m \leq \max \left\{ \frac{a_{p^k}^m \max\{s | s \in S\}}{q_{p^k}} | p^k \in P^k \right\}, k \in K; m \in M \tag{20}$$

$$\frac{(e_n - 1)}{2} + \frac{\sum_{x=2}^{e_n - 1} l_{d_x^n, d_{x+1}^n}}{w} \leq t_n \leq \frac{\max\{s | s \in S\}}{\sum_{x=2}^{e_n - 1} q_{d_x^n}}, n \in N \tag{21}$$

$$\sum_{k \in K} a_{h^k}^u + \frac{2 \sum_{k \in K} l_{o, h^k} a_{h^k}^u}{w} \leq t_u \leq \max \left\{ \frac{a_{h^k}^u \max\{s | s \in S\}}{q_{h^k}} | k \in K \right\}, u \in U \tag{22}$$

$$\frac{f_v - 1}{2} + \frac{\sum_{y=2}^{f_v - 1} l_{r_y^v, r_{y+1}^v}}{w} \leq t_v \leq \frac{\max\{s | s \in S\}}{\sum_{y=2}^{f_v - 1} q_{r_y^v}}, v \in V \tag{23}$$

The objective function, Equation (11), is the total logistics cost during the entire operation period. Constraints (12) and (13) indicate that the branch network has only one route from a hub island to each satellite island. Constraints (14) and (15) require that there is only one route in the main network (from the mainland to the hub island). Constraint (16) requires that the cycle supply of every satellite island transported by the BFR should not exceed the deadweight of the ship equipped with the BFRGs. Constraint (17) ensures that the total cycle supply of satellite islands transported by any CR in the branch network does not exceed the deadweight of the ship equipped with the CRs. Constraint (18) guarantees that the cycle supply of every hub island transported by the BFR does not exceed the deadweight of the ship equipped with the BFRGs. Constraint (19) requires that the total cycle supply of the hub islands transported by any CR in the main network should not exceed the deadweight of the ship equipped with the CR. Constraints (20) and (21) enforce the value range of the schedule of the BFRGs and CRs, respectively, in the branch network. Constraints (22) and (23) enforce the value range of the schedule of BFRGs and CRs, respectively, in the main network.

3. Algorithm

The location inventory routing problem of a remote island shipping network with a multi-size carrier and multi-travelling mode is an NP-hard problem. The genetic algorithm (GA) is suitable for solving NP-hard problems with high efficiency [42]. To solve this problem, we developed a genetic algorithm based on a stepwise configuration module (SC-GA). The stepwise configuration module is a calculation module for optimising the chromosome's corresponding travelling mode, schedule, ship type, size of each island wharf, cycle supply, and inventory capacity. Additionally, the SC-GA is a genetic algorithm embedded with the stepwise configuration module. The steps of the SC-GA are as follows: (1) based on the chromosome, obtain the location of each hub island, the number of routes of the main network, and the branch network, where islands are visited by each route and the sequence of islands. (2) Using the stepwise configuration module (SC module), stepwise optimise and configure the branch network and main network route parameters (ship size, schedule, cycle transport volume, and travelling mode of every route) and inventory parameters (cycle supply and inventory capacity), and then calculate the objective function of the chromosome. (3) Obtain the optimal solution of the model through iterations.

3.1. Chromosome Representation

To express the information on the location of each hub island, the number of routes of the main and branch networks in which islands are visited by each route, and the sequence of the islands, we design the chromosome for the main and branch networks using a large number of separators to fully express the entire solution space (under an extreme scenario, all routes are BFRs and visited by respective ships). In other words, a chromosome consists of the shipping network gene segment of transport from the mainland to hub islands (abbreviated as the hub island gene segment) and the shipping network gene segments of transport from the hub island to its satellite islands (each island gene segment), and we use $n-1$ (assuming a gene segment contains n islands) separators to divide the gene segment into n segments; therefore, the gene between two separators signifies the islands in one group. A possible chromosome is shown in Figure 3.

chromosome:	hub island gene segment:	10	14	0	2	0						
	archipelago 1 gene segment:	6	4	0	0	1	7	3	0	0	0	5
	archipelago 2 gene segment:	0	11	9	0	0	8	12	0			
	archipelago 3 gene segment:	13	16	0	18	0	0	17	15	0		

Figure 3. Chromosome expression.

