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Integrated scheduling of intermodal transportation with seaborne arrival uncertainty and carbon emission

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ABSTRACT

The world trade globalization process has triggered growing attention to port-centric supply chain (PCSC) management, wherein the land transport and maritime transport are connected by ports. Modern scheduling plans for PCSC should put more emphasis on intermodal transportation to achieve an effective and environmental-friendly management scheme. Therefore, this paper proposes an integrated scheduling model with an improved multiple heterogeneous coding genetic algorithm for PCSC management, wherein the intermodal transportation has been investigated under seaborne uncertainties. By analyzing the overall cost and carbon emission under different operational strategies, the effects and countermeasures of integrated scheduling on system optimization and carbon emission mitigation policy in PCSC are discussed. The results of case studies based on a departure port in Southeast China indicate that the integrated scheduling method proposed can significantly decrease the overall system cost and carbon emission. Moreover, suggestions on optimal resource allocation and carbon emission reduction are proposed.

1. Introduction

Maritime transport is one of the major transport modes of the international supply chain in today's globalized world. About 90% of the European Union's trade with third countries is handled through ports (The parliament magazine, 2015). Today's seaports, which are the crucial joint nodes of the supply chain, have got various added-value services integrated. By closely cooperating with other parties in the supply chain, the development of ports needs to enhance their competitiveness by cutting down the emission, mitigating the marginal costs, and achieving quick responses to various demands along the supply chain. Gradually, a port-centric hinterland with suppliers, producers, and shippers is formed. Here, extending from the concept of port-centric logistics defined by Mangan et al. (2008), this study is developed by targeting a port-centric supply chain (PCSC) in which all the added-value services (manufacture, packaging, transportation, etc.) are deployed around a central port. The PCSC has attracted substantial attention recently. One of the focal concerns related to PCSC lies in developing a suitable scheduling method.

In PCSC, various added-value services and multiple transportation options make the structure of PCSC more complex. Despite maritime transportation is full of uncertainties, one must-mentioned segment is the intermodal transportation system which can improve freight transportation carbon footprint. Ports take benefits from the on-dock railway since trains consume less fuel than trucks. However, how to make a smooth scheduling plan in such a complex system with multiple transportation modes is still unsolved since different transportation modes are under different operation patters. In the traditional supply chain management, by focusing on

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their interests, different parties develop their independent scheduling plans separately. The independent scheduling, in which scheduling problems at each segment (e.g. production, overland transportation, maritime transportation) are solved separately, is vulnerable to segment failure and will lead to further burdensome working load from a chain perspective. Considering that the activities in PCSC occur sequentially, integrated scheduling, which can achieve a cost-effective plan (Chen, 2004), is a suitable and worthwhile option.

Existing studies have proved that the integrated scheduling can avoid inefficiencies, reduce operational costs and resource waste, and further improve customer satisfaction (Gao et al., 2015; Geismar et al., 2008). Chen (2010) conducted a review study on integrated production and distribution scheduling problems (IPDS) and classified models in the literature into five classes based on their delivery method. The study highlighted that a fair number of studies mainly focused on the integrated scheduling with trucks from two streams. One stream is the vehicle routing problem (VRP). For example, Naso et al. (2007) integrated a multi-depot VRP with time windows and a production scheduling problem. They aimed to minimize the transportation costs, operation cost, cost caused by idle waiting, and other costs related to drivers' working time and outsourced production; Another stream is the scheduling problem considering the limited vehicle capacity. García et al. (2002) provided an exact algorithm to find the optimal solutions to the IPDS by considering finite available vehicles. Some studies have been conducted to investigate the scheduling issues with rail transportation. Hajiaghaei-Keshteli et al. (2014) developed an integrated scheduling model in which orders are transported by trains from one factory to multiple destination points. However, in the existing study, only a handful of studies have considered integrated scheduling with maritime transportation. Ma et al. (2013) studied an integrated scheduling model in which orders from a factory are delivered by vessels. Sun et al. (2015) proposed a practical approach for IPDS considering the variations and limits of maritime transport. More recently, Ganji et al. (2020) developed a multi-objective model for IPDS with heterogeneous trucks. Generally, most previous studies only focused on problems with a single mode of transportation.

Transportation has been considered as one of biggest contributors to carbon emission (Liu and Ge, 2018). The importance of intermodal transportation in the current economic environment has been recognized since the last century. At the Summit on North American Intermodal Transportation, the transportation minister of Canada Collenette (1997) noted that "intermodalism today is about safe, efficient transportation by the most appropriate combination of modes." The same point of view has also been mentioned by Yevdokimov (2000). Given the potential economic, social and environmental impacts been thoroughly analyzed, scholars concluded that the intermodal transport is also promising for indirect economic benefits, such as relieving traffic congestion (Handman, 2002), promoting technological innovation (Szyliowicz, 2003), improving the environment (Janic, 2007), and increasing efficiency.

Only a few studies investigated the IPDS considering intermodal transportation. Hammami et al. (2012) studied the production-distribution problem of containers transported either by trucks or by ships, whereas, combined transport was not considered. Similarly, the study by Azadian et al. (2015) only involved the choice of air or surface transportation. Frank Meisel et al. (2013) developed a model for combining overland transportation to study this issue at the strategy level (production volume, output volume, etc.) instead of an operational scheduling plan. Given the limited studies conducted, several points should be further investigated when making an integrated scheduling plan for a practical supply chain with intermodal transportation. Firstly, various transportation modes, e.g. train, ship, and truck, should be investigated all together under different operation methods. Trains and ships usually run with stable frequency under a timetable, while trucks can pick up cargo based on flexible demands. Secondly, the operation processes in transfer centers should be considered. Additional storage costs in transfer centers and time limitations of the transition process may complicate the issue further. Last but not the least, to study a scheduling issue considering intermodal transportation in a PCSC, the uncertainty features of maritime transportation should also be highlighted (Tongzon, 2009). Even though routes of liner ships are generally determined by shipping companies in advance. Due to complex influential factors, such as long-distance voyages and weather conditions, maritime transportation is under great uncertainty: ships may not arrive in port on time. Vernimmen et al. (2007) noted that the uncertainty of ship arrival times can seriously impact on other parties in the supply chain. This unavoidable delay must be taken into consideration when studying integrated scheduling with intermodal transportation in PCSC since ship reservation is one of the key parts in PCSC scheduling. Moreover, when running on-dock rail services, how to deploy the operation strategies to enhance the advances on reducing carbon emission and achieve the green, cost-effective and smooth freight transportation simultaneously remains unsolved.

To fill up those gaps on the integrated production and intermodal transportation scheduling issues in a PCSC, this paper developed an integrated scheduling model considering intermodal transport (IT-ISM). The model was built to determine the optimal production strategy and intermodal transportation schedule simultaneously in a made-to-order PCSC, wherein seeking lower total cost is the main objective. Here, considering the practical randomness of maritime transport, an improved genetic algorithm with a reduced feasible region is proposed. The reduced feasible region can effectively improve the convergence rate of the algorithm without losing the optimal solution. The integrated scheduling plan can not only achieve an overall cost reduction but also identify the resource bottleneck by investigating the sub-cost at each segment. Moreover, this study investigates the effectiveness of different operation strategies related to on-dock rail policy for carbon emission reduction. Then, comparisons of overall cost and carbon emission among baseline case and various cases with different train frequencies and carbon taxes are conducted.

This paper consists of five sections. Section 1 is an introduction with literature review. Section 2 illustrates the research problem in detail, presents the IT-ISM and all notations. The developed algorithm is introduced in Section 3. Section 4 conducts a case study with practical data. Finally, Section 5 presents conclusions and future research directions.

2. Problem description and programming formulation

2.1. Problem description

Fig. 1 illustrates a typical PCSC with multimodal transportation. There are three key segments: an inland industrial park with a transit center (TC-IP for short), an origin port, and several destination ports. From TC-IP to the origin port, cargo is transported by trains or trucks. Liner ships are responsible for the transport between the origin ports and destination ports.

