Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Research on comprehensive recovery of liner schedule and container flow with hard time windows constraints

Yibo Liu *, Xu Zhao, Rui Huang

College of Transportation Engineering, Dalian Maritime University, Dalian, 116026, China

ARTICLE INFO

Keywords:
Liner schedule and container flow integrated recovery problem
Hard time window constraint
Carbon emission
Adaptive mutation particle swarm algorithm

ABSTRACT

COVID-19 has had a huge impact on the global container market. Many liner companies have adopted a blank sailing for some voyages to adjust capacity, and vessel schedule reliability continues to be sluggish. From the perspective of the container liner company, this paper studies the integrated recovery of liner schedule and container flow under the background of suspension of shipping service. With the goal of minimizing the total cost of the liner company, the hard time window constraints of the container flow on the suspended routes are set to construct the integrated recovery problem. The increased carbon emission cost during the restoration of the container flow is taken into account. A mixed integer nonlinear programming model is established, and the adaptive mutation particle swarm optimization (AMPSO) is used to solve the model. The results show that the total cost of the model is reduced by 10.66% compared with the total cost of the shipping schedule recovery model that did not consider the recovery of container flow.

1. Introduction

With the spread of COVID-19 worldwide, the international container shipping industry has been greatly impacted. In the first half of 2020, liner companies have started to formulate plans for port suspension and port adjustment in order to cope with the collapse of container traffic caused by stagnation of commerce and trade. For example, the proportion of the suspended capacity of northwest Europe, Africa, Southeast Asia and other routes in the week from February 2 to February 8, 2020 accounts for more than 50%. After entering 2021, the demand for shipping rebounded, which led to the sluggish turnover of containers in many ports around the world, serious shortage of containers, and the inability of liner to berthing as planned. Members of the shipping alliance have constantly adjusted their capacity resources to adapt to changes in market demand, such as the cancellation of voyages to and from Asia and North America by Herbert in February 2021. The suspension plan of the liner company brings the container turnover trouble for the cargo owners, and the cargo owners also face the low schedule reliability rate under the epidemic. Therefore, it is of great practical significance to study the recovery of container flow under the background of linear suspension and consider the recovery of liner schedule under the background of low schedule reliability.

Low liner punctuality rate will cause interference to liner transportation. Disruption management management is to provide the optimal adjustment plan to deal with disruption management events in a timely manner. This optimal adjustment plan should be based on nature of the actual problem and the disruption management event to minimize the disturbance to the system. Costs should be properly considered in this adjustment plan. At present, disruption management management has been widely used in aviation, logistics, container transportation and other fields (Rezapour et al., 2018). The analysis of disruption management management is usually divided into two aspects: disruption management events and means for handling disruption management. In this paper, it focused on container shipping schedule disruption management events of suspension and port congestion caused by COVID-19, which will have a serious negative impact on cargo throughput of the port (Xu et al., 2021a).

Among the methods for dealing with liner schedule disruption management, there are two methods that are members of the shipping alliance widely used by liner companies and do not destruct the route structure:

(i) Increasing sailing speed: increase the speed as much as possible within the speed range of the ship to shorten the delayed liner sailing schedule.

* Corresponding author.
E-mail addresses: lyb_1120191410@dlmu.edu.cn (Y. Liu), zhaoxu@dlmu.edu.cn (X. Zhao), 18340830097@163.com (R. Huang).
(ii) Shorten the time in port: The cost of improving the working efficiency in port within the allowable range.

(iii) Delay cost of liner schedule delay: Delay of liner schedule has an impact on the interests of cargo owners, thereby reducing the liner company’s reliability on the route and causing losses to the liner company’s future earnings.

(iv) Cost of Carbon emission penalty: At present, international shipping accounts for about 3% of global greenhouse gas (GHG) emissions. If the shipping industry intends to make its due contribution to curbing global warming under the Paris Agreement, it must inevitably promote energy conservation and emission reduction. (Chen and FeiWan, 2019). Increasing speed will inevitably increase carbon emissions from fuel consumption, and this paper, cost of carbon emissions penalty is considered.

Recovery problem of container flow refers to re-planning the route for re-transporting the disturbed container to its destination port. In these disturbed container transportation, three additional costs will be incurred for the liner company:

(i) Cost of Container flow transportation: the transportation cost of transporting the disturbed container to the destination port through a certain transportation method.

(ii) Cost of Container flow handling: additional handling costs incurred in the process of transporting disturbed containers.

(iii) Cost of Carbon emission penalty: the environmental impact caused by the extra carbon emissions generated in the process of interfering with the container during transportation.

The theoretical framework of this paper is shown in Fig. 1. The hard time window constraint of the ship arrival time is used to establish the relationship between the liner schedule recovery problem and the container flow recovery problem. The hard time window constraint can effectively and accurately limit the transportation of the disturbed container flow, so as to provide the liner company with the most profitable shipping decision.

2. Literature review

Disruption management is an important issue in liner shipping. Approximately 70–80% of ships will experience delays in at least one port during round-trip transportation (Notteboom, 2006). GangQi (2004) defines disruption management as: during the execution of the plan, some disruption management events occurred due to internal and external uncertain factors that made the original plan impossible to implement, and a new plan needs to be formulated in real time. Meng and JianLu (2015) studied the optimization problem of berths and quay crane disturbance restoration, and proposed a method to adjust the original plan to deal with the actual disturbance. Liu et al. (2016) studied the rescheduling of unexpected failures of quay cranes during the execution of the berth plan, and established a two-stage disruption management model. Wang and Qiang (2012) considered the uncertain factors of ship sailing time and port time, determined the ship’s arrival time and sailing speed function on each route, and designed the liner shipping route. Vernimmen et al. (2007) present a case study to illustrate the impact of schedule unreliability on the level of safety stock that should be kept by a manufacturer who sources spare parts from overseas. Qi and Song (2012) aims at minimizing fuel consumption, taking into account the uncertain factors of port time, and proposes an optimized ship scheduling cycle. Fischer et al. (2016) studied the problem of ro-ro ship scheduling disruption management, established a mathematical model including robust optimization strategies and performed simulations. Xu et al. (2021b) focuses on the mechanism of interaction among the strategic choices of a shore power system including government, port enterprises, and liner companies. Based on an evolutionary game model, the influence of shore power implementation on the evolutionarily stable strategies of the multiple stakeholders is discussed.