In Figure 3, the hub island gene segment means that islands $2^{\#}$, $10^{\#}$, and $14^{\#}$ are the hub islands 1, 2, and 3, respectively. There are two route groups in the main network: from the mainland to island $10^{\#}$ and $14^{\#}$, successively (using the same ship), and from the mainland to island $2^{\#}$. The island $1^{\#}$ gene segment indicates that there are three routes to island $1^{\#}$ of the branch network: from island $2^{\#}$ to islands $6^{\#}$ and $4^{\#}$, successively (using the same ship), from island $2^{\#}$ to islands $1^{\#}$, $7^{\#}$, and $3^{\#}$, successively (using the same ship), and from island $2^{\#}$ to island $5^{\#}$. The island 2 gene segment indicates that there are two routes to island 2 of the branch network: from island $10^{\#}$ to islands $11^{\#}$ and $9^{\#}$, successively (using the same ship), and from island $10^{\#}$ to islands $8^{\#}$ and $12^{\#}$, successively (using the same ship). The island 3 gene segment indicates that there are three routes to island 3 of the branch network: from island $14^{\#}$ to islands $13^{\#}$ and $16^{\#}$, successively (using the same ship), from island $14^{\#}$ to island $18^{\#}$, and from island $14^{\#}$ to islands $17^{\#}$ and $15^{\#}$, successively (using the same ship). The above information expressed in the chromosomes encoding the hub island location and routing will provide data support for the SC module.

3.2. SC Module

The cycle supply and inventory capacity of each island visited on the same route are determined by the route's shipping schedule (t), and the ship size of any route in the branch and main network under different travelling modes is determined by the cycle supply of each island transported by the same route. The wharf scale of each island transported by the same route is determined by the ship size of the route; the range of t can be obtained according to Equations (20)–(23). Subsequently, we consider t to be an independent variable and the cycle supply, inventory capacity, ship size, wharf scale, total route cost, and inventory as dependent variables for every route in the branch and main networks under different travelling modes. Thus, the steps of the SC module are as follows: ① for the route of the branch network, we use the enumeration method, with t as an independent variable, to calculate the minimum total costs under back-and-forth and cycle transport travelling modes; we select the travelling mode with the lower minimum total cost and the corresponding shipping schedule, ship size, wharf scale, cycle supply, and inventory capacity of every island in this route as the optimal configuration solution of this route. Subsequently, using the above method, we successively optimise and configure all the routes in the branch network. ② We consider the total daily consumption of every island as the daily consumption of every hub island. ③ For the route of the main network, we use the enumeration method, with t as an independent variable, to calculate the minimum total costs under back-and-forth transport and cycle transport mode and choose the travelling mode with the lower minimum total cost and the corresponding shipping schedule, ship size, wharf scale, cycle supply, and inventory capacity of every island in this route as the optimal configuration solution for this route. Subsequently, using the above method, we successively optimise and configure all routes in the main network. The procedure is described as follows:

Step 1. Decode the information of the hub island location and a route in the branch network from the chromosome.
Step 2. Set the value range of schedule t of the route under back-and-forth and cycle transport modes according to Equations (20) and (21).
Step 3. Use an exhaustive method, with t as an independent variable, to calculate the minimum total costs of the route under the back-and-forth and cycle transport modes.
Step 4. Select the travelling mode with the lower minimum total cost, and define the corresponding shipping schedule, ship size, wharf scale, cycle supply, and inventory capacity of each island as the optimal configuration solution for the route.
Step 5. Repeat steps 1 to 4 and configure all routes in the branch network.
Step 6. Use the total daily consumption of every island as the daily consumption of every hub island.
Step 7. Decode the information of the hub island location and a route in the main network from the chromosome.
Step 8. Set the value range of schedule t of the route under the back-and-forth transport and cycle transport modes using Equations (22) and (23).
Step 9. Use the exhaustive method, with t as the independent variable, to calculate the minimum total costs of the route under the back-and-forth and cycle transport modes.
Step 10. Select the travelling mode with the lower minimum cost, and define the corresponding shipping schedule, ship size, wharf scale, cycle supply, and inventory capacity of each island as the optimal configuration solution for the route.
Step 11. Repeat steps 7 to 10 and configure all routes in the main network.
Step 12. Output the total cost of the chromosome and the optimal configuration solution for every route in the branch and main networks.

The specific steps are shown in Figure 4.

3.3. Fitness

For each chromosome in the SC-GA, the fitness value is equal to the total cost of the chromosome obtained by the SC module. The lower the fitness value, the better the chromosome.

3.4. Crossover

According to the characteristics of the chromosome, the delimiters and islands are crossed in the crossover operator of the SC-GA. This means that the offspring inherits the position of delimiters in parent 1 and the order of island numbers in parent 2. An example of a crossover operator is shown in Figure 5.

3.5. Mutation

Owing to the complex chromosomes, the mutation operator of the SC-GA has three different methods. The first operator is the exchange between island numbers in the same gene segment, the second is the exchange between the delimiter and island number in the same gene segment, and the third is the exchange between the island numbers of the hub island gene segment and each island gene segment. An example of a mutation operator is shown in Figure 6.