TC-IP produces multiple products from raw materials to meet diverse demands. Each order j contains only one kind of product and has a raw materials release time t_j^{RS}. After t_j^{RS}, the raw materials are stored in the TC-IP with a storage cost until the production line begins to produce order j. There are different production lines in TC-IP. One production line can produce more than one type of products with different production efficiencies. One order can only be produced by one production line. Finished orders are stored in the TC-IP until they are transported to the origin port, either by trains or trucks.

For transportation, the choice of overland transportation is mostly constrained by maritime transportation. In other words, scheduling on maritime transport should be made first, since overland transportation is more flexible than the maritime transportation. All shipment bookings are decided based on expected schedules published by liner shipping companies. Once a ship has been booked for an order, the order should arrive at the origin port before the cut-off day of the selected ship. For overland transportation to the origin port, an order can be delivered either by a train or a truck. Given that trains depart from the TC-IP to the origin port under a constrain of the fixed timetable. A finished order can only be assigned to a train whose scheduled departure time form TC-IP is latter than the order's production completion time. After production, the order must wait in TC-IP for the train's scheduled departure time. Alternatively, some orders can be delivered by trucks with a more flexible departure time. If an order is going to be transported by a truck, after the production a truck will be called. Then, overland transportation will start just after a short response and preparation time ε^V of the truck. After arriving at the origin port, a storage cost will be accrued until the follow-up shipping process begins.

Practically, the actual departure and corresponding arrival time of a ship do not always stick to the expected schedules. Weather conditions, operations in previous ports of call, and other complex factors all may lead to unmanageable delay. Thus, based on the expected schedules, a random term should be introduced to reflect the unavoidable delays in practice. The uncertain arrival delay of ships may further lead to uncertain downstream delivery. Generally, an expected pick up time t_j^D is given by customers for each order j at the destination port. Tardiness arrival at the destination port will lead to a tardiness cost c_j^{DT}. As for early arrival, free storage is provided at the destination port within an acceptable time. However, if orders arrive too early and the storage time exceeds the free storage time duration ϕ_g, an additional storage cost c_j^{DE} may be applied for the excess storage.

2.2. Assumptions and notations

To provide a practical scheduling tool for decision-makers, an IT-ISM model has been built with several essential assumptions: (1) All the production lines and operating machines are working independently under normal conditions (machinery breakdowns and

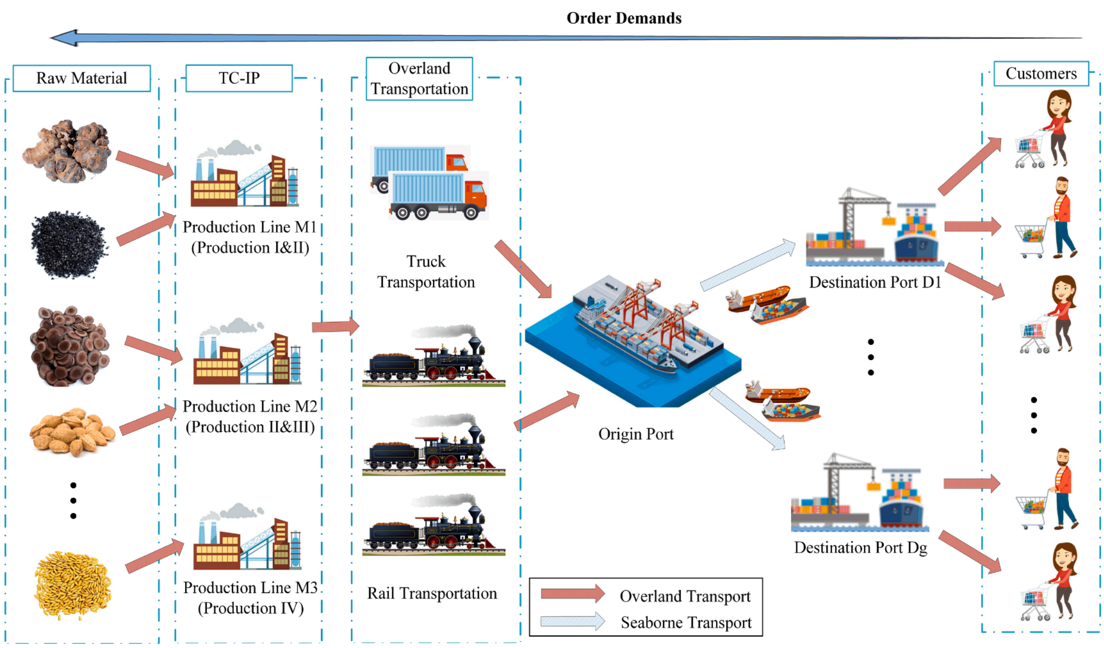

Fig. 1. Illustration of a port-centric supply chain with multimodal transportation.

uncommon emergencies are not taken into consideration); (2) All the production lines are initially available; (3) All order information and scheduled arrival times of ships are given at the beginning of the process; (4) The number of trucks is sufficient to transport all cargos of one order to a port at the same time; (5) Split transportation is not allowed in overland transportation and maritime transportation schemes, and (6) Customers will send trucks to pick up orders at destination ports based on the expected arrival date in the destination port. All the notations used in the model and their descriptions are summarized in Table 1.

2.3. Model formulation

The mathematical model is formulated as follows.

$$\mathrm{Min}\sum_{j\in J}\left(Z_j^{\mathrm{P}}+Z_j^{\mathrm{S}}+Z_j^{\mathrm{MT}}+Z_j^{\mathrm{LT}}+Z_j^{\mathrm{D}}\right) \tag{1}$$

where

$$Z_j^{\mathrm{P}}=q_j\sum_{i\in I}x_{ji}^{\mathrm{P}}c_{ji}^{\mathrm{P}} \tag{2}$$

$$Z_j^{\mathrm{MT}}=q_j\sum_{g\in G}x_{jg}^{\mathrm{G}}c_{jg}^{\mathrm{MT}} \tag{3}$$

Table 1
Notations and descriptions.

Notation	Description	Notation	Description
Sets		t^{TV}	The transportation time by trucks
I	Set of production lines	t_g^{G}	The shipping time to the destination port g
J	Set of orders	M	A large positive number
S	Set of ships	γ	The on-board loading efficiency
E	Set of trains	ϕ_g	The free storage duration of port g
G	Set of customers	δ^{O}	The required lead time before shipping in the origin port
Decision variables		ε^{V}	The response and preparation time of trucks
x_{ji}^{P}	1, if order j is assigned to production line i	α_{ji}	The production efficiency of order j on production line i
x_{js}^{S}	1, if order j is assigned to ship s	x_{jg}^{G}	1, if order j is for destination port g
x_{je}^{T}	1, if order j is assigned to train e	y_{sg}^{G}	1, if ship s is for destination port g
w_{jui}^{P}	1, if order j precedes order u on production line i	c^{TEM}	The monetary value of railway transportation's carbon emission from the production site to the departure port for unit cargo
w_{jus}^{S}	1, if order j precedes order u on ship s	c^{VEM}	The monetary value of road transportation's carbon emission from the production site to the departure port for unit cargo
Δ_s	The uncertain delay of ship s	***Auxiliary variables***	
Parameters		Z_j^{P}	The production cost of order j
c_{ji}^{P}	The unit production cost of order j on line i	Z_j^{S}	The storage cost of order j
c_{jg}^{MT}	The unit maritime transportation cost of order j to port g	Z_j^{MT}	The maritime transportation cost of order j
c_e^{LTE}	The rail-way transportation cost for unit cargo of train e	Z_j^{LT}	The overland transportation cost of order j
c^{LTV}	The road transportation cost for unit cargo	Z_j^{D}	The penalty cost of order j
$c_j^{\mathrm{S_1}}$	The unit storage cost of order j in the factory	$j(o)$	dummy order, the starting order
$c_j^{\mathrm{S_2}}$	The unit storage cost of order j in port	$j(e)$	dummy order, the ending order
c_j^{DT}	The unit tardiness penalty cost of order j	t_j^{LTO}	Starting time for overland transportation of order j
c_j^{DE}	The unit earliness penalty cost of order j	t_j^{LTC}	Completion time for overland transportation of order j
q_j	The quantity of order j	t_{ji}^{PO}	Starting time for the production of order j on production line i
q_s^{S}	The available loading capacity of ship s	t_{ji}^{PC}	Completion time for the production of order j on production line i
q_e^{E}	The max available loading ability of train e	t_s^{AR}	The actual arrival time of ships, equal to$t_s^{\mathrm{AS}}+\Delta_s$
t_j^{RS}	The release time for order j	t_s^{AD}	The actual departure time of ship s
t_j^{D}	The scheduled delivery time of order j	t_j^{FD}	The final delivery time of order j
t_s^{AS}	The scheduled arrival time of ship s	t_j^{LO}	The on-board loading start time of order j
t_e^{EO}	The scheduled departure time of train e	t_j^{LC}	Completion time for loading order j
t^{TE}	The transportation time by trains		

