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Revisiting a class of liner fleet deployment models

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ABSTRACT

A class of liner fleet deployment models in the literature is revisited. We point to an implicit (and unnecessary) assumption in this class of models that can lead to fleet deployment plans that employ more vessels than strictly necessary. New analytical results are derived to relax this assumption, leading to a new and more realistic liner fleet deployment model. In a case study, it is found that the new model can lead to a substantial reduction in the fleet deployment cost, up to 15 percent. Moreover, it is observed that the new model is particularly timely in the current era where vessel sharing agreements and mega vessels are the norm, as the cost savings grow with the vessel size.

1. Introduction

One decision of critical importance faced by shipping lines is the fleet deployment problem in which the number and types of ships to be assigned to the shipping routes need to be determined, in order to maximize profits (Christiansen, Fagerholt, Nygreen, & Ronen, 2013). This fleet deployment problem has been first addressed in the literature by Perakis and Jaramillo (1991) and Jaramillo and Perakis (1991) who formulated (integer) linear programming models for this planning problem. In these early and subsequent studies, it was customary to assume that the container shipping demand is known with complete certainty. Recently, this assumption has been relaxed, and shipping demand has been more realistically modeled as random variables (e.g. see Meng & Wang, 2010; Meng, Wang, & Wang, 2012; Ng, 2014, 2015; Wang, Meng, Wang, & Tan, 2013). Note that others have examined the fleet deployment problem in conjunction with other decision problems, including the liner network design problem, the maritime fleet size and mix problem and sailing speed optimization (e.g. see Andersson, Fagerholt, & Hobbesland, 2015; Brouer, Alvarez, Plum, Pisinger, & Sigurd, 2013; Huang, Hu, & Yang, 2015; Mulder & Dekker, 2014; Pantuso, Fagerholt, & Hvattum, 2014; Plum, Pisinger, & Sigurd, 2013).

In this paper, we revisit a variation of the liner fleet deployment model in the literature (e.g. see Meng & Wang, 2010; Meng et al., 2012; Wang, Wang, & Meng, 2011), and point to an implicit assumption in this class of models that can be relaxed "at no cost". This hidden assumption can lead to fleet deployment plans that employ more vessels than strictly necessary. To relax this assumption, new analytical results are derived, and a new liner fleet deployment model is presented. In a case study, it is then shown that the new model can lead to a substantial reduction in the fleet deployment cost, up to 15 percent.

The remainder of this paper is organized as follows. In Section 2, a variation of an existing liner fleet deployment model is presented. One of its hidden assumptions is then uncovered in Section 3, together with new analytical results to relax the assumption, leading to a new liner fleet deployment model. A case study illustrates the proposed model in Section 4, showing that significant cost savings are possible. Finally, Section 5 concludes the paper.

2. A class of liner fleet deployment model

Before a new liner fleet deployment model is presented, in this section we first briefly examine an existing variation of a class of liner fleet deployment model (e.g. see Meng & Wang, 2010; Meng et al., 2012; Wang et al., 2011).

Sets

R Set of routes
K Set of ship types

Parameters

c^{v}_{kr} The operating cost for a voyage (also referred to as roundtrip and loop in this paper) for a ship of type $k \in K$ on route $r \in R$
c^{i}_{k} The cost of chartering in a ship of type $k \in K$
c^{o}_{k} The revenue of chartering out a ship of type $k \in K$
l_k The number of ships of type $k \in K$ available in the liner company's own fleet

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m_k The maximum number of ships of type $k \in K$ that can be chartered from other ship owners
n_r The number of voyages required on route $r \in R$ to maintain the liner's desired minimum sailing frequency
h The planning horizon under consideration (in days)
t_{kr} The transit time of a ship of type $k \in K$ traversing route $r \in R$ (in days)
q_k The capacity of a ship of type $k \in K$ (in TEU)
d_r The maximum shipping demand among all port pairs on route $r \in R$
M_k A sufficiently large number, e.g. $l_k + m_k$, $k \in K$

Decision variables

u_{kr} The total number of ships of type $k \in K$ to be deployed on route r
v_k The number of ships of type $k \in K$ to be chartered from other ship owners
w_k The number of ships of type $k \in K$ to be chartered out
x_{kr} The total number of complete voyages (i.e. roundtrips) ships of type $k \in K$ completes on route $r \in R$
y_{kr} Equals 1 if vessels of type $k \in K$ are deployed on route $r \in R$, 0 otherwise.

Model (D1)

$$\min \sum_k \sum_r c^v_{kr} x_{kr} + \sum_k c^i_k v_k - \sum_k c^o_k w_k \quad (1)$$

subject to:

$$\sum_r u_{kr} \le l_k + v_k, \quad \forall k \in K \quad (2)$$

$$v_k \le m_k, \quad \forall k \in K \quad (3)$$

$$w_k = l_k + v_k - \sum_r u_{kr}, \quad \forall k \in K \quad (4)$$

$$x_{kr} \le u_{kr} \lfloor h/t_{kr} \rfloor, \quad \forall k \in K, \forall r \in R \quad (5)$$