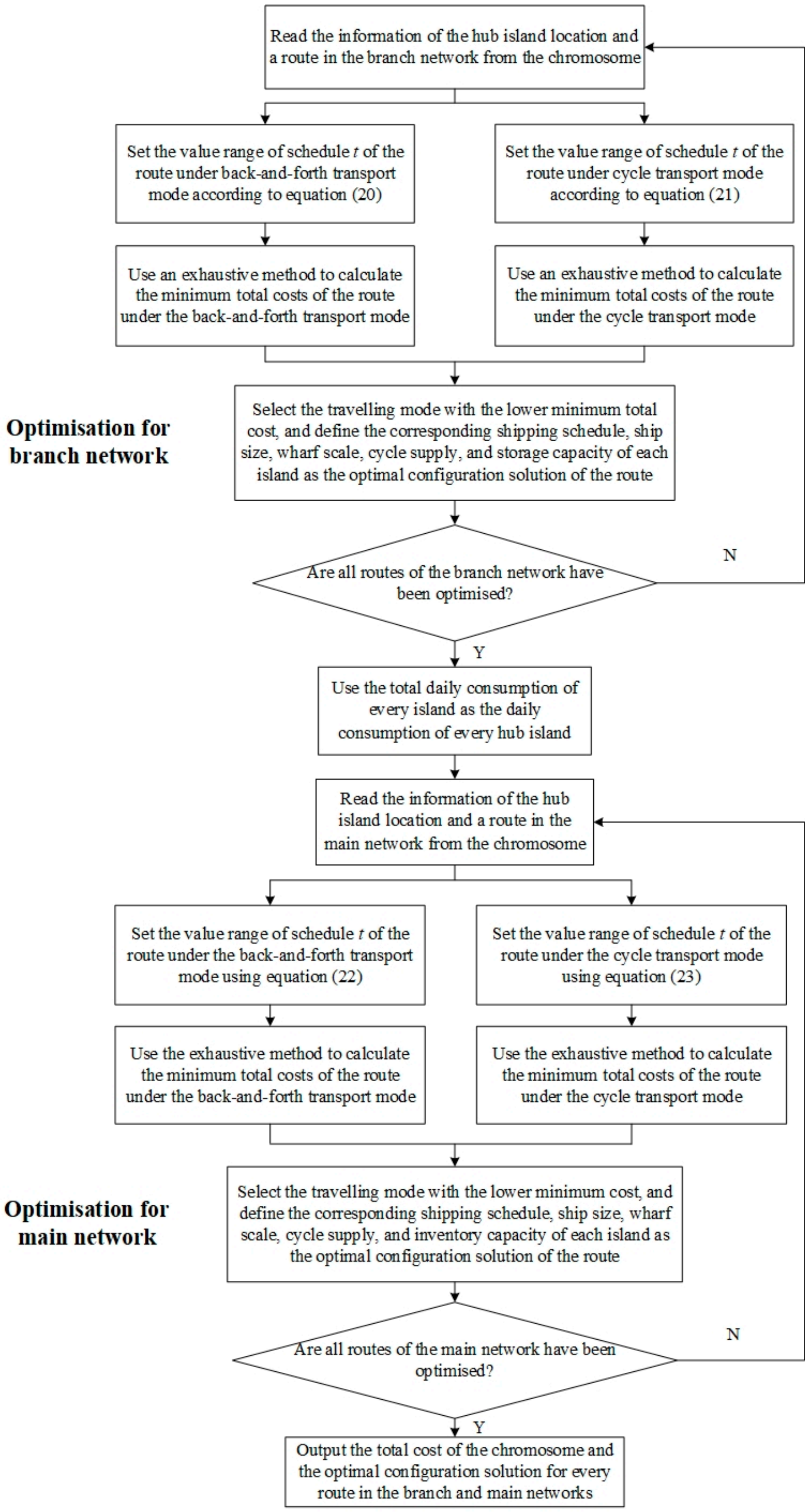

Figure 4. Framework of the SC module.