$$Z_j^{\mathrm{LT}} = q_j(\sum_{e \in E} x_{je}^{\mathrm{T}} (c_e^{\mathrm{LTE}} + c^{\mathrm{TEM}}) + \left(1 - \sum_{e \in E} x_{je}^{\mathrm{T}}\right)(c^{\mathrm{LTV}} + c^{\mathrm{VEM}}) \tag{4}$$

$$Z_j^{\mathrm{S}} = q_j[c_j^{S_1}(\sum_{i \in I} x_{ji}^{\mathrm{P}} t_{ji}^{\mathrm{PO}} - t_j^{\mathrm{RS}}) + c_j^{S_1}(t_j^{\mathrm{LTO}} - \sum_{i \in I} x_{ji}^{\mathrm{P}} t_{ji}^{\mathrm{PC}}) + c_j^{S_2}(\sum_{s \in S} x_{js}^{\mathrm{S}} t_s^{\mathrm{AD}} - t_j^{\mathrm{LTC}})] \tag{5}$$

$$Z_j^{\mathrm{D}} = q_j[c_j^{\mathrm{DE}} max(0, t_j^{\mathrm{D}} - t_j^{\mathrm{FD}} - \phi_g) + c_j^{\mathrm{DT}} max(0, t_j^{\mathrm{FD}} - t_j^{\mathrm{D}})] \tag{6}$$

The objective function (1) targets to minimize all costs including the production cost, storage cost at the factory and origin port, maritime transportation cost, overland transportation cost, and delivery penalty cost. The production and maritime transportation costs are defined by functions (2) and (3), separately. Function (4) defines the overland transportation cost Z_j^{LT}. If order j is transported by train e, Z_j^{LT} equals the unit cost of train e multiplied by the quantity q_j. Otherwise, Z_j^{LT} equals the unit trucking cost multiplied by the quantity q_j. The storage cost is defined in function (5). Storage cost occurs at both the factory and the origin port. In reality, after the raw materials are ready, there is a storage cost may be applied before the orders are produced. When the production process is completed, orders are stored in the factory before being transported to the port by trains or trucks. Origin ports charge storage fees based on the storage times of orders before shipping. Function (6) represents the penalty cost of earliness or tardiness for final delivery. Notably, there is generally a free storage period ϕ_g at destination ports.

2.3.1. Constraints

$$\sum_{i \in I} x_{ji}^{\mathrm{P}} t_{ji}^{\mathrm{PO}} \geq t_j^{\mathrm{RS}} \quad \forall j \in J \tag{7}$$

$$\sum_{i \in I} x_{ji}^{\mathrm{P}} = 1 \quad \forall j \in J \tag{8}$$

$$\sum_{j \in J \cup \{j(o)\}, j \neq u} w_{jui}^{\mathrm{P}} = x_{ui}^{\mathrm{P}} = \sum_{k \in J \cup \{j(e)\}, u \neq k} w_{uki}^{\mathrm{P}} \quad \forall i \in I, u \in J \tag{9}$$

$$\sum_{i \in I} \sum_{j \in J \cup \{j(o)\}, u \neq j} w_{jui}^{\mathrm{P}} = 1 \quad \forall u \in J \tag{10}$$

$$\sum_{i \in I} \sum_{u \in J \cup \{j(e)\}, u \neq j} w_{jui}^{\mathrm{P}} = 1 \quad \forall j \in J \tag{11}$$

$$w_{jui}^{\mathrm{P}} + w_{uji}^{\mathrm{P}} \leq 1 \quad \forall i \in I, j \in J, u \in J : u \neq j \tag{12}$$

$$\sum_{i \in I} x_{ui}^{\mathrm{P}} t_{ui}^{\mathrm{PO}} + \mathrm{M}(1 - \sum_{i \in I} w_{jui}^{\mathrm{P}}) \geq \sum_{i \in I} x_{ji}^{\mathrm{P}} t_{ji}^{\mathrm{PC}} \quad \forall j \in J \cup j(o), \forall u \in J \cup j(e) : u \neq j \tag{13}$$

$$\sum_{i \in I} x_{ji}^{\mathrm{P}} t_{ji}^{\mathrm{PC}} - \sum_{i \in I} x_{ji}^{\mathrm{P}} t_{ji}^{\mathrm{PO}} = \sum_{i \in I} \frac{x_{ji}^{\mathrm{P}} q_j}{\alpha_{ij}} \quad \forall j \in J \tag{14}$$

Functions (7) to (14) are constraints related to the production process. Constraint (7) indicates that the production process can only start after t_j^{RS}. Constraint (8) ensures that one order can only be produced in one production line. Constraints (9) to (12) guarantee the uniqueness of the production sequence. Constraint (13) prevents the production process of the latter order from the beginning until the prior order is finished. Constraint (14) states that the production time of order j equals to the order quantity q_j divided by the production efficiency α_{ij}.

$$\sum_{s \in S} x_{js}^{\mathrm{S}} = 1 \quad \forall j \in J \tag{15}$$

$$\sum_{s \in S} x_{js}^{\mathrm{S}} y_{sg}^{\mathrm{G}} = x_{jg}^{\mathrm{G}} \quad \forall j \in J, g \in G \tag{16}$$

$$\sum_{j \in J} x_{js}^{\mathrm{S}} q_j \leq q_s^{\mathrm{S}} \quad \forall s \in S \tag{17}$$

$$\sum_{j \in J \cup j(e)} w_{j(o)js}^{\mathrm{S}} t_j^{\mathrm{LO}} = t_s^{\mathrm{AR}} = t_s^{\mathrm{AS}} + \Delta_s \quad \forall s \in S \tag{18}$$

$$\sum_{j \in J \cup \{j(o)\}, u \neq j} w_{jus}^{\mathrm{S}} = x_{us}^{\mathrm{S}} = \sum_{k \in J \cup \{j(e)\}, u \neq k} w_{uks}^{\mathrm{S}} \quad \forall s \in S, u \in J \tag{19}$$

$$\sum_{s\in S}\sum_{j\in J\cup\{j(o)\},u\neq j} w^{S}_{jus} = 1 \quad \forall u \in J \tag{20}$$

$$\sum_{s\in S}\sum_{u\in J\cup\{j(e)\},u\neq j} w^{S}_{jus} = 1 \quad \forall j \in J \tag{21}$$

$$w^{S}_{jus} + w^{S}_{ujs} \leq 1 \quad \forall s \in S, j \in J, u \in J : u \neq j \tag{22}$$

$$t^{LC}_{j} = t^{LO}_{j} + \frac{q_j}{\gamma} \quad \forall j \in J \tag{23}$$

$$t^{LO}_{u} + \mathrm{M}(1 - \sum_{s\in S} w^{S}_{jus}) \geq t^{LC}_{j} \quad \forall j \in J \cup j(o), u \in J \cup j(e) : u \neq j \tag{24}$$

$$t^{AD}_{s} = \max\left(x^{S}_{js} t^{LC}_{j}\right) \quad \forall j \in J \tag{25}$$

$$t^{FD}_{j} = \sum_{s\in S} x^{S}_{js} t^{AD}_{s} + \sum_{g\in G} x^{G}_{jg} t^{G}_{g} \quad \forall j \in J \tag{26}$$