At present, scholars have been deepening the research on the vessel schedule recovery problem (VSRP). The problem of vessel schedule recovery problem (VSRP) is proposed by Brouer et al. (2013), which can evaluate the given interruption scenarios, and select the appropriate vessel schedule recovery plan to balance the influence of fuel consumption and delay on the cargo owner. Fagerholt (2000) evaluated the trade-off between transportation costs and the time window violations. Computational results based on data from a real ship scheduling problem are presented and used as a basis for the evaluation. Qi (2015) studied how disruptions can be effectively managed in liner shipping and showed how to model and formulate such problems to present a few key results of the solution schemes and managerial insights observed. Li

![Fig. 1. Schematic diagram of the integrated recovery cost of liner schedule and container flow.](image-url)
et al. (2015) proposed an operational level solution to recover the disrupted schedule caused by a delay, where they consider different operational actions such as speeding up, port skipping, and port swapping. Li et al. (2016) studied real-time schedule recovery policies for liner shipping under various regular uncertainties and the emerging disruption event that may delay a vessel from its planned schedule. Cheraghchi et al. (2018) studied the vessel schedule recovery problem (S-VSRP) based on the speed. The speed of each segment was obtained by using the multi-objective evolutionary algorithm, and the NSGA-II algorithm was found to be the best. Abioye et al. (2019) proposed the green vessel schedule recovery problem by adjusting the ship speed and canceling the port of berthing, considering the influence of carbon emission control area, and solved the nonlinear model by CPLEX. Xing and Wang (2019) divided the recovery strategies into three levels for hierarchical management to find the trade-off between service standards and recovery costs. Francesco and LaiZuddas (2013) studied the empty container transportation problem when the port is disturbed, and used the stochastic programming method to solve the problem.

As mentioned above, the research on the vessel schedule recovery problem (VSRP) focuses on the study of recovery methods, such as changing the order of ports of call and redesigning the route. In terms of algorithms, most of the research focuses on linear programming. However, due to today’s disruption events, like impact of the epidemic or port congestion, liner companies are often suspending the route that is impossible to make recovery. And liner companies will recommend alternate routes to cargo owners, which requires the recovery of container flow.

The existing literature has less research on the combination of ship schedule restoration and container flow restoration. We define the problem of comprehensive recovery of liner shipping schedule and container flow as restoring the cargo on the suspended route to the alternate route, and restoring the shipping schedule for the alternate voyage. In this way, liner companies can consider the impact of ship schedule restoration and container flow restoration at the same time to make optimal decisions.

3. Model construction

3.1. Problem description

In this paper, it takes the suspension plan adopted by a route of a certain week by the liner company as the background, the suspended route loading port of cargo will be transported to the alternate route loading port and then these cargoes will be transported to the destination port by the alternate route loading port. Under the influence of the continuous decline of liner schedule reliability, the liner of the alternate route was disrupted and a recovery plan from the disruption was required. In order to distinguish the alternate route from the normal route, the alternate route is hereinafter referred to as the “delayed route”. From the perspective of liner companies, it proposes a transportation plan with the minimum total cost by considering the recovery of container flow of the suspended route and the recovery of vessel schedule of the delayed route in this paper.

As shown in Fig. 2, the diamonds represent the ports of loading on the suspended routes. Due to the suspension of this route, we did not connect several loading ports into a route. Circles represent loading ports for the delayed route. The liner of the delayed route normally sails through the loading port indicated by the circle in sequence according to the shipping schedule. We use a straight line with an arrow to represent the delayed route. The overlapping circles and diamonds represent loading ports where the suspended and delayed routes overlap. The problem we want to study is how to transport the cargo from the loading port of the suspended route to the loading port of the delayed route.

For the container flow recovery of the suspended route, it considers three common and low-cost transportation modes of waterway, highway and railway for cargo transfer in this paper. Starting from the cargo owner’s original planned loading port of the suspended route and ending at a loading port of the delayed route, the container flow recovery process is completed before the liner ships of the delayed route arrive at the loading port. Usually, when the cargo is in the common loading port of the two routes, the liner company will advise the cargo owner to wait for the next liner of the loading port instead of transshipment. Therefore, it only considers the cargo recovery of the loading port of the suspended route which is different from the loading port of the delayed route. In this paper, the cargo owner can complete the
transportation plan through transshipment without having to find another liner route, and maintain the reputation of the liner company. While taking the suspension plan, the cargo owner’s interests can be recovered to the greatest extent.

Impact of container flow recovery will be considered. If the arrival time of delayed liner is too late, the cargo will be stored in the port for too long, resulting in higher costs; if the arrival time is too early, some cargoes will not be able to be shipped because their matched liner have not arrived at the loading port. After the cargo arrives at the container loading port, the cargo need to be boxed and transported in the rear and front yard by trucks (Chen and Yang, 2010). Therefore, we set the time window of container cargo flow as: the sum of the cargo arrival time and the maximum dispatch time is less than the delayed liner arrival time. It will establish a hard time window constraint to dump cargo on the container flow that has not arrived when the liner arrives at the loading port, and does not arrange a recovery plan for these container flows to meet the time connection of the cargo flow of the delayed route liner transportation.

We considered the container flow recovery problem in the previous paragraph. And we also considered the problem of liner schedule recovery. Under the influence of the continuous decline of liner schedule reliability, the liner of the delayed route was disrupted and a recovery plan from the disruption was required. Increasing the speed and shortening the time in port will be adopted to restore the schedule.