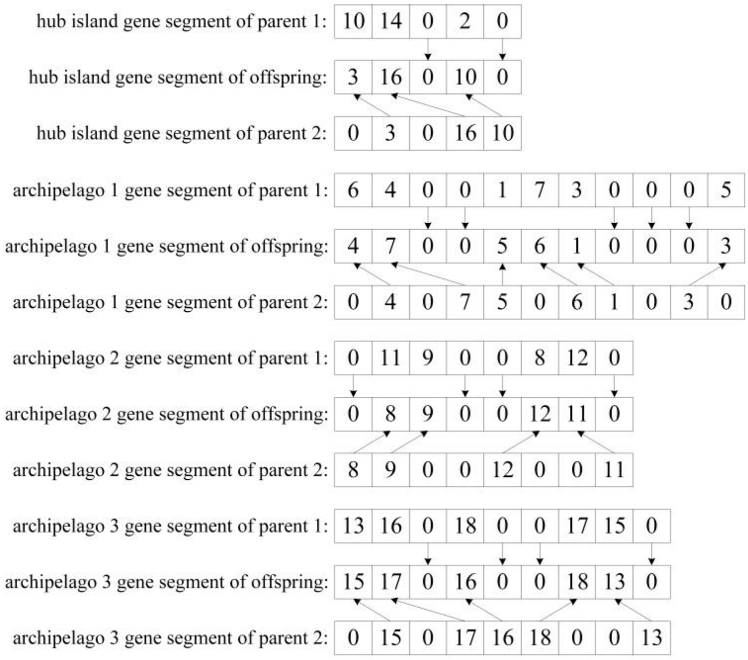

Figure 5. Crossover operator.

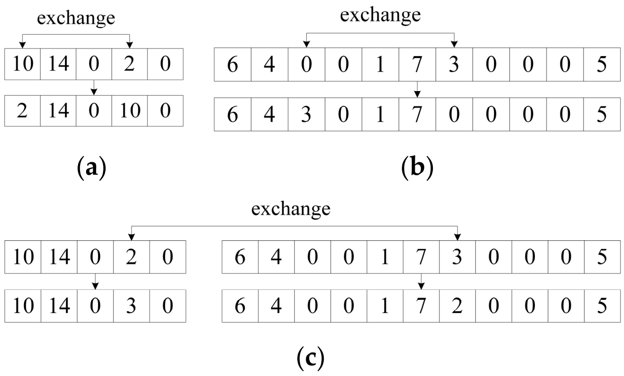

Figure 6. Mutation operator. (**a**) First mutation operator (using hub-island gene segment as an example). (**b**) Second mutation operator (using archipelago 1 gene segment as an example). (**c**) Third mutation operator (using the mutation between the hub-island and archipelago 1 gene segments as an example).

4. Instance Calculation

The models and algorithms in this paper are a general approach to the optimisation of remote island logistics networks. In this chapter, we perform an instance calculation, algorithm comparison, and sensitivity analysis.

4.1. Basic Instance and Its Results

In this section, we verify the validity of the model and algorithm with a basic instance and use the basic instance as a base for algorithm comparison and sensitivity analysis.

4.1.1. Data for the Basic Instance

In the basic instance, we assumed a total of 22 islands, divided into three archipelagos with 10, 7, and 5 islands, respectively. The relative locations of every island are shown in Figure 7. The daily supply demand of each island was randomly set between 10 and 200 tons (Table 3). The alternative ship sizes were 100, 500, 1000, 5000, 10,000, 15,000, and 20,000 t, and all ships were assumed to travel at 12 n mile/h. The assumed relevant costs of ship and wharf construction are listed in Table 4. The construction cost of the warehouse was assumed to be 240 dollars/m^2, and the storage cost was

0.3 dollars/t/day. The total time of system operation was 20 years, and Δt of the inventory system was 5 days.

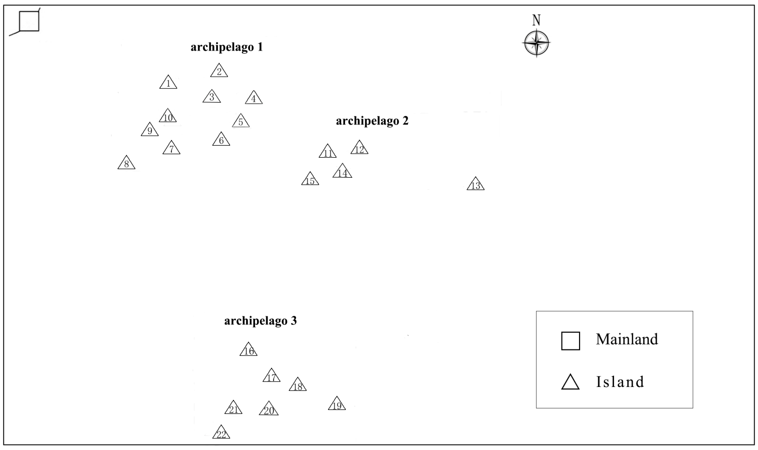

Figure 7. Relative locations of every island.

Table 3. Daily supply demand of every island.