Functions (15) to (24) describe constraints in the shipping process. Constraints (15) ensures that one order can only be shipped by one vessel. Constraint (16) limits that the destination port of the selected ship must be the same as the order. Constraint (17) defines that the loading volume of ship s cannot exceed the loading capacity. Constraint (18) indicates that the loading process can only start after the actual arrival of a ship. The actual arrival time of ship s is equal to the scheduled arrival time plus an uncertain delay. Δ_s is an uncertain term that cannot be predicted in advance. In the following case study, data related to the delay time have been collected from the case study port and got the distribution of Δ_s. Constraint (19) to (22) ensures the validity and uniqueness of loading sequences. Constraint (23) defines the loading time of order j, which is equal to the quantity q_j divided by the on-board loading efficiency γ. Constraint (24) limits the loading time sequences. Constraint (25) defines the calculation of actual departure time t^{AD}_{s}. Constraint (26) states that the final delivery time equals the departure time from the origin port plus the shipping time to the destinations.

$$\sum_{e\in E} x^{T}_{je} \leq 1 \quad \forall j \in J \tag{27}$$

$$t^{LTO}_{j} = \sum_{e\in E} x^{T}_{je} t^{EO}_{e} + (1 - \sum_{e\in E} x^{T}_{je})(\sum_{i\in I} x^{P}_{ji} t^{PC}_{ji} + \varepsilon^{V}) \quad \forall j \in J \tag{28}$$

$$t^{LTC}_{j} = t^{LTO}_{j} + \sum_{e\in E} x^{T}_{je} t^{TE} + (1 - \sum_{e\in E} x^{T}_{je}) t^{TV} \quad \forall j \in J \tag{29}$$

$$\sum_{i\in I} x^{P}_{ji} t^{PC}_{ji} < t^{LTO}_{j} < t^{LTC}_{j} \leq t^{LO}_{j} - \delta^{O} \quad \forall j \in J \tag{30}$$

$$\sum_{j\in J} x^{T}_{je} q_j \leq q^{E}_{e} \quad \forall e \in E \tag{31}$$

Constraint (27) states that one order can be transported by only one type of overland transport. Constraint (28) defines the starting time of overland transportation. If order j is transported by train e, t^{LTO}_{j} equals to the scheduled departure time of train e. Otherwise, t^{LTO}_{j} equals to the production completion time plus the response and preparation time of the trucks. Constraint (29) defines t^{LTC}_{j}, the completion time for overland transportation of order j, is equal to t^{LTO}_{j} plus the overland transportation time. Constraint (30) indicates that overland transportation can start when the production process is completed. Moreover, orders must be transported to the origin port before the cut-off time. Constraint (31) limits the loading volume of the trains.

3. Genetic algorithm

The integrated scheduling problem, considering multiple customers and factories, was proven to be an NP-hard problem (Fu et al.,

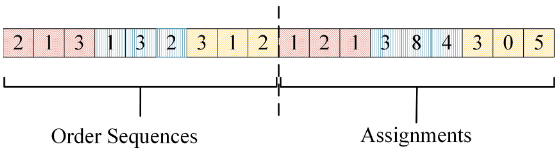

Fig. 2. A simple multiple heterogeneous coding chromosome.

2018; Zhong et al., 2010). Various improved heuristic algorithms have been studied to solve similar problems. The genetic algorithm is one of the common methods used to solve such NP-hard integrated scheduling problems and has been proved to be effective (Behnamian et al., 2012; Grunder et al., 2013; Tang and Gong, 2008; Ullrich, 2013; Guo et al., 2020). Behnamian et al. (2012) conducted an experiment to compare genetic algorithm performances under different parameters. By adopting this two-stage genetic algorithm concept, in this study, an improved multiple heterogeneous coding method genetic algorithm with heuristic rules has been proposed.

In the IT-ISM, the assignment and sequence issues need to be determined at the same time. To solve these decision issues within one-stage, multiple heterogeneous coding methods in a genetic algorithm (MHC-GA) has been developed. Here, a simple case with three orders (J1–J3) is introduced as an example (in Fig. 2). In this case, there are 2 production lines (M1 and M2), 10 ships (S1–S10), and 5 trains (T1–T5). "0" is used to indicate road transportation.

As shown in Fig. 2, the numerical values in the first half are the order numbers, while the numerical values in the latter half are the number of production lines, ships, trains, or trucks. The first half of the chromosome indicates the order sequence, the latter half indicates the production and transportation assignments. The first and latter halves of the genes have a one-to-one correspondence. Red segments are genes related to the production process, blue segments are genes associated with maritime transportation, and overland transportation genes are shown in yellow. Taking order J3 as an example, J3 is going to be produced by M1 and then shipped to the destination by ship S8. Train T3 will transport J3 from the TC-IP to the origin port. From the aspect of a production line (e.g., M1), as shown in the red segments, J2 and J3 are both produced on line M1. J2 will be produced before J3, since in red segments of the first half, J2 is ahead of J3.

Figs. 3 and 4 illustrate the crossover and mutation operations, respectively. The crossover operation aims to diversify the order sequences, and the mutation operation targets at the assignments. By using the multiple heterogeneous coding methods, the crossover and mutation operations must be improved at the same time to ensure the validity of offspring.

As shown in Fig. 3, the first two genes are selected for crossover operations. Then, a check operation will be executed. For duplicate orders, the last duplicate order gene will be changed to a missing order to guarantee the validity after crossover. For example, in the first half of offspring 1, J3 appears four times, while J1 only appears twice. Then in the check operation, the last J3 will be changed to the absent J1. After the check operation, the latter half of a gene will be rearranged to ensure that the assignments of the orders' new offspring are the same as those of the parents. The genes in the latter half were checked one by one. Take J3 as an example, in the parent chromosome 1, J3 is produced by M1, transported by train T3, and ship S8. Then after crossover in the first half of offspring 1, the latter half will be re-arranged to ensure J3 was still assigned to M1, T3, and S8. At this point, the whole chromosome has been updated through crossover operations.

Mutation operations aim to change assignment genes within the feasible region. The mutation on production line assignments will impact on the production completion time of an order, and lead to invalid assignments for liner ship and overland transportation assignment. Similarly, the mutation of shipment assignments may make the overland transportation scheme invalid. Thus, after mutation, a double-check operation must be implemented to confirm the validity of the aforementioned processes.

In addition, as the key part of the scheduling plan in a port-centric supply chain. The feasible region of ship reservation was further reduced by excluding potential aberrant operations with heuristic rules. Considering liner ships are sorted and numbered by their arrival time at the origin port, the start and endpoint of the ship selection region on their arrival time should be decided as follows.

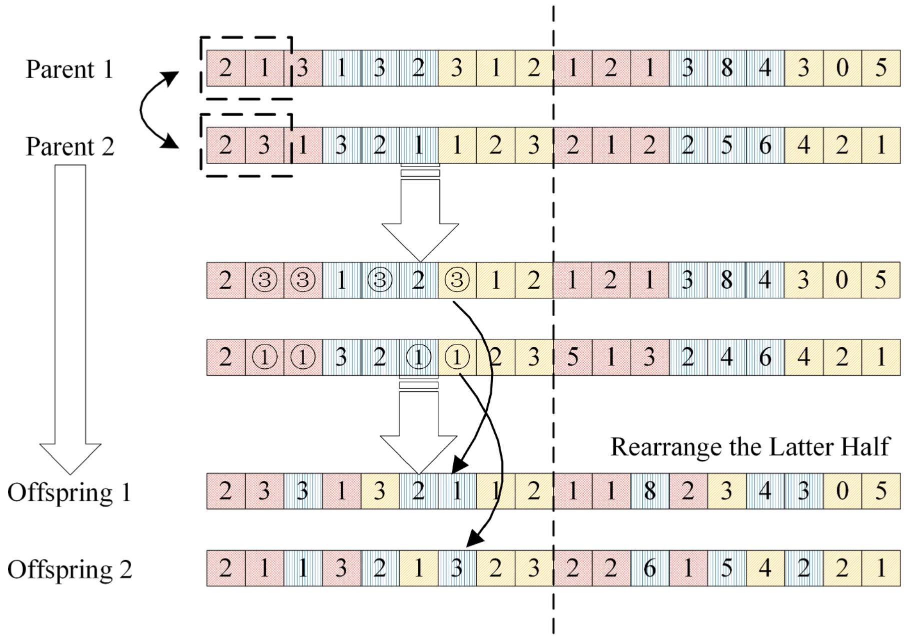

Fig. 3. Process of crossover operations.

