Joint Optimization of Ship Sailing Speed and Container Handling Rate for a Near-sea Liner Service Route

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Abstract. This paper jointly designs the optimal ship sailing speeds on shipping legs and the optimal handling rates at ports of a near-sea liner service route operated by a container liner shipping company. A mixed integer linear programming model is developed, which can be solved directly by the commercial solvers to give a global optimal solution. The model is further applied to a real-life case. Results demonstrate that both bunker price and unit inventory cost affect the optimal ship sailing speed and the optimal container handling rate.

1. Introduction
Container liner shipping plays a very important role in international trade. Compared with dry-bulk shipping, liner container shipping follows fixed port rotations and fixed schedules with high efficiency. Since the length of a near-sea route is always short and the total wait time at ports takes up a considerable proportion of the total round-trip time, container lines operating near-sea routes pay more attention to the efficiency of container terminal handling than those operating ocean routes.

A higher container handling efficiency with a higher container handling cost implies a shorter container handling time, which means that container sailing speeds on shipping legs can be adjusted at an appropriate decrease. On the contrary, a lower container handling efficiency with a lower container handling cost leads to a longer container handling time, which means that container sailing speeds need to be increased appropriately. Hence, when designing containership sailing speed on each shipping leg for a near-sea service route, container handling rate should be taken into account. In a word, when designing containership sailing speed, carriers must balance the trade-off between the vessel operating cost, fuel cost, container handling cost, and inventory cost.

This study falls into the research topic of ship scheduling problem that is a tactical level decision problem made every three to six months [1-3]. The ship scheduling problem has been investigated in the literature over recent decades. The work by Agarwal and Ergun [4] was the first academic study to incorporate fixed service frequency in ship scheduling and cargo routing problem. Wang and Meng [5] optimized containership sailing speed on each shipping leg incorporating fleet size, container transshipment, and container routing in a liner shipping network. Wang et al. [6,7] studied the liner shipping route schedule design problem with port hard time windows. Du et al. [8] studied the fleet deployment problem in liner shipping considering collaborative transportation. Zhen et al. [9] jointly designed the fleet size, ship schedule, sailing speed per leg, and cargo allocation for a given shipping network with multiple routes. Mulder et al. [10] jointly optimized containership sailing speed and buffer times for a fixed shipping route using a stochastic dynamic program. Wang et al. [11] studied the sailing speed and bunker purchasing optimization problem considering stochastic bunker prices.
Zhuge et al. [12] dealt with a schedule design problem under vessel speed reduction incentive programs. Zhao et al. [13] focused on the sailing speed optimization problem for slow steaming considering loss aversion mechanism.

Overview of the above literature shows that current studies seldom incorporate the effect of container handling rate in the sailing speed optimizing problem, while the container handling rate has a significant influence on the design of sailing speed in near-sea shipping routes. Hence, this article jointly determines the optimal ship sailing speed on each shipping leg and the optimal container handling rate at each port of call for a fixed service route operated by a near-sea liner shipping company, which can provide some useful management decision support for them.

2. Problem description
Consider a near-sea shipping route CPS service operated by SITC Container Lines as shown in Figure 1, which includes \( P = \{1, 2, ..., N\} \) ports of call. A liner service is defined as a loop route, hence, the container ships in this service start from Manila North, then sequentially visit Manila South, Shanghai, Ningbo and finally return to Manila North to complete the round-trip journey.

The voyage between the two adjacent ports is called a shipping leg numbered by the starting port \( i \), and the voyage from \( N \)th port of call back to the first one is called leg \( N \). The length of leg \( i \) is denoted by \( l_i \).

To facilitate the establishment of the model, we made the following assumptions:
- We suppose that the port rotation is to be known.
- We assume that the container shipping demand at each port of call is given in advance.
- We assume that the vessel fleet is homogeneous.
- The total time spent at a port includes two parts, i.e. the wait time and container handling time, and the wait time at each port of call is fixed.