Island	Daily Supply Demand (tons)	Island	Daily Supply Demand (tons)	Island	Daily Supply Demand (tons)
$1^{\#}$	21	$9^{\#}$	40	$17^{\#}$	120
$2^{\#}$	31	$10^{\#}$	59	$18^{\#}$	73
$3^{\#}$	191	$11^{\#}$	25	$19^{\#}$	61
$4^{\#}$	33	$12^{\#}$	10	$20^{\#}$	181
$5^{\#}$	132	$13^{\#}$	31	$21^{\#}$	80
$6^{\#}$	119	$14^{\#}$	40	$22^{\#}$	104
$7^{\#}$	52	$15^{\#}$	12		
$8^{\#}$	171	$16^{\#}$	96		

Table 4. Estimate table of relevant costs.

Ship Size (Tonnage Class)	Purchase Costs (Thousand Dollars)	Daily Maintenance Costs (Thousand Dollars/Month)	Shipping Costs (Dollar/Nautical Mile)	Corresponding Wharf Construction Costs (Thousand Dollars)
100	40	0.68	0.8	2000
500	150	1.40	2.5	6000
1000	280	1.88	3.0	10,000
5000	1200	4.00	7.0	20,000
10,000	1800	4.80	8.5	24,000
15,000	2500	6.00	10.0	30,000
20,000	3000	6.50	12.0	32,000

4.1.2. Results of the Basic Algorithm

We used MATLAB R2014a to run the SC-GA algorithm, operating in a Windows 7 environment with an Intel Xeon CPU E5-2650 v2 @2.60 GHz and 48 GB of memory. The population size was $pop = 30$, the crossover rate was $p_c = 0.5$, the mutation rate was $p_m = 0.055$, and the maximum generation was $MaxGen = 2000$.

The optimal result was obtained after 948 generations. The remote island shipping network is shown in Figure 8. The results show that islands $3^{\#}$, $14^{\#}$, and $20^{\#}$ islands were selected as the hub islands of the three sets of islands. There were twelve ships equipped in the remote island shipping network: two ships of 5000 t, one ship of 1000 t, five ships of 500 t, and four ships of 100 t. There were 28 wharfs in the remote island shipping network. Four wharfs of 5000, 1000, 500, and 100 t were equipped on island $3^{\#}$, two wharfs of 5000 and 100 t were equipped on island $14^{\#}$, two wharfs of 5000 and 500 t were equipped on island $20^{\#}$, and every satellite island had a wharf of 1000, 500, or 100 t.

The inventory capacity of all the islands was 28,510 t. The optimised routings are listed in Tables 5–8. The wharf, inventory capacity, and cycle supply of each island are listed in Table 9. The convergence process of the SC-GA algorithm is shown in Figure 9.

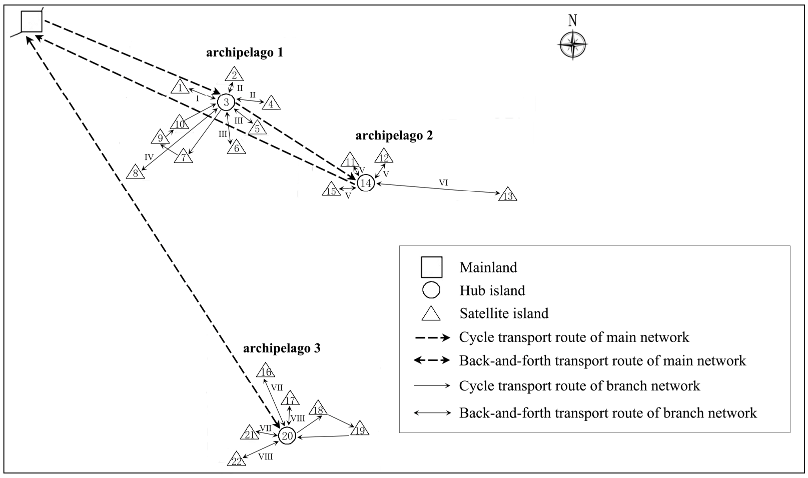

Figure 8. Shipping network for the island. Note: The Roman numerals in the diagram are the branch network back-and-forth route group numbers; the same number indicates the same back-and-forth route group.

Table 5. Route configuration of a shipping network from the mainland to every hub island.

Route	The Cycle Route from the Mainland to Hub Island	The Back-and-Forth Route from the Mainland to Hub Island
Islands and order of visit	$3^{\#}$, $14^{\#}$	$20^{\#}$
Ship size (tonnage class)	5000	5000
Schedule (days)	5	6

Table 6. Routes of shipping network in archipelago 1 from the hub island to every satellite island.

