Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

SHIP FLEET TYPE DECISION CONSIDERING EMPTY CONTAINER ALLOCATION

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This paper addresses a problem of ship fleet type decision considering container fleet sizing and empty container repositioning (denoted as empty container allocation). Empirically, the ship fleet type decision is made according to laden container transportation, and does not consider the empty container allocation. This study hence builds a mixed-integer programming model for the problem. Based on the model, it is founded that the empty container allocation has an underlying network flow structure given a fixed ship fleet type and thus can be transferred to a standard minimum cost flow problem. Supposing the empty container allocation is optimized, some properties for the ship fleet type decision are investigated, e.g., given the maximum number of containers that will be carried by ships, the best ship type may not necessarily be the ship type whose capacity is close to the maximum number. Meanwhile, it is shown that if the empty container repositioning is not considered when determining the ship fleet type, the total cost may increase significantly.

Keywords: Ship fleet type, container fleet sizing, empty container repositioning, network flow.

1 Introduction and Background

In shipping liner industry, shipping companies normally deploy container ships to transport laden containers among ports by weekly-serviced shipping routes. Given a shipping route, one critical decision is to determine the capacity of container ships deployed over a given planning horizon, which is the ship fleet type decision. Traditionally, the liner shipping operators determine the capacity only by considering the laden container transportation, which guarantees that the deployed ships have the capacity to just accommodate all the laden container transportation in all the voyages. However, if we further consider possible empty container repositioning on the shipping route, the ship fleet type decision can be more complicated. The empty container repositioning provides the shipping liner with the motivation to deploy a ship fleet with a larger capacity (Song and Dong, 2013). Although it will raise the fixed operation cost, it gives the shipping liner more flexibility and capacity to reposition empty containers among ports. Then, the container fleet sizing is intertwined with the ship fleet deployment and the empty container repositioning. The container fleet sizing determines the total number of containers flowing along the whole planning horizon. As those containers would be either in the depots or on the ships, the effects on the ship fleet type decision are inevitable. Meanwhile, more empty containers can be repositioned to fulfill cargo transport demand if the container fleet is large.

Given a shipping route, our study aims to solve a ship fleet type decision problem considering the container fleet sizing and empty container repositioning, in order to minimize the total cost that occurs in a given planning horizon. The problem focuses on decisions at both tactical level and operational level. At the tactical level, a ship type for the fleet of container ships is to be determined (i.e., ship fleet type decision), which decides the capacity of ships deployed. Meanwhile, the problem also needs to decide how many empty containers are leased in the depots of the ports initially among the route for the usage of the whole planning horizon, which is the container fleet sizing. At the operational level, upon each weekly service, the problem aims to decide how many empty containers in the depot of each port are used to fulfill the weekly laden container demands from origin ports to destination ports. If there are empty containers surplus in ports, the empty container repositioning is also the critical decision to relieve the empty container deficit in other ports. If there are empty containers deficit in some ports, the shipping liner may lease empty containers from local container leasing containers and return them at the destinations ports. Here, we summarize the empty container repositioning at the operational level and the container fleet sizing at the tactical level as the empty container allocation in the problem.

2 Model Formulation

In the problem, the given shipping route has a fixed port rotation such that the itinerary of this route forms a loop. Let $p \in P$ represent the index of the ports on a round trip. Based on the given route, the shipping liner has a set of O–D port pairs D. The laden container demands rise between those pairs in each week. We represent (o, d) as the index for the O–D port pairs, where $o \in P, d \in P$. For the given shipping service route, there is one week interval for each port to be visited by one round trip and its next round trip. Let e represent the index of round trips, and E as the set of round trips for one planning horizon. The weekly laden container demands for each port accumulate between the visiting times of two adjacent round trips and are fulfilled by the latter round trip. At the beginning of the planning horizon, there is a candidate set V of ship types that can be deployed on the shipping route.