Arrangement of the container flow recovery plan will generate additional carbon emissions, and it will also generate a lot of additional carbon emissions when the liner speeds up to restore the shipping schedule. Therefore, when calculating the total cost of liner companies, in this paper, it considers the price of carbon tax, and takes carbon emissions when the liner speeds up to restore the shipping schedule. Additional carbon emissions, and it will also generate a lot of additional costs into the objective function, so as to optimize the impact of transportation plan on the environment in the calculation process.

3.2. Model assumptions

Considering the complexity of the problem, the following assumptions are made:

① Each port operates 24 h a day.
② Fuel prices remain constant during the liner voyage.
③ Situation that the liner is disturbed for many times is not taken into account.
④ The cargo owners agreed to accept the container flow recovery plan of the shipping company.
⑤ Due to the different initial time of cargo transportation, the cargoes of the same shipment are transported by one mode of transportation without splitting.
⑥ Shipping companies have the ability to restore container flow through multiple modes of transportation.
⑦ The speed of container transportation between ports is constant.
⑧ Ignore the effect of the cargo loaded in the container flow recovery on the maximum quantity of additional containers that the ship can load.

3.3. Symbol description

(1) Set:
$I$: Set of port of delayed liner routes;
$I_r$: Set of loading port of delayed liner routes;
$A$: Set of cargo shipments that require container flow recovery;
$K$: Set of alternative transportation modes for container flow recovery;

(2) Model parameters
$v_{min}$: Minimum speed limit for the liner ship;
$v_{max}$: Maximum speed limit for the liner ship;
$e^{max}_i$: The maximum time at port that can be shortened for the i-th port;
$d_{i,i+1}$: Distance between the i-th port and the i+1-th port on the delayed liner route;
$q_i$: Unit time cost of shortening in port;
$c_i$: Original planned time of the delayed liner at port; 
$t_i$: Original planned berthing time of the liner; 
$c^p_i$: Penalty cost for the departure of the ship schedule per unit time;
$q_a$: Quantity of containers for the a-th shipment;
$d_{ai}$: Distance from the a-th shipment to the i-th loading port of the delayed route through the k-th mode of transportation;
$k_{ai}$: Transportation cost per unit container per unit distance by the k-th mode of transportation;
$k_{ao}$: Loading and unloading cost per unit container through the k-th mode of transportation;
$k_{ai}$: Unit time cost of container stacking at the loading port; 
$k_{ad}$: Penalty cost of rejuction per unit container in ath cargo shipment;
$EF$: Daily fuel consumption of liner ship auxiliary engine; 
$MF$: Daily fuel consumption of main engine of liner ship; 
$V_{max}$: Maximum speed; 
$C_{i}$: Carbon emissions per unit distance per unit container transported by the k-th mode of transportation; 
$p_{k}$: Penalty cost per unit of carbon emissions; 
$c_i$: The inward pilotage time of the liner at the i-th port; 
$c_i$: The outward pilotage time of the liner at the i-th port; 
$t_{i}$: Departure time of a-th cargo to be transported by the k-th mode of transport at the i-th port; 
$t_{i}^{1}$: The time when the a-th shipment arrives at the original planned loading port; 
$v$: Transport speed of the k-th mode of transportation; 
$c^p$: Preparing time arrangement by the liner company for the k-th mode of transportation for the cargo owner; 
$C$: Maximum transport capacity of transport mode k; 
$T$: The maximum dispatch time of the a-th shipment at the port;

(3) Decision variables
$v_{i,i+1}$: Sailing speed of the delayed route liner ship from the i-th to the i+1-st port; 
$c$: Shortened port time of the liner in the i-th port; 
$t$: Actual berthing time of the ship; 
$x$: Binary variable, when it is equal to 1, it means that the ath shipment is transported to the i-th loading port of the delayed route through the k-th transportation mode, otherwise it is equal to 0.

3.4. Mathematical model

Order $f(v_{i,i+1})$ represents the fuel consumption rate ($t/n$ mile) of liner sailing from port $i$ to port $i+1$, according to the research of Fagerholt.
and LaporteNorstad (2010):

\[ f(v_{i+1}) = (24v_{i+1})^{-1} \left( c_1 + c_2 \cdot v_{i+1}^3 \right) \]  

(1)

\( c_0 \) is the performance coefficient of the ship, and \( c_1 \) is the fuel consumption rate of the ship every day. The comprehensive recovery problem of liner schedule and container flow is expressed by a mixed integer nonlinear programming (MINLP) model. The objective function is to minimize the total cost of the liner company in the process of related disruption management recovery. It includes eight parts, namely eight terms: liner ships, the cost of fuel oil, \( c_0 \), the cost of shortening the time in port \( C_h \), the penalty cost of ship delays \( C_h \), the transportation cost of all restored container flows \( C_t \), the handling cost of all restored container flows \( C_h \), the cost of all restored container flows stored in the loading port \( C_h \), the penalty cost of the rejected container flow \( C_t \) and the total carbon emission cost of the liner ship and container flow restoration \( C_h \).

\[ C_1 = \sum_{i \in I} f(v_{i+1}) \cdot d_{i,i+1} \]  

(2)

\[ C_2 = \sum_{i \in I} \sum_{j \in J} t_{ij} \cdot c_{ij}^{a}(v_{i+1}) \]  

(3)

\[ C_3 = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{ak}\cdot y_{ak}\cdot q_k\cdot d_{iak}\cdot c_{iak}^{a}(v_{i+1}) \]  

(4)

\[ C_4 = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{ak}\cdot y_{ak}\cdot q_k\cdot v_{i+1}\cdot c_{iak}^{a}(v_{i+1}) \]  

(5)

\[ C_5 = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{ak}\cdot y_{ak}\cdot q_k\cdot v_{i+1}\cdot c_{iak}^{a}(v_{i+1}) \]  

(6)

\[ C_6 = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{ak}\cdot y_{ak}\cdot q_k\cdot v_{i+1}\cdot c_{iak}^{a}(v_{i+1}) \]  

(7)

\[ C_7 = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{ak}\cdot y_{ak}\cdot q_k\cdot v_{i+1}\cdot c_{iak}^{a}(v_{i+1}) \]  