Route	Cycle Route I	Back-and-Forth Route Group I	Back-and-Forth Route Group II	Back-and-Forth Route Group III	Back-and-Forth Route Group IV
Islands and order of visit	$7^{\#}$, $9^{\#}$, $10^{\#}$	$1^{\#}$	$2^{\#}$, $4^{\#}$	$5^{\#}$, $6^{\#}$	$8^{\#}$
Ship size (tonnage class)	500	100	100	500	1000
Schedule (days)	3	4	3	3	4

Table 7. Routes of shipping network in archipelago 2 from the hub island to every satellite island.

Route	Back-and-Forth Route Group V	Back-and-Forth Route Group VI
Islands and order of visit	$11^{\#}$, $12^{\#}$, $15^{\#}$	$13^{\#}$
Ship size (tonnage class)	100	100
Schedule (days)	4	3

Table 8. Routes of shipping network in archipelago 3 from the hub island to every satellite island.

Route	Cycle Route II	Back-and-Forth Route Group VII	Back-and-Forth Route Group VIII
Islands and order of visit	$18^{\#}$, $19^{\#}$	$16^{\#}$, $21^{\#}$	$17^{\#}$, $22^{\#}$
Ship size (tonnage class)	500	500	500
Schedule (days)	3	5	4

Table 9. Wharf, inventory capacity, and cycle supply of every island.

Archipelago	Island	Number (Berth)	Berth (Tonnage Class)	Inventory Capacity (Tons)	Supply (Tons)
Archipelago 1	1#	1	100	189	84
	2#	1	100	248	93
	3#	4	100, 500, 1000, 5000	8490	4245
	4#	1	100	264	99
	5#	1	500	1056	396
	6#	1	500	952	357
	7#	1	500	416	156
	8#	1	1000	1539	684
	9#	1	500	320	120
	10#	1	500	472	177
Archipelago 2	11#	1	100	225	100
	12#	1	100	90	40
	13#	1	100	248	93
	14#	2	100, 5000	1180	590
	15#	1	100	108	48
Archipelago 3	16#	1	500	960	480
	17#	1	500	1080	480
	18#	1	500	584	219
	19#	1	500	488	183
	20#	2	500, 5000	7865	4290
	21#	1	500	800	400
	22#	1	500	936	416

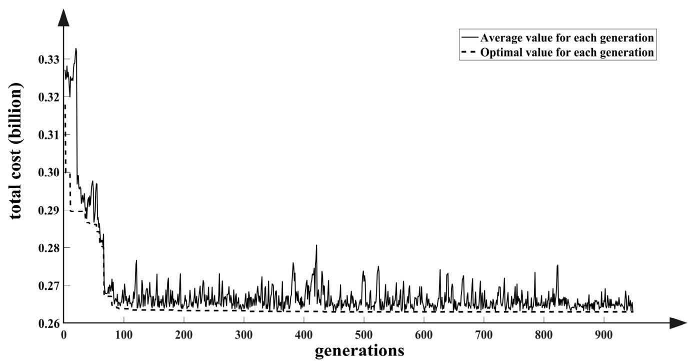

Figure 9. Algorithm converge process.

4.2. Different Sizes of Instances and Their Results

To further test the performance of the algorithm in this study, we performed separate computational experiments for different numbers of islands and different demand level instances.

4.2.1. Instance of Different Number of Islands

We assumed three instances for different numbers of islands, with 28, 34, and 40 islands in each instance. The values of the costs and basic parameters in the instances were the same as in the basic instance, except for the number of islands. We used the method proposed in this paper to calculate each of these three instances 10 times, and the results are shown in Table 10. The analysis indicated that the difference between the average of the results of 10 calculations for each instance and the best optimisation results that can be obtained by the algorithm in this study was small, and the standard deviation was also relatively small. Additionally, the results of at least 5 out of 10 calculations for each instance were the best optimisation results. These analysis results indicated that the algorithm in this study has good stability when solving instances with different numbers of islands. In addition, the computation time increased significantly with the number of islands, indicating that the computation time of the algorithm is relatively long when the number of islands is large.

Table 10. Results of 10 calculations for each instance of different numbers of islands.

Number of Islands	Calculation Results (Thousand Dollars)			Number of Occurrences of the Best Optimisation Result	Average Calculation Time (s)
	Best Optimisation Result	Average Value	Standard Deviation		
22 (basic instance)	262,949.40	266,796.34	4681.11	5	330.84
28	338,808.57	338,973.90	252.75	7	548.73
34	403,613.77	403,633.46	52.29	8	905.27
40	469,668.34	471,765.72	2097.40	5	1113.26

Note: The best optimisation results in the table are the best results obtained by the algorithm in this study, not the theoretical optimal solution of the instance.