2.1 *Notations*

Input parameters:N: number of ships deployed in the shipping service route; C_v: fixed operation cost when the ships in Type v are deployed; K_v: container capacity of the ships in Type v with the unit of TEUs; w: number of weeks that are needed for the devanning; $d_{od,e}$: number of laden container shipment demand from Port o to Port d that should be transported by the e^{th} round trip; s_p: unit weekly storage cost of an empty container in Port p; r_{od}: unit repositioning cost of an empty container from Port o to Port d, including container loading and unloading cost; l_{od}: unit short-term leasing cost of a standard container from Port o to Port d; I_p: initial number of empty containers available owned by the shipping liner in Port p; L_p: long-term leasing cost of a container for the planning horizon usage in Port p.

Decision variables:ε_v: binary, set to one if the ships in Type v are deployed, otherwise zero; ζ_p: integer, number of long-term leasing containers in Port p; $\alpha_{od,e}$: integer, number of empty containers used to satisfy the laden container demands from Port o to Port d by the e^{th} round trip; $\beta_{od,e}$: integer, number of empty containers repositioned from Port o to Port d by the e^{th} round trip; $\gamma_{od,e}$: integer, number of short-term empty containers leased in Port o for the e^{th} round trip and will returned in Port d; $\delta_{p,e}$: integer, inventory level of empty containers at Port p after visited by the e^{th} round trip; $\eta_{p,e}$: integer, number of containers in the container ship on the e^{th} round trip after it visits Port p.

2.2 *Mathematical model*

[$\boldsymbol{M1}$] min $\sum_{v\in V} C_v\varepsilon_v + \sum_{p\in P} L_p\zeta_p + \sum_{e\in E}\sum_{(o,d)\in D} l_{od}\gamma_{od,e} + \sum_{e\in E}\sum_{(o,d)\in D} r_{od}\beta_{od,e} + \sum_{e\in E}\sum_{p\in P} s_p\delta_{p,e}$ (1)

subject to

$\sum_{v\in V}\varepsilon_v = 1$ (2)

$\alpha_{od,e} + \gamma_{od,e} = d_{od,e}$ $\quad\forall(o,d)\in D, e\in E,$ (3)

$I_p + \zeta_p + \sum_{d=p,o<d,(o,d)\in D}\beta_{od,e} = \sum_{o=p,(o,d)\in D}(\alpha_{od,e}+\beta_{od,e}) + \delta_{p,e}\ \forall p\in P, e=1,$ (4)

$\delta_{p,e-1} + \sum_{d=p,o<d,(o,d)\in D}\beta_{od,e} + \sum_{d=p,o>d,(o,d)\in D}\beta_{od,e-N} + \sum_{d=p,o<d,(o,d)\in D}\alpha_{od,e-w} + \sum_{d=p,o>d,(o,d)\in D}\alpha_{od,e-N-w} = \sum_{o=p,(o,d)\in D}(\alpha_{od,e}+\beta_{od,e}) + \delta_{p,e}\forall p\in P, e\in E\backslash\{1\},$ (5)

$\eta_{p,e} = \sum_{o\le p,d>p,(o,d)\in D}(d_{od,e}+\beta_{od,e}) + \sum_{d\ge p+1,o>d,(o,d)\in D}(d_{od,e-N}+\beta_{od,e-N})$
$\quad\forall p\in P/\{P\}, e\in E,$ (6)

$\eta_{p,e} = \sum_{o>d,(o,d)\in D}(d_{od,e}+\beta_{od,e})$ $\quad\forall p=|P|, e\in E,$ (7)

$\eta_{p,e} \le \sum_{v\in V} K_v\varepsilon_v$ $\quad\forall p\in P, e\in E,$ (8)

$\varepsilon_v\in\{0,1\}$ $\quad\forall v\in V,$ (9)

$\zeta_p\in\mathbb{Z}_+$ $\quad\forall p\in P,$ (10)

$\alpha_{od,e},\beta_{od,e},\gamma_{od,e}\in\mathbb{Z}_+$ $\quad\forall(o,d)\in D, e\in E,$ (11)

$\delta_{p,e},\eta_{p,e}\in\mathbb{Z}_+$ $\quad\forall p\in P, e\in E,$ (12)

In the above model, Objective (1) minimizes the total cost, including the fixed operation cost, the long-term leasing cost, the short-term leasing cost, the repositioning cost, and the storage cost. Constraint (2) guarantees that only one type of ships can be selected. Constraints (3) enforce that the laden container demands in each port by each round trip must be fulfilled by using the available empty containers or short-term leasing containers in the port. Constraints (4) provide the inventory equations for empty containers in each port after visited by the 1^{st} round trip. Constraints (5) list the inventory equations in Port p after visited by the e^{th} round trip. Constraints (6-7) calculate the number of containers carried in the deployed ship on the e^{th} round trip after visiting Port p. Constraints (8) enforce that the number of containers carried in the ships cannot exceed the capacity of the type of the deployed ships. Constraints (9-12) define the decision variables.