(8)

\[ C_8 = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{ak}\cdot y_{ak}\cdot q_k\cdot v_{i+1}\cdot c_{iak}^{a}(v_{i+1}) \]  

(9)

\[ \min C = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 \]  

(10)

Constraints:

\[ v_{\text{min}} \leq v_{i+1} \leq v_{\text{max}}, i = 1, 2, \ldots, I \]  

(11)

\[ T_j = \left( T_j + r_{ij}^{v_{i+1}} + d_{i+1,j/k}/v_{i+1} + t_i + t_j^a \right), i = 1, 2, \ldots, I, j = 1, 2, 3, \ldots, I \]  

(12)

\[ 0 \leq t_j^a \leq t_j^{\max} \]  

(13)

\[ \sum_{k \in K} x_{ak} = 1, a = A \]  

(14)

\[ T_{ak} = T_j + d_{ak}/v_{i+1} + r_{ij}^{a}, a = A, i = I, k \in K \]  

(15)

\[ T_{ak} = T_j + d_{ak}/v_{i+1} + r_{ij}^{a}, a = A, i = I, k \in K \]  

(16)

\[ q_k \cdot x_{ak} < \mu_t \cdot \text{CAP}_{t}, i \in I \]  

(17)

\[ q_k \cdot x_{ak} < \mu_t \cdot \text{CAP}_{t}, a = A, k \in K \]  

(18)

\[ y_{ak} = \begin{cases} 1, & \text{if } \sum_{k \in K} \sum_{i \in I} t_{ik} x_{ak} + t_a < \sum_{k \in K} \sum_{i \in I} T_{iak} \cdot y_{ak} \\ 0, & \text{otherwise} \end{cases} \]  

(19)

\[ t_{ij}^{\max} = \sum_{k \in K} \sum_{i \in I} T_{iak} \cdot y_{ak} - \sum_{k \in K} \sum_{i \in I} T_{iak} \cdot y_{ak} - t_a \quad \text{if } \sum_{k \in K} \sum_{i \in I} t_{ik} x_{ak} + t_a < \sum_{k \in K} \sum_{i \in I} T_{iak} \cdot y_{ak} \\ 0, & \text{otherwise} \]  

(20)

\[ y_{ak} \in \{0, 1\}, a \in A, i \in I, k \in K \]  

(21)

\[ y_{ak} \in \{0, 1\}, a \in A \]  

(22)

Among the constraints, formula (11) limits the speed range of liner ships; formula (12) gives the recursive relationship of berthing time of liner ships; formula (13) limits the range of shortening the time in port; formula (14) restrict each cargo shipment to be recovered to an delayed route loading port by one mode of transportation; Formula (15) indicates that the time for the cargo to arrive at the arrival port of the delayed route is equal to the total time of the origin planned loading port plus the transportation time, plus the time for the shipping company to prepare the transportation plan; formula (16) indicates that the actual port in time is equal to the planned port time minus the shortened in port time; formula (17) indicates that at each loading port of the delayed route, the additional container capacity of liner ships is limited; Formula (18) represents the capacity limit of each mode of transportation for container flow recovery; formula (19) represents the time window constraint, which means that when the cargo arrives at the loading port and the time for loading and unloading is less than the arrival time of the liner ship, the cargo can be loaded, otherwise the cargo will be dumped; Formula (20) is the time window constraint, which means that when the cargo arrives at the loading port and the time for loading and unloading is less than the arrival time of the liner ship, the cargo stacking time is equal to the difference between them; formulas (21) and (22) are binary variables.

Moreover, we have also constructed a liner schedule recovery model that does not consider container cargo flow recovery, based on the parameters and variables defined above.

\[ C_1 = \sum_{i \in I} f(v_{i+1}) \cdot d_{i,i+1} \]  

(23)

\[ C_2 = \sum_{i \in I} c_{i}^{v_{i+1}} \cdot d_{i,i+1} \]  

(24)

\[ C_3 = \sum_{i \in I} (T_j - T_i^a) \cdot c_{ij}^{v_{i+1}} \]  

(25)

\[ C_4 = \sum_{i \in I} x_{ak} \cdot y_{ak} \cdot q_k \cdot d_{iak} \cdot c_{iak}^{v_{i+1}}(v_{i+1}) \]  

(26)

\[ C_5 = \sum_{i \in I} x_{ak} \cdot y_{ak} \cdot q_k \cdot v_{i+1} \cdot c_{iak}^{v_{i+1}}(v_{i+1}) \]  

(27)

\[ \min C = C_1 + C_2 + C_3 + C_4 + C_5 \]  

(28)

Restrictions:

\[ v_{\text{min}} \leq v_{i+1} \leq v_{\text{max}}, i = 1, 2, \ldots, I \]  

(29)

\[ T_j = \left( T_j + t_{ij}^{v_{i+1}} + d_{i+1,j/k}/v_{i+1} + t_i + t_j^{a} \right), i = 1, 2, \ldots, I, j = 1, 2, 3, \ldots, I \]  

(30)

\[ 0 \leq t_{ij}^{v_{i+1}} \leq t_{ij}^{\max} \]  

(31)

Among the constraints, formula (29) limits the speed range of liner ships; formula (30) gives the recursive relationship of berthing time of
liner ships; formula (31) limits the range of shortening the time in port.

This model indicates that the liner company only considers the resumption of the liner shipping schedule and rejects all the affected container flows. This is a classic vessel schedule recovery problem (Brouer et al., 2013). In the following sections, we will solve the two models in the context of actual cases, and then compare the results of the two processing methods.