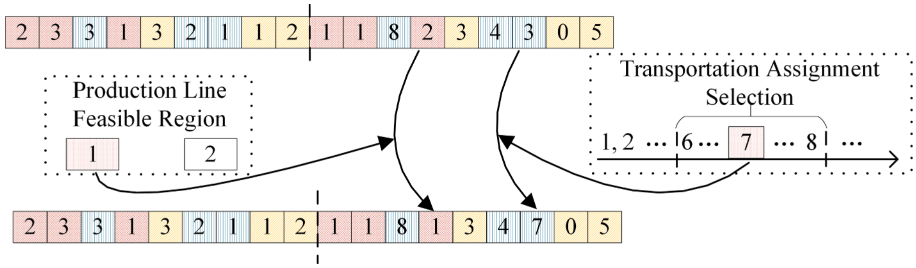

Fig. 4. Process of mutation operations.

Firstly, there is a required lead time considering the inspection and other procedures in port. The start point of feasible selection should be the ship with the smallest number, whose arrival time is greater than or equal to the total minimum time required for order production, overland transportation, and necessary operation in the origin port. Then, the endpoint of the feasible ship selection range was controlled based on the concept of an acceptable delay. Here, for this case, the delay penalty will be limited to no more than twofold of the maritime transportation cost. This endpoint limit is a general case and can be adjusted based on the actual conditions. For example, if customers have very high time requirements, then the endpoint can be set to ensure that the order only picks up a ship with an expected delivery time no later than the order's final delivery time. Among all the feasible ships, an order will give priority to the ship whose arrival time in the destination port is close to the order's final delivery time. Finally, a comparison analysis between the basic MHC-GA (BMHC-GA) and MHC-GA with a reduced feasible region (IMHC-GA), by focusing on the convergence rate and solution quality, is conducted and presented in the case study part at Section 4.

4. Case study

A case study is conducted based on a port located in Southeast China with one inland TC-IP. As an example, 20 Orders (J1–J20) under three product categories (Products I to III) has been investigated in a two-month integrated scheduling plan. As a proof of concept, these three product categories are designed with different time sensitivities and the corresponding range of the lead time ($t_j^{D} - t_j^{RS}$) and unit tardiness penalty cost c_j^{DT}, as shown in Table 2. In the TC-IP, five production lines (M1–M5) are available to produce products with different production efficiency α_{ji} and unit cost c_{ji}^{P}. Trains depart from the TC-IP to the origin port every three days. Each train can load products at a maximum of 50 TEUs. The unit road transportation cost for a container is 1.32 USD per kilometre (based on the statistical mean value of China in 2019). The unit rail-way transportation cost for a container is 0.375 USD per kilometre, which is obtained from the China Railway Customer Service Center. Then, from the TC-IP to the departure port, c_e^{LTE} is 186 USD per container, and c^{LTV} is 656 USD per container. According to Bouchery and Fransoo's work (2015), the carbon emission of linear train for a container per kilometre is 0.22 kg, while the road transportation poses 0.9 kg emission for a container per kilometre. Based on the statistical data in 2019, the carbon price of Shanghai is 4 USD/ton. Then, from TC-IP to the departure port, c^{TEM} is 0.44 USD per container, c^{VEM} is 1.8 USD per container.

Table 3 shows input factors related to the two destination ports (destination port A and B) of 20 orders. Port A is a port in Southeast Asia. Port B is located in North America. Then, shipping time t_g^{G} and shipping cost c_{jg}^{T} to the destination ports can be estimated and are also shown in Table 3. For each destination port, six liner ships are available with an expected and fixed timetable. The storage cost in port is higher than that in the TC-IP. Data of ship arrival delay is collected from the case port. Fig. 5 is the historical statistic result of ships' uncertain arrival delays in the case study port in 2017.

The program is coded in MATLAB R2018a. The basic algorithm parameters selection is based on the study of Behnamian et al.

Table 2
Inputs related to product types.

Product Type		Product I			Product II		Product III	
Orders		J1–J8			J9–J13		J14–J20	
t_j^{RS}(Day)		U (0,15)						
$t_j^{D} - t_j^{RS}$(Day)		U (40,60)			U (30,60)		U (20,30)	
c_j^{DE}(USD)		40			40		40	
c_j^{DT}(USD)		150			190		220	
Production Line	Line Number	M1	M3	M5	M2	M5	M2	M4
	α_{ji}(TEU/ Hour)	0.44	0.44	0.45	0.35	0.35	0.4	0.35
	c_{ji}^{P}(USD)	180	180	200	210	210	190	170
$c_j^{S_1}$ (USD)		10						
$c_j^{S_2}$ (USD)		20						
q_j(TEU)		U (20,80)						

Table 3
Inputs related to destinations.

	Destination Port A	Destination Port B
t_g^G(Hour)	270	420
c_{jg}^T(USD)	220	2200
Orders	J1, J2, J6, J10, J11, J12, J18, J19	J3, J4, J5, J7, J8, J9, J13, J14, J15, J16, J17, J20
The number of ships	6 (DAS1–DAS6)	6 (DBS1–DBS6)
The arrival interval	U (0,500)	U (0,500)
q_s^S(TEU)	80	

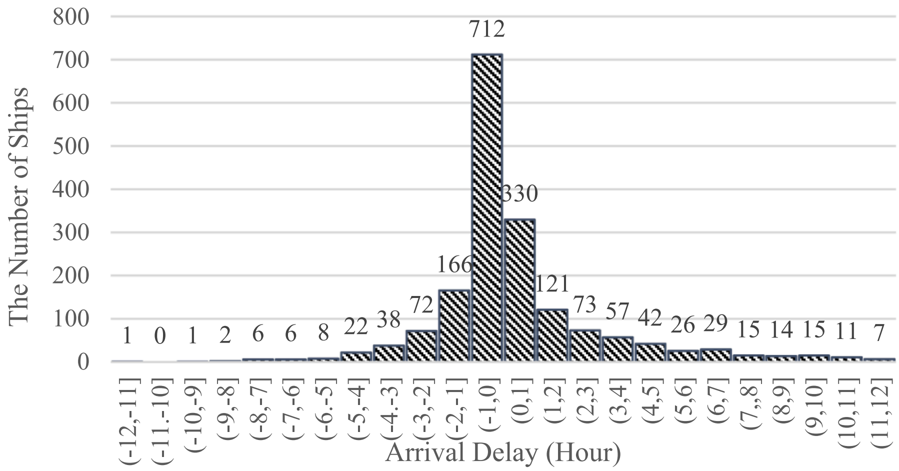

Fig. 5. The frequencies of arrival delays.

(2012). In this study, given that the algorithm in this research is a single-level genetic algorithm, the crossing-over rate can decrease to 0.7. Meanwhile, the population size was increased to an initial number of 1000. The aberration rate is 0.05 and the maximum evolutionary generation is 3000.