3 Property Analysis

In this section, we would investigate some properties of the problem under some assumptions in order to find more insights on the problem.

3.1 *Empty container allocation*

If we only consider the empty container allocation for the problem, we can reformulate the problem as a minimum cost flow problem, such that the problems can be solved effectively.

Proposition 1: Suppose that in the problem, the ship fleet type decision is not considered, i.e., the type of ships deployed in the shipping route is given with the capacity as K. Then, the problem can be transformed to a minimum cost flow problem.

Proof: See Section 4.2 of Wang et al. (2017). ■

For the minimum cost flow problem, we have an integer property, whose proof can be found in many operations research books:

Lemma 1: The coefficient matrix of the minimum cost flow problem is totally unimodular. If all the input parameters for the minimum cost flow problem are integral, the LP solution obtained by solving the LP relaxation is feasible and thus optimal for the problem.

3.2 *Ship fleet type decision*

Assuming that the empty container allocation has been optimized, there are some properties for the ship fleet type decision.

Proposition 2: For the ship fleet type decision, suppose that the capacity of the ship types has economies of scale, i.e., the fixed operation cost function $C = f(K)$ is a strictly concave function. Here, we rank the set of ship types with an increasing container capacity order such that $K_1 < K_2 < \cdots < K_v < \cdots < K_{|V|-1} < K_{|V|}$ and $C_1 < C_2 < \cdots < C_v < \cdots < C_{|V|-1} < C_{|V|}$. Due to the concavity, we have $\frac{C_v - C_{v-1}}{K_v - K_{v-1}} > \frac{C_{v+1} - C_v}{K_{v+1} - K_v}, \forall v \in V/\{1, |V|\}$. Under this condition, if we relax constraints (9) and solve the model $\boldsymbol{M1}$, we can obtain $\eta^*_{p,e}, \forall p \in P, e \in E$ and denote $\omega^* = \max\{\eta^*_{p,e} | \forall p \in P, e \in E\}$ as the maximum number of containers carried by ships among all the voyages. Thereafter, there are following properties in terms of $\varepsilon_v, \forall v \in V$ in the optimal LP solution: (i) if $\omega^* \le K_1$, it holds that $\varepsilon_1^* = 1$ and $\varepsilon_v^* = 0, \forall v \in V/\{1\}$; (ii) if $K_1 < \omega^* < K_{|V|}$, it holds that $\varepsilon_1^* > 0, \varepsilon_{|V|}^* > 0$ and $\varepsilon_v^* = 0, \forall v \in V/\{1, |V|\}$; thus, $\varepsilon_1^* = \frac{K_{|V|} - \omega^*}{K_{|V|} - K_1}, \varepsilon_{|V|}^* = \frac{\omega^* - K_1}{K_{|V|} - K_1}$; (iii) if $\omega^* = K_{|V|}$, it holds that $\varepsilon_{|V|}^* = 1$ and $\varepsilon_v^* = 0, \forall v \in V/\{|V|\}$.

Proof: (i) If $\omega^* \le K_1$: for the ship deployment, we can simplify the model with the given ω^* as $z = \min\{\sum_{v\in V} C_v \varepsilon_v \mid \sum_{v\in V} \varepsilon_v = 1;\ \sum_{v\in V} K_v \varepsilon_v \ge \omega^*;\ 0 \le \varepsilon_v \le 1, \forall v \in V\}$. Assume that we have the optimal solution $\varepsilon_v^*, \forall v \in V$, in which there is a $v' > 1$ such that $\varepsilon_{v'}^* > 0$. Here, we can design a new solution $\tilde{\varepsilon}_v, \forall v \in V$ such that $\tilde{\varepsilon}_1 = \varepsilon_1^* + \varepsilon_{v'}^*$, $\tilde{\varepsilon}_{v'} = 0$ and $\tilde{\varepsilon}_v = \varepsilon_v^*, \forall v \in V/\{1, v'\}$. This new solution is still feasible (i.e., $\sum_{v\in V} K_v \tilde{\varepsilon}_v \ge \omega^*$) and $\sum_{v\in V} C_v \tilde{\varepsilon}_v < \sum_{v\in V} C_v \varepsilon_v^*$ for the objective, which disobeys the optimal assumption. Therefore, if $\omega^* \le K_1$, we can conclude that the optimal solution is $\varepsilon_1^* = 1$ and $\varepsilon_v^* = 0, \forall v \in V/\{1\}$;