4. Solution method

In this paper, choice of transportation mode of each cargo in the process of container flow recovery is considered, discrete variables and increase the number of decision variables are added, which is a non-deterministic polynomial problem (NP problem). In this paper, the adaptive mutation particle swarm optimization algorithm is used to solve the global optimization problem. Compared with the traditional particle swarm optimization algorithm, the operation of this algorithm is as follows:

(1) If the decision variables are divided into real variables and integer variables, the decision variables in the k-th particle are as follows:

\[ (x_i, y_i) = (x_i^1, x_i^2, \ldots, x_i^n, y_i^1, y_i^2, \ldots, y_i^n) \]  

(32)

n represents the dimension of real variables. M represents the dimension of integer variables. According to Tan et al. (2014), real variables and integer variables are generated according to the following formula:

\[ x_i = x_i^d + \text{rand} \times (x_i^u - x_i^d) \]  

(33)

\[ y_i = \text{round}(y_i^d + \text{rand} \times (y_i^u - y_i^d)) \]  

(34)

where, \( x_i^d, x_i^u, y_i^d, y_i^u \) represent the lower and upper bounds of real and integer variables respectively.

(2) Introducing adaptive inertia weight

\[ w_i^t = \begin{cases} 
 w_{\text{min}} + (w_{\text{max}} - w_{\text{min}}) \frac{f(x_i^d) - f_{\text{min}}}{f_{\text{average}} - f_{\text{min}}} & \text{if } f(x_i^d) < f(x_i^d) \\
 w_{\text{max}} & \text{if } f(x_i^d) > f(x_i^d)
\end{cases} \]  

(35)

where, \( w_{\text{min}}, w_{\text{max}} \) are the preset minimum and maximum inertia coefficients. \( f_{\text{average}}, f_{\text{min}} \) is the average fitness of all particles when iterating to the d-th times, \( f_{\text{average}} \) is the minimum fitness of all particles when iterating to the d-th times. The smaller the fitness is, the closer the distance from the optimal solution is and the more local search is needed; the larger the fitness is, the farther the optimal solution is and the more integrated search is needed.

(3) Introducing adaptive mutation operation:

Where, d is the number of current iterations of the particle, D is the number of iterations required by the algorithm, \( x_{i,d} \) is the position of the i-th particle from iteration to d times, and \( \eta \) is a random variable that obeys Gauss(0,1) distribution. The mutation probability decreases with the increase of the number of iterations, which highlights the global search ability in the early stage of the algorithm and the local search ability in the later stage.

The algorithm flow is as follows:

① According to the type of decision variable, each particle is assigned a random initial position and velocity that meets the initial conditions.

② Calculating fitness of each particle according to the fitness function.

③ Comparing Fitness of each particle’s current position and fitness of its historical best position. If the fitness of the current position is smaller, update the historical best position instead of the current position.

④ Comparing fitness of each particle’s current position and fitness corresponding to its global best position. If the fitness of the current position is smaller, update the overall best position instead of the current position.

⑤ The adaptive inertia weight is calculated by making the mutation probability of the particle position decreases with the increase of the number of iterations.

⑥ Updating the speed and position of each particle.

⑦ If the end condition is not met, return to step 2. If the end condition is met, the algorithm ends.

5. Case analysis

Taking the suspension plan of COSCO Shipping Lines Co., Ltd. in the 18th week of 2020 as an example. Route RES1 was suspended due to the impact of the epidemic on cargo demand. The suspension caused the detention of cargo that was planned to be transported on the originally scheduled voyage. The liner company proposed an alternative service plan for the credibility of the shipper. The cargo owner can complete the transportation of the stranded cargo through the routes of the same liner company in the same area. The problem is that the cargo of the cargo owner is stuck at the loading port of RES1 which is different from the loading port of the delayed route RES2. This brings the trouble of transshipment for the cargo owner to complete the new transportation plan. In the case, the loading ports of the two routes are located along the coast of China, and the transshipment can be completed by short-distance land or sea transportation.

From the perspective of liner companies, this article arranges container cargo flow recovery plans for shippers. This article chooses waterway transportation, road transportation and railway transportation to restore the container flow. The transportation costs of these three modes of transportation are controllable. Container cargoes with different transportation volumes and different transportation distances can be flexibly dispatched and selected.

In the case, the route RES2 was difficult to guarantee the punctuality rate due to the disruption management of the epidemic, and the liner company’s resumption of the route RES2 was the second issue to be considered. In order to ensure the stability of the sailing routes during the period affected by the epidemic, this article did not adopt the means of canceling some of the sailing schedules of calling ports. Use the most commonly used and most effective two methods to speed up the voyage and shorten the time in port to restore the sailing schedule.

The information of the container to be restored by the shipper is shown in Table 1, and the suspension plan information is shown in Table 2.
The liner company only provides suggested alternative service plans for owners of cargo. In this paper, it will arrange a specific container flow recovery plan for each shipment based on the needs of owners of cargo. Assuming that due to a certain disruption management event, the departure time of the alternative service route ship from Shanghai Port is delayed by 12 h. At this time, appropriate measures need to be taken to restore the schedule. At this time, a comprehensive recovery problem of liner schedule and container flow is constructed.

5.1. Data sources

The speed range of the liner ships operated by RES2 route is [10kn, 25kn], the ship performance coefficient is 0.024, and the daily fuel consumption of auxiliary engines is 2 t/d. In this paper, it adopts waterway transportation, road transportation and railway transportation to recover the container flow, and the transportation speed is 12kn, 120 km/h and 100 km/h respectively. The schedule of the RES2 route is shown in Table 3.

We define the sailing time of the RES2 schedule as time 0.

5.2. Result analysis

In this paper, it uses MATLAB R2018b to program, the parameters of the adaptive mutation particle swarm algorithm are set as follows: the initial population size is 500, the number of iterations is 200, the preset maximum inertia coefficient is 0.9, the minimum inertia coefficient is 0.4, self-learning factor and group learning factor settings is 0.5. The convergence process of the algorithm iteration obtained by solving is shown in Fig. 3, the calculated liner correlation results are shown in Table 4.