4.2.2. Instance of Different Demand Levels

We assumed three instances for different demand levels, each with a daily island demand of 120%, 140%, and 160% of the basic instance. The value of the costs and basic parameters in the instances were the same as in the basic instance, except for the island's daily demand. We used the method proposed in this paper to calculate each of these three instances 10 times, and the results are shown in Table 11.

Table 11. Results of 10 calculations for each instance of different demand levels.

Demand Levels	Calculation Results (Thousand Dollars)			Number of Occurrences of the Best Optimisation Result	Average Calculation Time (s)
	Best Optimisation Result	Average Value	Standard Deviation		
100% (basic instance)	262,949.40	266,796.34	4681.11	5	330.84
120%	299,987.96	299,988.06	0.30	9	501.37
140%	340,076.01	340,076.01	0.00	10	373.33
160%	357,156.68	357,362.02	407.12	7	455.61

Note: The best optimisation results in the table are the best results obtained by the algorithm in this study, not the theoretical optimal solution of the instance.

The analysis indicated that the difference between the average of the results of 10 calculations for each instance and the best optimisation results that can be obtained by the algorithm in this study was small, and the standard deviation was also relatively small. Additionally, the results of at least 5 out of 10 calculations for each instance were the best optimisation results. These analysis results indicated that the algorithm in this study has good stability when solving the instances of different demand levels. In addition, the computation time increased significantly with demand levels, indicating that changes in demand levels have a relatively small impact on the algorithm's running time.

4.3. Algorithm Comparison

In order to analyse the performance of the algorithm in this article, we compare SC-GA with the other three algorithms in the relevant studies on the location inventory routing problem. As can be seen from Table 1 in the literature review, there is no paper that has studied the location inventory routing problem considering emergency inventory, multi-size carrier and multi-travelling mode simultaneously. Saif-Eddine et al. (2019) [32], Kaya and Ozkok (2020) [34] and Liu et al. (2015) [37] studied the location inventory routing problem considering a multi-size carrier, emergency inventory and multi-travelling mode, respectively, which is similar to the problem studied in this paper. Therefore, we compare SC-GA with the algorithms in these studies. Among them, Saif-Eddine et al. (2019) [32], Kaya and Ozkok (2020) [34], and Liu et al. (2015) [37] designed an improved genetic algorithm, a simulated annealing algorithm and a pseudo-parallel genetic algorithm integrating simulated annealing algorithm, respectively. In our algorithm comparison, we used SC-GA, the improved genetic algorithm (IGA), the simulated annealing algorithm (SA) and the pseudo-parallel genetic algorithm integrating simulated annealing algorithm (PPGASA) to calculate the instance in Section 4.1.1 for 10 times, respectively. The results are shown in Table 12. In terms of optimisation results, the best optimisation result and average result of SC-GA are better than IGA, SA and PPGASA, with the difference rates ranging from 11.29% to 17.66% and 12.61% to 18.95% respectively, indicating that the algorithm in this article is more capable of optimisation. In terms of computation time, the computation time of SC-GA is shorter than IGA and PPGASA, but longer than SA, indicating that the computation time of the algorithm in this article is moderate. It can be seen that for the location inventory routing problem of a remote island shipping network considering emergency inventory, multi-size carriers and multi-travelling modes, the optimisation results of SC-GA are better than IGA, SA and PPGASA in the above studies, and the computation time is in the medium level. This shows that the algorithm in this article is able to obtain better results in a reasonable computation time; that is, it has good performance.

Table 12. Results of 10 calculations for each algorithm.

Algorithm	Optimisation Results				Calculation Time	
	Best Optimisation Result (Thousand Dollars)	Difference from SC-GA (%)	Average Value (Thousand Dollars)	Difference from SC-GA (%)	Average Calculation Time (s)	Difference from SC-GA (%)
SC-GA	262,949.40	-	266,796.34	-	330.84	-
IGA [32]	295,381.62	12.33	310,176.77	16.26	659.72	99.41
SA [34]	309,389.88	17.66	317,367.36	18.95	282.34	−14.66
PPGASA [37]	292,628.33	11.29	300,432.48	12.61	380.41	14.98