(ii) If $K_1 < \omega^* < K_{|V|}$: for the ship deployment model, assume that the optimal solution is $\varepsilon_v^*, \forall v \in V$, in which there is a $v' \in V/\{1, |V|\}$ such that $\varepsilon_{v'}^* > 0$. Here, for the capacity $K_{v'}$, we can represent it by $K_{v'} = \lambda K_1 + (1-\lambda) K_{|V|}$, where $\lambda \in (0,1)$. Thereafter, we can design a new solution $\tilde{\varepsilon}_v, \forall v \in V$ such that $\tilde{\varepsilon}_1 = \varepsilon_1^* + \lambda \varepsilon_{v'}^*$, $\tilde{\varepsilon}_{|V|} = \varepsilon_{|V|}^* + (1-\lambda)\varepsilon_{v'}^*$, $\tilde{\varepsilon}_{v'} = 0$ and $\tilde{\varepsilon}_v = \varepsilon_v^*, \forall v \in V/\{1, v', |V|\}$. By this solution, we have $\sum_{v\in V} K_v \tilde{\varepsilon}_v = \sum_{v\in V} K_v \varepsilon_v^*$, which means this new solution is still feasible. For the new objective, it can be rearranged as follows:

$$\begin{aligned}
\textstyle\sum_{v\in V} C_v \tilde{\varepsilon}_v &= C_1 \tilde{\varepsilon}_1 + C_v \tilde{\varepsilon}_v + C_{|V|} \tilde{\varepsilon}_{|V|} + \textstyle\sum_{v\in V/\{1,v',|V|\}} C_v \tilde{\varepsilon}_v \\
&= C_1(\varepsilon_1^* + \lambda \varepsilon_{v'}^*) + C_{|V|}(\varepsilon_{|V|}^* + (1-\lambda)\varepsilon_{v'}^*) + \textstyle\sum_{v\in V/\{1,v',|V|\}} C_v \varepsilon_v^* \\
&= C_1 \varepsilon_1^* + C_{|V|} \varepsilon_{|V|}^* + (\lambda C_1 + (1-\lambda) C_{|V|}) \varepsilon_{v'}^* + \textstyle\sum_{v\in V/\{1,v',|V|\}} C_v \varepsilon_v^* \\
&< C_1 \varepsilon_1^* + C_{|V|} \varepsilon_{|V|}^* + C_{v'} \varepsilon_{v'}^* + \textstyle\sum_{v\in V/\{1,v',|V|\}} C_v \varepsilon_v^* = \textstyle\sum_{v\in V} C_v \varepsilon_v^*
\end{aligned} \tag{13}$$

where $\left(\lambda C_1 + (1-\lambda) C_{|V|}\right) < C_{v'}$ for the sake of the concavity. Here, it turns out that the objective for the new solution is better than assumed optimal objective. Therefore, in the optimal solution, it must be that $\varepsilon_{v'}^* = 0, \forall v \in V/\{1, |V|\}$. If $\varepsilon_1^* > 0, \varepsilon_{|V|}^* > 0$ and $\varepsilon_v^* = 0, \forall v \in V/\{1, |V|\}$, the objective becomes $z = C_1 \varepsilon_1^* + C_{|V|} \varepsilon_{|V|}^*$, where $\varepsilon_1^* + \varepsilon_{|V|}^* = 1$.Here, assume that $K_1 \varepsilon_1^* + K_{|V|} \varepsilon_{|V|}^* = \omega$, then $z = C_1 \frac{K_{|V|} - \omega}{K_{|V|} - K_1} + C_{|V|} \frac{\omega - K_1}{K_{|V|} - K_1}$. We can deem the objective as a function for ω, i.e., $z = f(\omega)$. Then, $f'(\omega) = \frac{C_{|V|} - C_1}{K_{|V|} - K_1} > 0$, which means if ω increase by one unit, the objective will increase by $\frac{C_{|V|} - C_1}{K_{|V|} - K_1}$. Therefore, in the optimal solution, $\omega = \omega^*$, then, $\varepsilon_1^* = \frac{K_{|V|} - \omega^*}{K_{|V|} - K_1}, \varepsilon_{|V|}^* = \frac{\omega^* - K_1}{K_{|V|} - K_1}$.