The obtained container flow recovery results are shown in Table 5. In this case, the total operating cost of the liner company is calculated to be 7.88 × 10^6 USD. Remove the items $C_3$, $C_4$ and $C_5$ in the Objective function, it will get a pure vessel schedule recovery problem (VSRP), and calculate the liner company’s operation, the total cost is 8.82 × 10^6 USD. In this paper, a comprehensive recovery model of liner shipping schedule and container flow is constructed, and the total cost obtained is reduced by 10.66% compared with the total cost of the VSRP problem. The speed results obtained by VSRP are shown in the third column of Table 4. Through comparison, it can be found that the speed of the loading port segment of the delayed route is significantly different, while the speed of the remaining segments is almost the same. Loading at the loading port of the route does have an impact on the delayed route liner voyage plan. The model in this paper is effective in establishing the relationship between the restoration of the schedule of the liner and the restoration of the container. Table 6 shows the arrival time of the cargo and the actual arrival time of delayed liner. The hard time window constraint is guaranteed.

Fig. 4 shows the cost changes of the restored container flow. It can be seen that the transportation and handling costs are the highest. Under the same conditions of the original loading port, the change is basically

| Alliance code | Original loading port | Original scheduled sailing date | Alternative service plan |
|---------------|-----------------------|--------------------------------|--------------------------|
| RES1          | Tianjin               | 2-May                          | RES2 via Ningbo 9-May    |
|               | Qingdao               | 4-May                          | RES2 via Ningbo 9-May    |
|               | Nansha                | 9-May                          | RES2 via Shekou 14-May   |

| Port of call | Pilot time into port/h | Arrival time/h | Departure time/h | At port time/h | Departure pilot time/h | Minimum time that can be shortened |
|--------------|------------------------|----------------|------------------|---------------|------------------------|----------------------------------|
| Shanghai     | 0                      | 0              | 36               | 36            | 2                      | 4                                |
| Ningbo       | 2                      | 57             | 81               | 24            | 2                      | 2                                |
| Taibei       | 1                      | 107            | 127              | 20            | 1                      | 3                                |
| Xiamen       | 1                      | 143            | 163              | 20            | 2                      | 5                                |
| Shekou       | 2                      | 188            | 212              | 24            | 1                      | 5                                |
| Singapore    | 3                      | 296            | 320              | 24            | 2                      | 6                                |
| Djibouti     | 2                      | 522            | 558              | 36            | 2                      | 4                                |
| Jeddah       | 2                      | 615            | 663              | 48            | 1                      | 0                                |
| Sukona       | 1                      | 704            | 740              | 36            | 1                      | 5                                |
| Aqaba        | 1                      | 769            | 921              | 52            | 1                      | 1                                |
| Djibouti     | 2                      | 896            | 926              | 30            | 1                      | 3                                |
| Singapore    | 3                      | 1172           | –                | –             | 2                      | 0                                |

Table 2. The liner company only provides suggested alternative service plans for owners of cargo. In this paper, it will arrange a specific container flow recovery plan for each shipment based on the needs of owners of cargo. Assuming that due to a certain disruption management event, the departure time of the alternative service route ship from Shanghai Port is delayed by 12 h. At this time, appropriate measures need to be taken to restore the schedule. At this time, a comprehensive recovery problem of liner schedule and container flow is constructed.

Table 3. Vessel schedule of RES2.

Table 4. Computational results related to vessel schedule recovery.

Table 5. The obtained container flow recovery results.
consistent with the change of the container volume of each cargo. For example, the destination loading port of the second and the third cargo is different, and the mode of transportation of the 5th and the 6th cargo is different. However, the transportation and loading and unloading costs vary significantly with the volume of containers. This is related to the small distance difference between various modes of transportation, and the volume of containers is a more sensitive factor. The causes of storage at port are related to the storage time, and it can be seen from the figure that the change is less affected by the volume of containers. It can be seen from the 4th to 7th cargo that the storage cost of cargo with large container volume can also be insensitive to the change of container volume, which is related to the time convergence of cargo. The penalty cost of carbon emission is not affected by the change of container volume, which is more related to the choice of transportation mode.

Fig. 5 shows the time distribution of the restored container flow. The sum of the initial transportation time and the transportation time of the cargo corresponds to the actual arrival time of the cargo, and the stacking time of the cargo corresponds to the actual delivery time of the cargo. It can be seen that the stacking time of the 8th to 11th cargo from Nansha is much longer than that from Tianjin and Qingdao, which shows that the starting time of the cargo is quite different from the arrival time of the liner. The 4th cargo is transported by waterway, and the transportation time is relatively long, while the starting time of the 4th cargo is less than that of the cargo at the same starting port, which shortens the storage time of the 4th cargo. The storage time of 11th cargo is longer than that of Nansha port and Shekou port, which is similar to the low cost of waterway transportation. Therefore, when the port of departure and the port of destination of the restored container flow are fixed, the earlier shipment will choose the longer and lower-cost transportation method to shorten the storage time of the cargo and reduce the storage cost.

5.3. Sensitivity analysis

In the result of the comprehensive recovery model, the liner of this voyage abandoned the transportation of the first cargo. Table 6 shows

| Cargo number | Departure time/h | Transit time/h | Time of arrival/h | Actual arrival time of delayed liner/h |
|--------------|-----------------|---------------|------------------|---------------------------------------|
| 1            | 48              | –             | –                | –                                     |
| 2            | 23              | 20.78         | –                | 2.22 60.71                            |
| 3            | 2               | 18.54         | –                | 20.54 60.71                           |
| 4            | 6               | 38.19         | –                | 32.19 60.71                           |
| 5            | 21              | 8.14          | –                | 29.14 60.71                           |
| 6            | 36              | 7.93          | –                | 43.93 60.71                           |
| 7            | 43              | 9.94          | –                | 52.94 60.71                           |
| 8            | 20              | 27.63         | –                | 7.63 60.71                            |
| 9            | 42              | 25.72         | –                | 67.72 144.16                          |
| 10           | 35              | 29.67         | –                | 6.33 144.16                           |
| 11           | 48              | 4.83          | –                | 35.83 190.13                          |

Table 6 Results of cargo-related transportation time.
the impact of changes in the relevant parameters of the first shipment on the transportation decision. The purpose is to analyze the factors that cause the rejection of the goods.