5. Conclusions

Firstly, this article analyses the characteristics of material demand of the remote islands and the actual situation of shipping disruptions caused by tropical cyclones. Then, we study the design of the remote island shipping network from the perspective of ensuring the sustainable material supply of the remote islands. With the objective of minimising the total cost, we establish a location inventory routing optimisation model for a remote island shipping network considering emergency inventory, multi-size carrier, and multi-travelling modes. Subsequently, we develop a genetic algorithm based on a stepwise configuration module (SC-GA) to solve the model. The results of the computations show that SC-GA is able to obtain good results in an acceptable time. The SC-GA still has good stability when solving large-scale cases, but the computation time of the algorithm is relatively long when the number of islands is relatively large. Through the comparison of algorithms, we find that the optimisation result of SC-GA is better than the improved genetic algorithm, the simulated annealing algorithm and the pseudo-parallel genetic algorithm integrating simulated annealing algorithm. In summary, the model and algorithm developed in this article are able to systematically optimise the location of each island's hub island, the number of routes of the main network and branch network, the travelling mode of every route, which islands are visited in each route and the sequence of the islands, ship size and schedule of each route, wharf scale, inventory capacity, emergency inventory and cycle supply and other aspects involved in the design of remote islands shipping network from the perspective of the system as a whole and have application value in the construction of shipping network and logistics cost optimisation of remote islands (such as the Da Cunha Islands, the Svalbard Islands, the Kerguelen Islands, the islands in the South China Sea, the Ogasawara Islands, etc.). At the same time, the algorithm established in this article has good performance in solving the location inventory routing problem considering emergency inventory, multi-size carriers and multi-traveling modes, which can provide a reference for algorithm design of the location inventory routing problem in other logistics network design.

6. Lessons to Be Learnt

There are many variables involved in the design of a remote island shipping network studied in this article, which makes our research very difficult, especially in the model establishment and algorithm design. To solve this problem, we sort out the relationship between the variables in detail and find that in a closed logistics system of a remote island shipping network, wharf scale is directly related to ship size, the storage capacity of each island is directly related to cycle supply, and the ship size of a route and the cycle supply of the relevant islands are directly related to the shipping schedule of that route. Therefore, wharf scale, ship size, inventory capacity and cycle supply are all related to the shipping schedule of the route. Based on this thinking, we consider the shipping schedule of every route as the independent variable of the dependent variables such as wharf scale, ship size, inventory capacity and cycle supply in the process of constructing the model and algorithm, thus simplifying the number of decision variables, making the model simpler and clearer, and making the chromosome structure in the algorithm also simplified, improving the operation efficiency and optimisation effect of the algorithm. This research idea can provide a reference for the design of shipping networks for specific cargos [13,29], closed-loop supply chain optimisation [34,39,40], and retail distribution network design [35,37].

There are two important assumptions in this study. The first one assumes that there is only one type of material (basic living materials) that is transported in the remote island shipping network, and the second one assumes that the daily consumption of each island is deterministic. These two assumptions are realistic for some remote islands that are relatively underdeveloped and have a small and stable population. However, for some remote islands where aquaculture is well-developed, these two assumptions simplify the problem to a great extent. In practice, the goods required by remote islands where aquaculture is well-developed include not only basic living materials but also aquaculture tools and feeds. With the development of aquaculture, the demand for tools and feeds in these remote islands is constantly changing; that is, the demand is uncertain. Therefore, this kind of shipping network design problem of remote islands with well-developed aquaculture belongs to the shipping network design problem of remote islands with multiple products and uncertain demand, and its logistics cost must be higher than the instance results of this article. At the same time, this article considers the remote island shipping network as a closed system, which is a constraint on the boundaries of the problem. However, some resource-rich remote islands have the potential to become open logistics systems; that is, during the development of the resource-rich remote islands, new islands or mainland ports may join the original shipping network. Therefore, this kind of shipping network design problem of remote islands belongs to the problem of optimising an open logistics system from a development perspective. The above two kinds of problems cannot be solved by the model and algorithm in this article, and they will be our next step to investigate.

By comparing with the algorithms in the relevant studies, we find that the optimisation results of SC-GA for location inventory routing problems considering emergency inventory, multi-size carriers and multi-traveling modes are better than the improved genetic algorithm, the simulated annealing algorithm and the pseudo-parallel genetic algorithm integrating simulated annealing algorithm. The specific reason is that we take the travelling mode, schedule and ship size of each route and the cycle supply, inventory capacity and wharf scale of each island as sub-problems of hub island location and route optimisation and embed the corresponding optimisation module (SC module) in the computation process of the chromosome objective function. In this method of algorithm design, the total cost corresponding to each chromosome is the minimum total cost for that location and routing case, thus avoiding the situation where better location and routing solutions are eliminated by the algorithm because of poorer values of other variables. Compared with the improved genetic algorithm [31–33], the simulated annealing algorithm [34,35] and the pseudo-parallel genetic algorithm integrating simulated annealing algorithm [36,37], which do not embed the optimisation module in the calculation of chromosome objective function, the algorithm in this article has a stronger global optimisation ability in solving location inventory routing problem and can make the algorithm obtain better results as much as possible.

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