(iii) If $\omega^* = K_{|V|}$: for the ship deployment model, in order to fulfill the constraint $\sum_{v\in V} K_v \varepsilon_v \ge \omega^*$, the only feasible solution is $\varepsilon_{|V|}^* = 1$ and $\varepsilon_v^* = 0, \forall v \in V/\{|V|\}$, and thereafter it is optimal. ■

Proposition 3: Suppose that we relax Constraints (9), and solve the model $\boldsymbol{M1}$ to obtain the optimal LP solution $\varepsilon_v^*, \forall v \in V$. Denote $\omega^* = \max\{\eta^*_{p,e} | \forall p \in P, e \in E\}$ as the maximum number of containers carried by the deployed ships among all the voyages, or equivalently, $\omega^* = \sum_{v \in V} K_v \varepsilon_v^*$. Suppose that ω^* is between K_{v_1} and K_{v_2}. Then it is possible that neither ship type v_1 nor ship type v_2 should be deployed in the optimal integer solution to the model $\boldsymbol{M1}$.

Proof: We construct an example to prove the proposition. Assume that $|E| = 1$, $|P| = 3$. In this only one round trip, there are 3200 laden containers to be transported from Port 1 to Port 2, 5000 laden containers from Port 1 to Port 3, and 2000 laden containers from Port 2 to Port 3 (i.e., $d_{12,1} = 3200$, $d_{13,1} = 5000$, and $d_{23,1} = 2000$). Assume that the fixed operation cost for the ship type 1, 8, 9, and 10 are 1000, 10500, 11500 and 12000 respectively. Initially, we have 10000 empty containers in Port 1 (i.e., $I_1 = 10000$), and no empty containers in Port 2 (i.e., $I_2 = 0$). Then, for a container, we assume the long-term leasing cost is much higher than the short-term leasing cost and the repositioning cost. Assume that the reposition cost from Port 1 to Port 2 is 3 (i.e., $r_{12} = 3$), the short-term leasing cost from Port 2 to Port 3 is 4 (i.e., $l_{23} = 4$).

If we only consider the laden container transportation, the numbers of laden containers carried on the two voyages are 8200 and 7000, which means the ship type with its capacity less than 8200 cannot be selected as the best ship type, and $\omega^* \geq 8200$. In this case, there are 2000 empty containers deficit in Port 2, and 1800 empty containers surplus in Port 1 for the laden demand. If we can reposition more empty containers from Port 1 to Port 2, it will save the cost for the short-term leasing in Port 2 by $l_{23} - r_{12}^S = 1$ for each repositioning empty container. However, repositioning one more empty container in the voyage from Port 1 to Port 2, ω^* will increase by one, thereafter the ship fixed operation cost will increase by $\frac{C_{|V|} - C_1}{K_{|V|} - K_1} = 1.22$ based on the proof of Proposition 4. Thus, we can conclude that in the relaxation model, $\omega^* = 8200$, which means no empty containers will be repositioned from Port 1 to Port 2.