In the result of the comprehensive recovery model, the liner of this dropped transportation of the 1st shipment cargo. Table 7 shows the impact of changes in the relevant parameters of the 1st shipment cargo on the transportation decision, aiming to analyze the factors that cause the rejection. The first two rows in the table show that the change in the initial waiting time of the goods will affect the transportation decision. When the initial transportation time is the 80th hour of the liner schedule, the transportation decision of the 1st shipment cargo changes.

The 1st shipment cargo will be transported by rail to Ningbo Port. The arriving time of the liner at Ningbo Port is not earlier than that of 69th hour due to the delay of the ship schedule, and the transit time from Tianjin Port to Ningbo Port will be close to that of 80th hour. It shows that for the actual port time of the liner, a relatively suitable departure time can reduce the possibility of cargo rejection. Data of the third row to the eighth row in the table respectively show the impact of changes in container volume and rejection cost on transportation decision. The product of the penalty cost of rejecting a unit container and the volume of the container is the total penalty cost of container rejecting a shipment. The calculation results in the table show that either the cargo quantities or the unit penalty cost increases, it will make the decision to transport rather than reject. The model calculates that the sum of the maximum transportation and handling costs of goods transported from Tianjin Port to Ningbo Port is US$61,203, and the total cost of the sudden change in the change in container volume and unit rejection cost in the table is less than US$61,203. Cargo owner can compare the maximum cost of their cargo to the nearest liner port of call and the total transportation cost to estimate whether the cargo will be recovered by the liner company.

The constant changes in the international shipping market will bring fluctuations in transportation price. In liner shipping, transportation price per container will seriously affect the estimated cost of rejection. In this paper, it multiplies the unit rejection cost of each shipment by price per container will seriously affect the estimated cost of rejection. In liner shipping, the transportation decision of the first shipment under different conditions.

Table 7
The transportation decision of the first shipment under different conditions.

| $T_i$/h | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
|--------|----|----|----|----|----|-----|-----|-----|
| $y_1$  | 0  | 0  | 0  | 1  | 1  | 1   | 1   | 1   |
| $q_y$/TEU | 20 | 60 | 100| 140| 180| 220 | 260 | 300 |
| $y_2$  | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   |
| $C_y$/USD | 10000| 30000| 50000| 70000| 90000| 110000| 130000| 150000|
| $C_y$/USD | 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 |
| $y_3$  | 0  | 0  | 0  | 1  | 1  | 1   | 1   | 1   |
| $C_y$/USD | 30000| 60000| 90000| 120000| 150000| 180000| 210000| 240000|

6. Conclusion

In this paper, it studies the comprehensive recovery of liner schedule and container flow. Based on the method of accelerating voyage and shortening the time in port, the recovery of container flow in the suspended route is considered, and the goal is to minimize the total cost of the liner company. The nonlinear mixed integer programming model uses adaptive mutation particle swarm algorithm to solve the model, at the same time, the optimal recovery plan for the delayed route liner schedule and the optimal loading port and transportation mode for the container flow of the suspended route are obtained. The results show that the total cost of the integrated recovery model of liner schedule and container flow established in this paper is reduced by 10.66% compared with the total cost of the pure schedule recovery problem.

The innovation of this article is firstly reflected in the establishment of a connection between the recovery of liner schedules and the recovery of container cargo flow. The consideration of the low on-time rate of liners and the suspension of some routes is extremely consistent with the actual situation of the current liner shipping market. And in this paper, it considers the carbon emissions impact of the liner’s accelerated voyage and transshipment plan design. Finally, a mathematical model of comprehensive restoration considering the interests of liner companies, shippers and the environment is constructed.

Specifically, the main conclusions and management insights are demonstrated in the following:

(i) While the liner company provides delayed route solutions for the cargo owners of the suspended routes, it also carries out the transshipment of the container flow for the cargo owners. In the comparison calculation of the models in this paper, it is proved that it can save the cost of the liner company. And it can be carried out when the replacement route is low on schedule and the schedule is restored at the same time. The cost savings brought about by resuming container flows increase with the increase in transportation cost. This provides a better solution for the liner market that has been suspended or jumped to port due to the epidemic and port congestion. On the one hand, it saves the interests of shippers whose previous transportation needs cannot be met. On the other hand, it enables liner companies to avoid the impact of large-scale dumping of goods and complete the transportation plan with a lower total cost.

(ii) In the process of formulating a container flow recovery transportation plan for the cargo owner, the transportation cost caused...
by the choice of the transshipment method and the cost of cargo storage stacking at the port are mainly considered. Choosing the transshipment mode with higher efficiency will make the storage time of the cargo in the port longer. Therefore, the actual arrival time of the liner must be comprehensively considered to complete the time connection. Through the comprehensive recovery model, a transportation plan with the least transportation cost can be formulated for the liner company.

(iii) From the perspective of cargo owners affected by the suspension or port jump, the use of delayed route plans provided by liner companies can solve the problem of difficulty in finding suitable voyages. The cargo owner can estimate whether the liner company will arrange cargo flow recovery for it by comparing the total transportation value of the cargo with the transportation cost to the nearby alternative shipping line loading port.

When the supply in the shipping market exceeds its demand, liner companies can charge appropriate surcharges to shippers whose transportation demand is disrupted, which is beneficial to both parties. When the supply in the shipping market exceeds its demand, liner companies can solve the problem of difficulty in finding suitable transportation plans to solve the problem of hard-to-find a container.

Data availability

No data was used for the research described in the article.

CRediT authorship contribution statement

Yibo Liu: Project administration, Writing – review, Methodology, Editing. Xu Zhao: Conceptualization, Final approval. Rui Huang: Methodology.

Conflicts of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Declaration of competing interest

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

References

Abioye, O.F., Dulebenets, M.A., Pasha, J., Kavoosi, M., 2019. A vessel schedule recovery problem at the liner shipping route with emission control areas. Energies 12 (12), 2380. https://doi.org/10.3390/en12122380.