$$\sum_k x_{kr} \ge n_r, \quad \forall r \in R \quad (6)$$

$$\sum_k x_{kr} q_k \ge d_r, \quad \forall r \in R \quad (7)$$

$$u_{kr} \le M_k y_{kr}, \forall k \in K, \quad \forall r \in R \quad (8)$$

$$\sum_k y_{kr} = 1, \quad \forall r \in R \quad (9)$$

$$v_k, w_k \ge 0, \quad \forall k \in K, \forall r \in R \quad (10)$$

$$u_{kr}, x_{kr} \ge 0 \text{ and integer}, \quad \forall k \in K, \forall r \in R \quad (11)$$

$$y_{kr} \in \{0, 1\}, \forall k \in K, \quad \forall r \in R \quad (12)$$

The objective function (1) states that the goal is to minimize the total cost, considering the operating cost, the cost of chartering ships and the revenue from chartering ships out. Constraint (2) ensures that the total number of ships (of type k) deployed does not exceed what is available to the shipping company. In constraint (3), a maximum is imposed on the number of ships that can be chartered from others, whereas constraint (4) is a conservation constraint that ensures that all ships that are not deployed are chartered out to maximize profit. The maximum number of *complete* voyages (on route r) ships of type k can make within the planning horizon of h days is given by the product of u_{kr}(the number of ships of type k assigned to route r) and $\lfloor h/t_{kr} \rfloor$, where $\lfloor a \rfloor$ denotes the largest integer smaller or equal to a, see constraint (5). Constraint (6) states that the number of voyages to be completed on route r should at least correspond to the liner's desired minimum sailing frequency on route r. Constraint (7) guarantees that the deployed vessel capacity is sufficient to transport the container demand between all port pairs on route r. (It is to be noted that the results in this paper can be readily adapted to the case of uncertain demand, see Ng, 2014, 2015). Constraints (8) and (9) ensure that only one vessel type will be used on route r (Ng, 2015). Indeed, if $y_{kr} = 1$, indicating that vessels of type k are deployed on route r, then (8) simply becomes redundant. On the other hand, if $y_{kr} = 0$, u_{kr} will be equal to zero because of (8). Constraint (5) then ensures that x_{kr} equals zero. The remaining constraints (10)–(12) enforce non-negativity and integrality of the decision variables in the model.

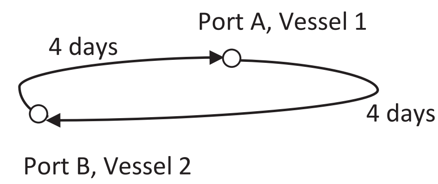

Fig. 1. Illustrative example.

3. Uncovering an implicit assumption in Model (D1) and new analytical results

In this section we uncover an implicit assumption in Model (D1) and derive new analytical results for more cost-effective fleet deployment plans.

One implicit assumption in constraints (5) and (7) is that containers can only be transported between port pairs if vessels complete an entire loop. That is, if a vessel departs from a given port, visits various ports on its journey, but is only able to return to its initial port at time $h + \varepsilon$, where $\varepsilon > 0$ is an arbitrarily small number, then Model (D1) would consider this vessel as being *unable to transport any containers within the planning horizon*. Indeed, in such a case $\lfloor h/t_{kr} \rfloor = 0$, and thus, $x_{kr} = 0$, by constraint (5). Constraint (7) then states that no such vessel can carry any containers that count toward satisfying the shipping demand. In other words, such vessels will not be deployed, no matter how low its voyage cost c^v_{kr} is.

As an alternative illustration of this phenomenon, suppose that $h = 30$ days and $t_{kr} = 8$ days. If $u_{kr} = 2$, then the time separation between the two vessels (vessels 1 and 2) is 4 days at all times (since otherwise the vessel service would not be regular). As implicitly in (5), suppose that vessel 1 starts from Port A and vessel 2 from Port B. Fig. 1 illustrates this scenario.

Within the planning horizon, it is clear that each vessel can sail 3 complete loops, transporting up to $6q_k$ TEUs from Port A to Port B (and from Port B to Port A), as given by (5). After the 3 loops, there are 6 days left before the end of the planning horizon. Within these 6 days, it is easy to see that vessel 1 (vessel 2) can transport up to an additional q_k TEUs from Port A to Port B (from Port B to Port A). That is, the maximum number of TEU's that can be transported from Port A to Port B (and Port B to Port A) within the planning horizon is $7q_k$ TEUs, which is strictly more than what Model (D1) allows ($6q_k$ TEUs). Consequently, as will be numerically demonstrated in our case study in Section 4, the number of vessels assigned to the routes can be unnecessarily large in Model (D1), leading to unnecessarily high costs.

Since there is no reason why container movements as part of partial loops should not be considered, next we extend Model (D1) to account for such partial loops. To this end, we first need Lemma 1 that generalizes the above discussion.

Lemma 1. *The number of times each port on route r can be visited within the planning horizon by a vessel of type k is given by*

$$u_{kr} \lfloor h/t_{kr} \rfloor + \lfloor u_{kr} (h/t_{kr} - \lfloor h/t_{kr} \rfloor) \rfloor \quad (13)$$

That is, by focusing on both complete and partial loops, the number of TEUs that can be transported to each port within the planning horizon, increases by $(\lfloor u_{kr} (h/t_{kr} - \lfloor h/t_{kr} \rfloor) \rfloor) q_k$.