4.1. Comparison of algorithm

The introduced heuristic rules related to aberrant operation might impact on the computation speed and solution quality. To further testify the performance of the proposed algorithm, a 10-round comparison analysis of the convergence rate and the solution optimality between algorithms "with" (IMHC-GA) and "without" (BMHC-GA) the heuristic rules is conducted. If the approximate optimal solution found by the IMHC-GA is better than that of the BMHC-GA in one run, score 1 (S1) equals to 1; otherwise, S1 equals to

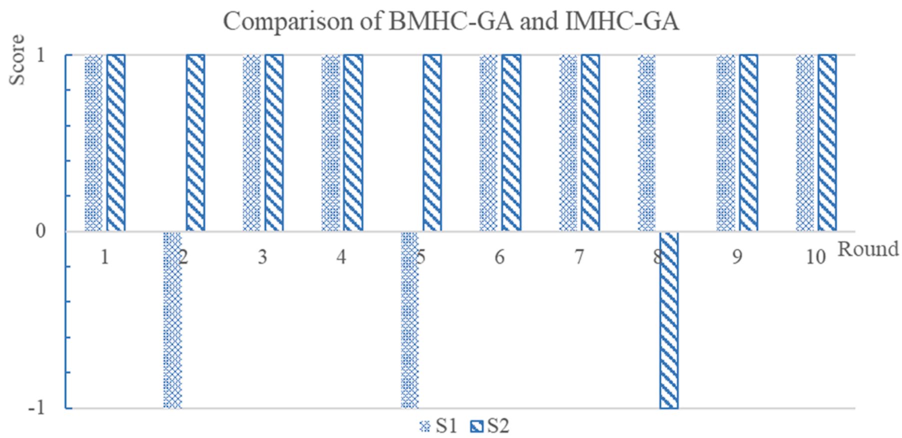

Fig. 6. Comparison of the BMHC-GA and IMHC-GA.

−1. If the IMHC-GA finds the results faster than the BMHC-GA in one run, score 2 (S2) equals to 1; otherwise, S2 equals to −1. As shown in Fig. 6, among the comparison of two models in 10 rounds, the IMHC-GA model (with heuristic rules) won in 8 rounds for the convergence rate and outperformed the traditional model without heuristic rules in 9 rounds for the solution quality.

4.2. Results analysis

In addition, a cost comparison between integrated scheduling (IS) and non-integrated scheduling (NIS) has also been conducted. Fig. 7 shows the cost of NIS and IS. As shown in Fig. 7, IS is an efficient way of reducing the overall cost. The total cost decreases nearly 4000 USD from NIS to IS. The integrated scheduling method can make a tradeoff between each sector and achieve a reduction in overall cost.

The whole process Gantt chart is shown in Fig. 8, and the production process of each production line is illustrated in Fig. 9. When comparing the duration of each process for every order, maritime transport consumes the longest time duration and the land transport time is relatively short. The storage time in different locations (storage at factories, origin ports, and destination ports) shows a negative correlation with the different storage costs. For example, the storage time in the factory is significantly higher than the storage time in ports. In another context, the processing time to fulfill orders of product III is apparently less than time for other products. For example, the average processing time of product I (J1–J8) is 978 h, which is 64% bigger than that of product III (J14–J20). Product III has the shortest required lead time and the highest penalty cost. The observation indicates that the integrated scheduling can well allocate the resource to processing orders with higher time sensitivity.

Fig. 9 illustrates the results of the production process. As shown in Fig. 9, the production utilization might be imbalanced. For instance, M1 and M3 are the specialized production line for product I. However, after produced order 4, the production line M3 is idle most of the time compared with M1. This provides important hints for further decision making on resource investment: the production resources for the product I are relatively abundant.

The resulting graph of convergence with the proportion of different sub-cost is shown in Fig. 10. The proportion of storage costs, overland transportation costs, and production costs are relatively stable. The maritime cost is fixed in the model since all destinations are known inputs. During evolution, the proportion of fixed maritime cost increases since the total cost decreases. A significant decrease can be seen in the penalty cost and overland transportation cost. During the first 500 iterations, the penalty costs decrease from 7% to 5%. Finally, the proportion of penalties decreased to 4%, approximately.

Fig. 11 presents the detailed loading results of trains. Fig. 12 shows the detailed loading results for ships. Among 20 orders, 19 orders select train transportation. Meanwhile, regarding the loading conditions, another important observation is that the tasks of T3, T7, T10, and T13 trains are heavier than other trains. It can provide valuable hints for the train scheduling department by recognizing and predicting the potential peak season in the railway operation. Stakeholders may want to improve the loading ability of railway transportation in the peak season thereafter.

4.3. Carbon emission sensitive analysis of railway deployment

Carbon emission is one of the focal points in the container tranportation (Yu et al., 2017). As stated before, on-dock railway service

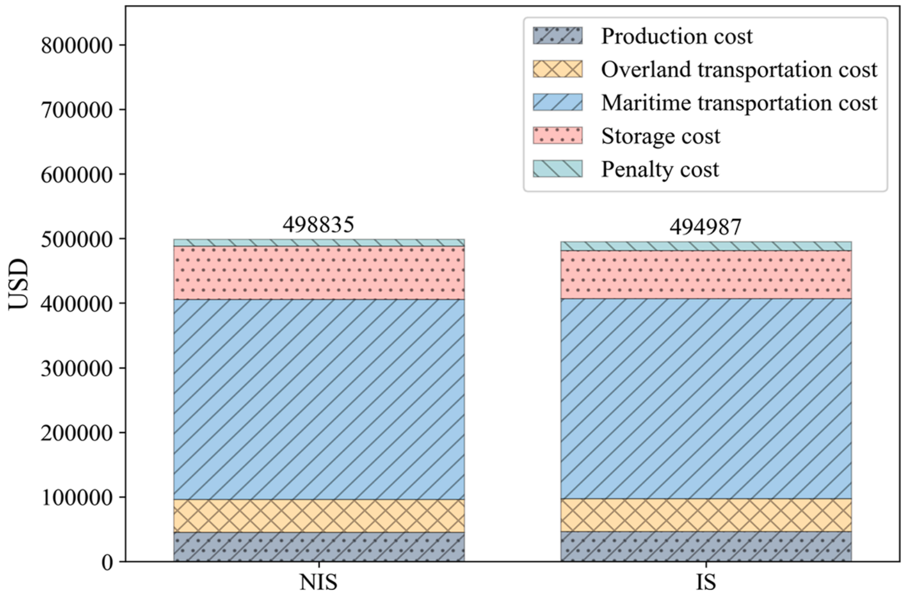

Fig. 7. Cost comparison between NIS and IS.

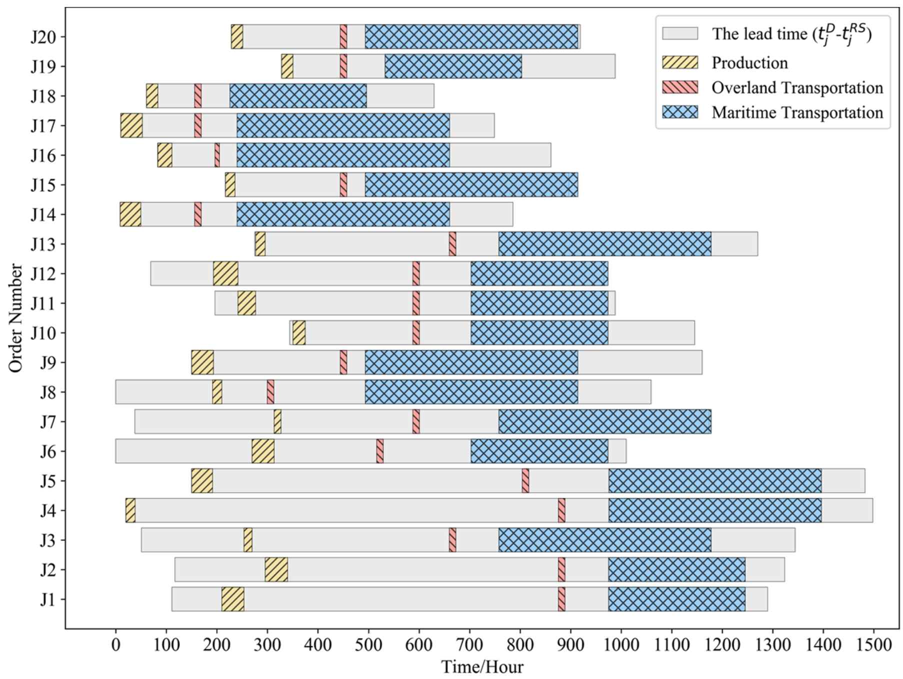

Fig. 8. The process gantt chart for each order.