Table 1: Costs by selecting different ship types

Ship type	Total cost	Ship fixed operating cost	Short-term leasing cost	Repositioning cost
1000-TEUs	Infeasible	N.A.	N.A.	N.A.
8000-TEUs	Infeasible	N.A.	N.A.	N.A.
LP model (8200 TEUs)	17,800	9,800	8,000	0
9000-TEUs	18,700	11,500	4,800	2,400
10000-TEUs	18,200	12,000	800	5,400

Under this case, in the optimal feasible solution, the ship type 8 cannot be the best ship type due to its capacity limitation for the laden container transportation, as shown in the row “LP model (8200 TEUs)” of Table 1. However, using the ship type 9 is not optimal either, by the following comparison between using the ship type 9 and using the ship type 10: If we use the ship type 9, the short-term leasing cost can be saved by $(9000 - 8200) \times (4 - 3) = 800$ as extra 800 empty containers can be repositioned to Port 2; if we use the ship type 10, the short-term leasing cost can be saved by $(10000 - 8200) \times (4 - 3) = 1800$. Thus, the ship type 10 is better than the ship type 9. Although the operation cost would rise by $C_{10} - C_9 = 500$ using ship type 10, the short-term leasing saving in Port 2 using the ship type 10 is more with $1800 - 800 = 1000$ than that of using the ship type 9, as shown in the rows “9000-TEUs” and “10000-TEUs” of Table 1.

In summary, under the above situation, ship type 8 and ship type 9 are not the best ship as ship type 8 is infeasible and ship type 10 is better than ship type 9. ■

Proposition 4: If the empty container repositioning is not considered for the ship fleet type decision, the total cost could rise by infinite times in the worst case.

Proof: We can construct an example to prove the proposition. Assume that $|E| = 1$, $|P|$ is an even number. In this only one round trip, the laden container demands only exist between two adjacent ports with the same 4000 laden demands (i.e., $d_{p(p+1),1} = 4000, \forall p \in P/\{|P|\}$). Initially, we have 8000 empty containers in all the ports with an odd port index (i.e., $I_p = 8000, \forall p \in \{1, 3, 5, \dots, |P| - 1\}$), and no empty containers in all the ports with an even port index (i.e., $I_p = 0, \forall p \in \{2, 4, 6, \dots, |P|\}$). Then, for a container, we assume that the long-term leasing cost is much higher than the short-term leasing cost, and the short-term leasing cost is much higher than the repositioning cost.

Under this example, if we choose the best ship type with only considering the laden container transportation, the best ship type is the ship type with its capacity as $K = 4000$, because that the maximum number of laden containers carried among all the voyages is 4000. Assume that the fixed operation cost for this ship is 4500. Then, in all the even ports, the shipping liner has to lease 4000 empty containers by the short-term leasing as no empty containers can be repositioned for the sake of capacity limitation. Thus, the total cost can be calculated by: $\sum_{p\in\{2,4,6,\dots,|P|-2\}} 4000 l_{p(p+1)} + 4500$.

If we choose the best ship with considering the laden container transportation and the empty container repositioning, the best ship is the ship with its capacity as $K = 8000$ as the 4000 surplus containers in the odd ports can be repositioned to the even ports. Assume that the fixed operation cost for this ship is 7000. Then, the total cost can be calculated by $\sum_{p\in\{1,3,5,\dots,|P|-3\}} 4000 r_{p(p+1)} + 7000$. Therefore, the ratio between two total costs is $\frac{\sum_{p\in\{2,4,6,\dots,|P|-2\}} 4000 l_{p(p+1)} + 4500}{\sum_{p\in\{1,3,5,\dots,|P|-3\}} 4000 r_{p(p+1)} + 7000}$. Assume that all the repositioning costs are the same as r and all the short-leasing costs are the same as l, then the ratio can be written as $\frac{4000 l(|P|-2)/2+4500}{4000 r(|P|-2)/2+7000}$. As the short-term leasing cost l is much higher that the repositioning cost r, if the $|P|$ is large enough, the ratio is close to infinity. ■

4 Conclusion

This paper studies the ship fleet type decision problem considering empty container allocation. Different from traditional research works on the ship fleet deployment, our study incorporates both the laden container transportation and the empty container repositioning into ship fleet type decision. In this paper, a mixed-integer programming model is formulated for the problem to make all the tactical level decisions and operational level decisions on the problem. Based on the model, we investigate some properties to derive insights on the problem. For instance, we find that if the empty container repositioning is not considered when determining the ship fleet type, the total cost may increase significantly.

Acknowledgment

This study is substantially supported by the National Natural Science Foundation of China (No. 71701178).

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