Broer, B.D., Dirksen, J., Pisinger, D., Plum, C.E.M., Vaaben, B., 2013. The Vessel Schedule Recovery Problem (VSRP) - a MIP model for handling disruptions in liner shipping. Eur. J. Oper. Res. 224 (2), 362–374. https://doi.org/10.1016/j.ejor.2012.08.015.

Chen, C., Yang, Z., 2010. Optimizing time windows for managing export container arrivals at Chinese container terminals. Marit. Econ. Logist. 12 (1), 111–126. https://doi.org/10.1057/mel.2009.21.

Chen, J., Fei, Y., Wan, Z., 2019. The relationship between the development of global maritime fleets and GHG emission from shipping. J. Environ. Manag. 242 (Jul.15), 31–39. https://doi.org/10.1016/j.jenvman.2019.03.136.

Cheraghchi, F., Abualhaol, I., Falcon, R., Abilemon, R., Raabemi, B., Petriu, E., 2018. Modeling the speed-based vessel schedule recovery problem using evolutionary multiobjective optimization. Information ences 448–449, 53–74. https://doi.org/10.1016/j.ijevo.2018.03.013.

Fagerholt, K., 2000. Evaluating the trade-off between the level of customer service and transportation costs in a ship scheduling problem. Marit. Pol. Manag. 27 (2), 145–153. https://doi.org/10.1006/josc.2000.0265.

Fagerholt, K., Laporte, G., Norstad, I., 2010. Reducing fuel emissions by optimizing speed on shipping routes. J. Oper. Res. Soc. 61 (3), 523–529. https://doi.org/10.1057/jors.2009.77.

Fischer, Andreas, Fagerholt, Kjetil, Stalhane, Magnus, Nokhart, Hakon, Rakke, Jorgen, 2016. Robust planning and disruption management in roll-on roll-off liner shipping. Transport. Res. Part E Logistics Transp. Rev. 91, 51–67. https://doi.org/10.1016/j.tre.2016.02.013.

Francesco, M., Lai, M., Zuddas, P., 2013. Maritime repositioning of empty containers under uncertain port disruptions. Comput. Ind. Eng. 64 (3), 827–837. https://doi.org/10.1016/j.cie.2012.12.014.

Gang, Y., Qi, X., 2004. Disruption Management: Framework, Models and Applications: Disruption Management: Framework, Models and Applications. World Scientific Publishing Co. Pte. Ltd. https://doi.org/10.1142/5632 number 5632, June.

Li, C., Qi, X., Lee, C., 2015. Disruption recovery for a vessel in liner shipping. Transport. Sci. 49 (4), 900–921. https://doi.org/10.1287/trsc.2015.0589.

Li, C., Qi, X., Song, D., 2016. Real-time schedule recovery in liner shipping service with regular uncertainties and disruption events. Transp. Res. Part B Methodol. 93 (nov), 762–788. https://doi.org/10.1016/j.trb.2015.10.004.

Liu, C., Li, Z., Zhang, C., 2016. Behavior perception-based disruption models for berth allocation and quay cargo assignment problems. Comput. Ind. Eng. 97 (Jul), 258–275. https://doi.org/10.1016/j.cie.2016.04.008.

Meng, Z.L., Jian, G.J., Liu, C.X., 2015. Real-time disruption recovery strategy for integrated berth allocation and crane assignment in container terminals. Transportation Research Rec. J. Transp. Res. Board 2479 (2479), 49–59. https://doi.org/10.3141/2479-07.

Notteboom, T.E., 2006. The time factor in liner shipping services. Marit. Econ. Logist. 8 (1), 19–39. https://doi.org/10.1057/palgrave.mel.9100348.

Qi, X., 2015. Disruption Management for Liner Shipping. International Series in Operations Research & Management Science, 220. Springer, Cham. https://doi.org/10.1007/978-3-319-11891-8_8.

Qi, X., Song, D.P., 2012. Minimizing fuel emissions by optimizing vessel schedules in liner shipping with uncertain port times. Transport. Res. Part E 48 (4), 863–880. https://doi.org/10.1016/j.trpe.2012.02.001.

Rezapour, S., Khosrojerdi, A., Rasoulifar, G., Allen, J.K., Mistree, F., 2018. Disruption Management: Architecting Fail-Safe Supply Networks, first ed. CRC Press, Boca Raton. https://doi.org/10.1201/9781498772406.

Tan, Y., Tan, Gz., Deng, Sg, 2014. Hybrid particle swarm optimization with chaotic search for solving integer and mixed integer programming problems. J. Cent. South Univ. 21, 2731–2742. https://doi.org/10.1016/j.iscs.2011.04.2235-6.

Vernimmen, B., Dullaert, W., Engelen, S., 2007. Schedule unreliability in liner shipping: origins and consequences for the hinterland supply chain. Marit. Econ. Logist. 9 (3), 191–213. https://doi.org/10.1057/palgrave.ml.9100182.

Wang, S., Qiang, M., 2012. Liner ship route schedule design with sea contingency time and port time uncertainty. Transp. Res. Part B 46 (5), 615–633. https://doi.org/10.1016/j.trb.2012.01.003.

Xing, J., Wang, Y., 2019. Disruption management in liner shipping: a service-cost trade-off model for vessel schedule recovery problem. In: 2019 5th International Conference on Transportation Information and Safety (ICTIS). https://doi.org/10.1109/ICTIS.2019.8883603, 2019.

Xu, L., Yang, S., Chen, J., Shi, J., Yang, C., 2021b. Evolutionary game analysis on behavior strategies of multiple stakeholders in maritime shore power system. Ocean Coast Manag. 202, 105508. https://doi.org/10.1016/j.ocecoaman.2020.105508.

Xu, L., Di, Z., Chen, J., Shi, J., Yang, C., 2021a. The effect of COVID-19 pandemic on port performance: evidence from China. Ocean Coast Manag. 209, 105660. https://doi.org/10.1016/j.ocecoaman.2021.105660.