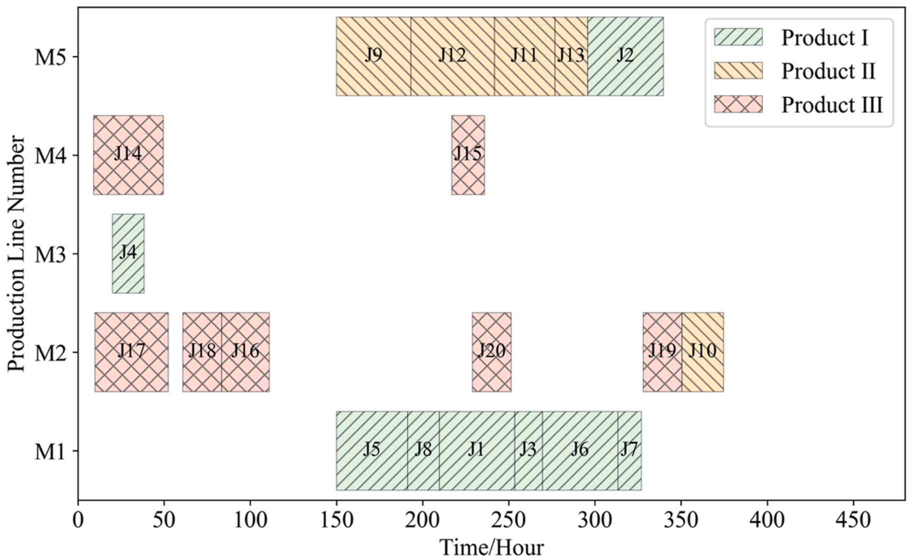

Fig. 9. The production process gantt chart for each production line.

is considered to be a green option with a low unit cost. Policymakers such as the governments, port operators, definitely encourage the utilization of railway transportation to meet the carbon emission target. However, the fixed departure schedules of trains make this option lack of flexibility. Considering the delay penalty and storage cost brought by the inappropriate train, shippers sometimes may choose road transportation to achieve the goal of minimizing overall cost. One big concern of the policymakers is how to encourage the utilization of railway transportation. Increasing the operation frequency of train seems to be the most direct way. However, the deployment of train resources should also consider the cargo volume demand and the additional fixed cost for every new run of the train. That is to say, higher operation frequency of train will lead to higher unit transportation cost and less wagons per train.

Another way to promote the usage of railway transport is to increase the carbon tax. Higher carbon tax enlarges the transportation cost gap between trucks and trains, and is expected to enhance the adoption of railway transportation. In line with this consideration, two additional cases have been considered to investigate shippers' responses to these two operational strategies under the integrated

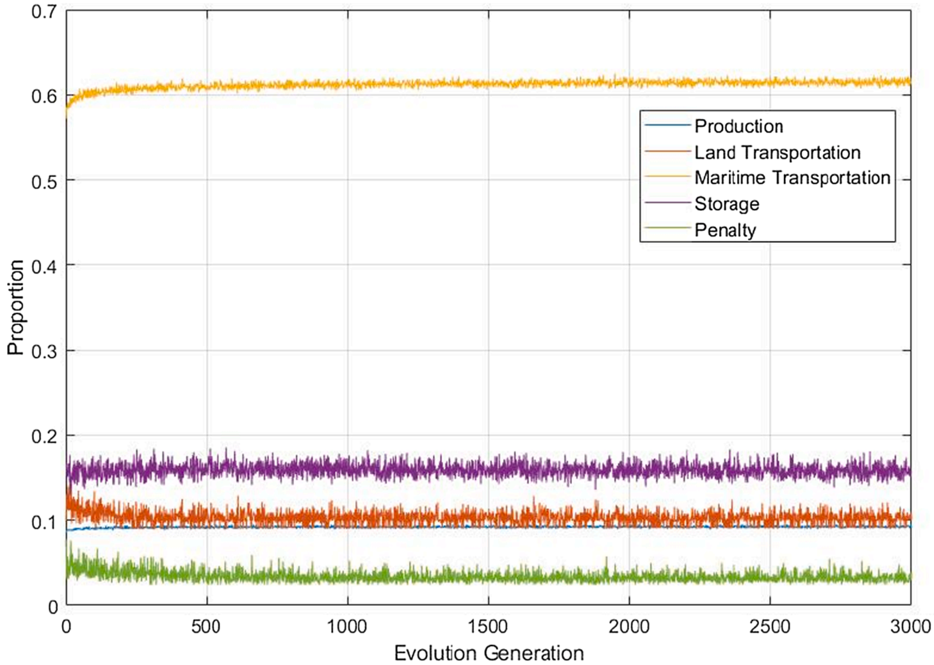

Fig. 10. The proportion of each sector's cost.

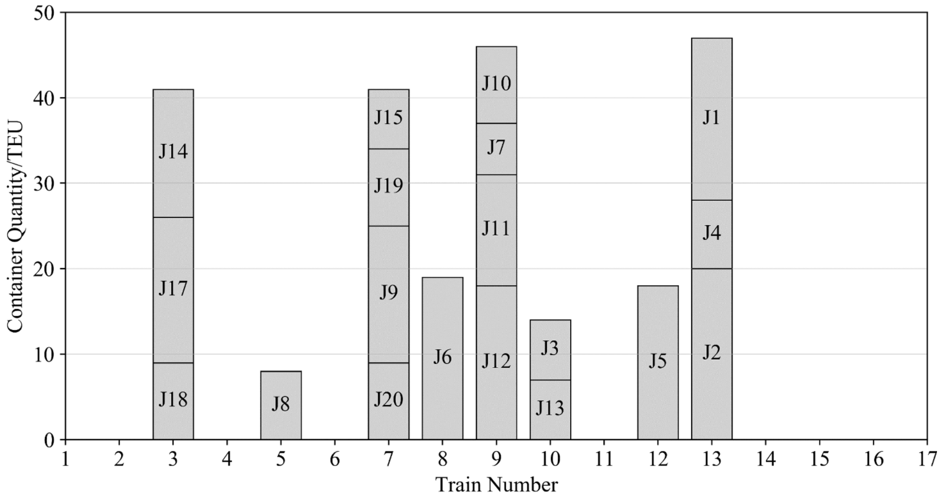

Fig. 11. The loading condition for each train.

scheduling scheme. Case 1 is the baseline scenario presented in the last section. In case 2, the departure interval was reduced to 2 days which means a train departure from TC-IP every 2 days. Then, based on the number posted by World Bank Group (2019), the carbon tax increased from 4 USD/ton (adopted by Shanghai pilot ETS) to 16 USD/ton (adopted by California CaT) in case 3. According to the work of Zhang et al. (2013), the fixed cost of a new train run is approximately 300 USD. Considering that, c_e^{LTE} of case 2 is nearly 9 USD higher than that of case 1. The related parameters are shown in Table 4.

Two metrics are compared: the total cost and carbon emissions. Though the monetary value of carbon emission is included in the total cost, to obtain a better understanding of these cases from the perspective of environmental protection, the carbon emissions of overland transportation (CEOT) has been calculated additionally. For each order, the CEOT was calculated by multiplying the unit carbon emission per run between the TC-IP and the origin port with the order quantity. The carbon emission of the linear train for a container per kilometre is 0.22 kg, while the road transportation has 0.9 kg emission for a container per kilometre. Then in the trip from the TC-IP to the departure port, the railway's carbon emission for one container is 0.11 tons, and road transportation's carbon emission for one container is 0.45 tons. The results are shown in Fig. 13.

In the NIS and IS (baseline case 1), order J16 is transported by trucks. The CEOT of case 1 is 30.7 tons. When cutting down the

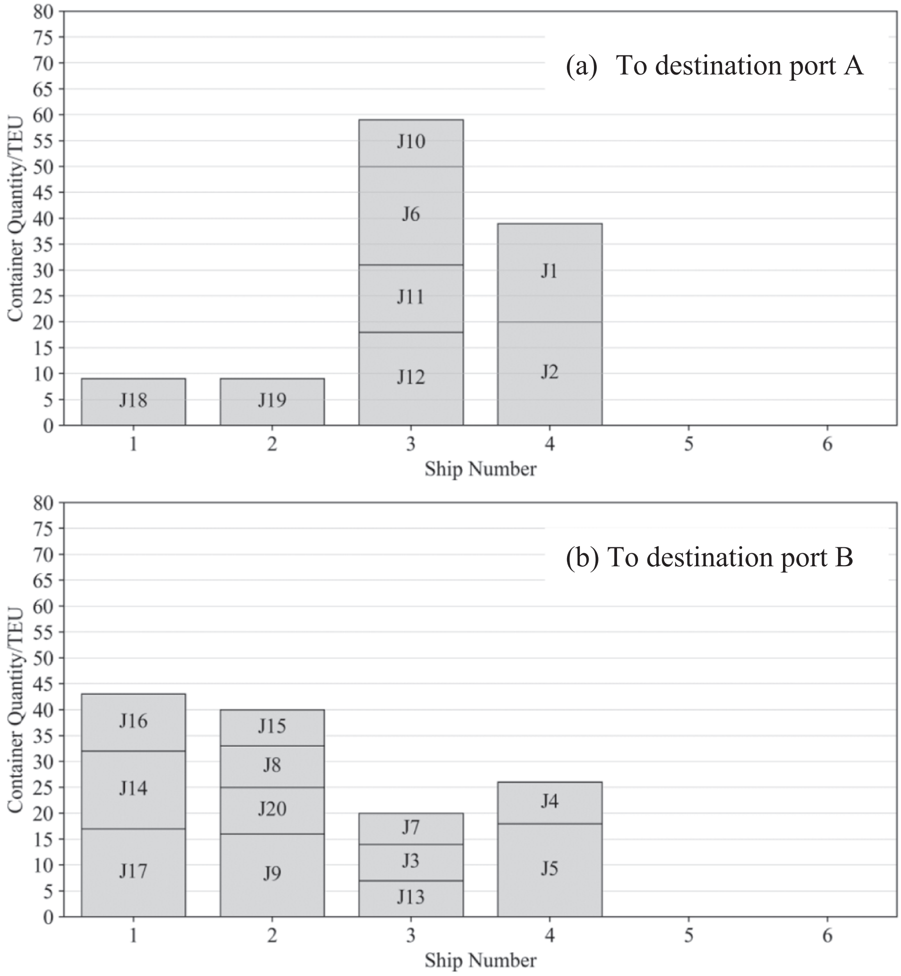

Fig. 12. The loading condition for each ship.

Table 4
Parameters in the extended cases.

	Case 1	Case 2	Case 3
Departure Interval (Hour)	72	48	72
q_e^{E}(TEU)	50	30	50
Carbon Tax (USD/ton)	4	4	16
c_e^{LTE}(USD)	186	195	188
c_e^{LTV}(USD)	660	660	665

train's departure interval to two days (case 2), all orders choose rail-way transportation. In case 2, the CEOT decreases to 23.1 tons. However, the total cost of case 2 increase by 1151 USD compared with the baseline case. In case 2, the capacity gap between a train and a ship is larger than that of case 1. Sometimes, not all orders shipped by the same vessel can be shipped by the train with the most appropriate schedule. Thus, some orders have to take earlier trains and be stored in the port. This leads to an increase of the storage cost. In case 2, the storage cost is 6% higher than that of case 1. In case 3, the train's departure interval is 72 h, and the carbon tax increase to 16 USD/ton (the price adopted by California). All orders select to be tranportated by trains in case 3. The CEOT of case 3 is the same as that of case 2. Compared with the baseline case 1, the total cost of case 3 increased 400 USD. The results of case 2 and case 3 indicates that both two strategies can enhance the utilization of railway transportation and reduce the carbon emission. In this case study, however, increasing the train operation frequency led to a significant increase in the total cost. Compared with case 2, increasing the carbon tax is a more acceptable way to promote the green system development. Additionally, the impact of the increasing carbon tax is more obvious in the integrated scheduling compared with the non-integrated scheduling. In NIS, the production plan and the maritime transportation plan which have been made separately, put time constraints on the overland transportation plan. Thus,

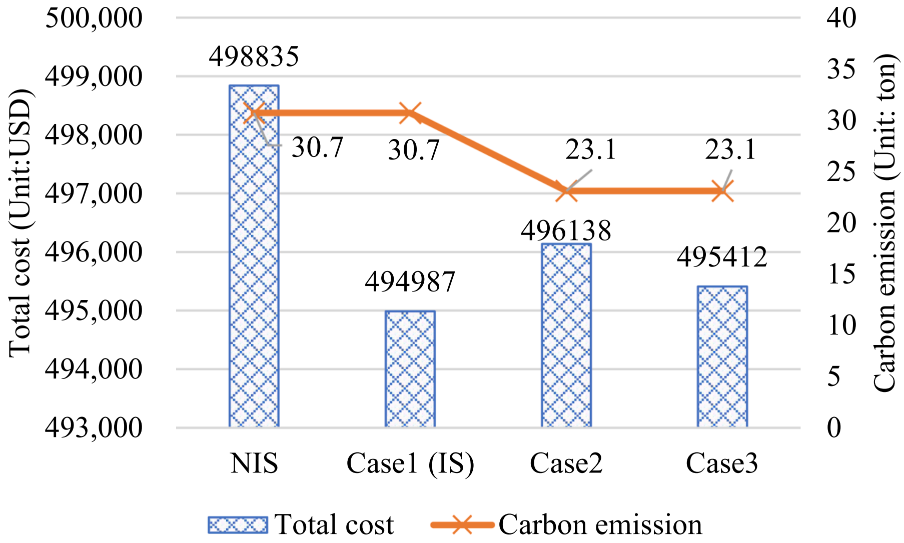

Fig. 13. The total cost and carbon emissions of overland transportation.

changes in carbon tax brought very limited impacts on the overland transportation scheduling plan.

5. Summary and conclusions

Given the limited research on integrated scheduling (IS) of multimodal transportation in a Port-Centric Supply Chain (PCSC) management topic, this paper proposes an integrated production and distribution model to improve the system performance of a PCSC from both environmental and economical point of view. Herein, intermodal transportation, including both overland transportation and seaborne transportation with uncertain delay, is considered. Under the dual constraints of the raw materials release date and required delivery date, the optimal integration scheduling plan is achieved by answering the following four questions, including (1) which production line will be used to produce the order, (2) how will the production sequence of each line be, (3) which trains or trucks will be chosen, and (4) which liner ship will be booked. Then, the multiple heterogeneous chromosome codes with improved crossover and mutation operations are developed, in this study, to solve those complex scheduling issues. Specifically, a cost-effective scheduling plan with additional consideration on the heterogeneous randomness of the entire supply chain process has been developed in this paper.

Based on the IS plan, valuable information can be obtained to support the resource allocation at each stage of the supply chain for different stakeholders. Notably, idle resources, such as the production line of M3 in the case study, can also be identified to further improve the system efficiency and services. Further investments in production lines for products II and III could be considered based on the current operating system. Moreover, targeting at the overland transportation process, the identified loading conditions of trains can also be used to improve the resource allocation from the perspective of train station management. A higher operation frequency may lead to a lower CEOT value but increase the total cost significantly. Instead of applying the existing isolated management protocols or simply increasing the trains' operation frequency, an integrated management plan can be expected to increase the utilization of train resources and reduce the carbon emission with a higher carbon tax. The environmental benefit of the increasing carbon tax is obvious in an integrated scheduling plan. By applying the integrated scheduling method, the PCSC system becomes more flexible. Shippers can adjust both the upstream and downstream processes in response to any changes in the system.

As for future research topics, the unbalanced departure intervals of trains and decentralized factories, instead of using one industrial center with centralized shipments, might be investigated. Together with the scheduling model proposed in this paper, future studies are expected to work on how to deploy train resources considering the cargo volume, cargo value, and downstream maritime transportation resources.

CRediT authorship contribution statement

Wenyuan Wang: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Xinglu Xu:** Methodology, Software, Formal analysis, Writing - original draft. **Ying Jiang:** Investigation, Resources, Writing - review & editing. **Yunzhuo Xu:** Data curation, Validation, Writing - original draft. **Zhen Cao:** Visualization, Data curation, Writing - original draft. **Suri Liu:** Software, Visualization, Formal analysis.

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