![Figure 1. CPS service operated by SITC Container Lines.](image)

3. Mathematical model
In this section we present a mathematical model of the problem that aims to minimize the sum of the vessel operating cost, fuel cost, container handling cost, and inventory cost. The notation on sets, parameters and decision variables are illustrated as follows:

We denote by \( C^{opr} \) the fixed weekly operating cost of one containership, and denote by \( m \) the number of ships deployed on the designed service route. We define \( r_i \in R \) as one kind of sailing speed corresponding to leg \( i \). We denote by \( f_i \) and \( t_i \) the bunker consumption and sailing time that corresponds to the sailing speed \( r_i \) on leg \( i \), respectively. Let the binary variables \( X_i \) indicate whether the sailing speed \( r_i \) is used at port of call \( i \). We denote by \( t_i^{wa} \) the fixed wait time at port of call \( i \), including the time of pilotage in and out. The liner shipping company has various agreements with the terminal operator at each port of call, and each agreement has one kind of container handling rate \( s \in S \). Each handling rate has a corresponding container handling time \( t_i^{hd} \) and container handling cost \( c_i^{hd} \), measured in minutes per TEU and in US dollars per TEU respectively. Let the
binary variables $\rho_s \in \{0,1\}$ indicate whether the container handling rate $s \in S$ is used at port of call $i$. We denote by $q_i^{ld}$ the total number of containers loading and discharging at port of call $i$, and denote by $q_i$ the number of containers transported on leg $i$. Let $\alpha$ be the unit bunker price, and $\beta$ be the unit inventory cost. Thus, the problem of jointly optimizing ship sailing speed and container handling rate for a near-sea liner service route can be expressed as follows:

$$\min \{C^{opr} m + \alpha \sum_{i \in P} \sum_{r \in R_i} l_i \cdot f_{ir} \cdot x_{ir} + \sum_{i \in S} \sum_{s \in S} q_i^{ld} \cdot \rho_s \cdot c_{is}^{ld} + \beta \sum_{i \in P} \sum_{r \in R_i} q_i \cdot t_{ir} \cdot x_{ir} \}$$  \hspace{1cm} (1)

subject to:

$$\sum_{i \in P} \sum_{r \in R_i} l_i \cdot f_{ir} \cdot x_{ir} + \sum_{i \in P} \sum_{r \in R_i} f_{ir}^{fix} + \sum_{i \in S} \sum_{s \in S} t_{is}^{ld} \cdot \rho_s \cdot q_i^{ld} \leq 168m$$  \hspace{1cm} (2)

$$\sum_{r \in R_i} x_{ir} = 1, \hspace{0.5cm} \forall i \in P$$  \hspace{1cm} (3)

$$x_{ir} \in \{0,1\}, \hspace{0.5cm} \forall i \in P, \forall r_i \in R_i$$  \hspace{1cm} (4)

$$\sum_{s \in S} \rho_s = 1, \hspace{0.5cm} \forall i \in P$$  \hspace{1cm} (5)

$$\rho_s \in \{0,1\}, \hspace{0.5cm} \forall i \in P, \forall s \in S$$  \hspace{1cm} (6)

$$m \in \mathbb{Z}^+$$  \hspace{1cm} (7)

The objective function (1) minimizes the sum of the vessel operating cost, fuel cost, container handling cost, and container inventory cost. Constraint (2) ensures that the designed shipping service route should maintain a weekly service frequency. Constraint (3) ensures that only one kind of sailing speed can be selected on each shipping leg. Constraint (4) defines $x_{ir}$ as a binary variable. Constraint (5) ensures that only one kind of container handling rate can be used at each port of call. Constraint (6) defines $\rho_s$ as a binary variable. Constraint (7) defines the number of deployed ships $m$ as an integer variable.

4. Numerical experimentation and analysis

It is noticeable that the proposed model is a mixed integer linear programming model. Therefore, it can be solved efficiently by state-of-the-art MILP solvers such as ILOG CPLEX which has higher capacity for large-scale optimization.

In this section, to evaluate the applicability of the proposed model, we conduct numerical experiments based on the shipping line mentioned in section 2. The operating cost $C^{opr} = US$200,000/week. the bunker price $\alpha = US$300/t, and the unit inventory cost $\beta = US$0.5/h. The wait time per port of call and the length per leg are shown in Table 1. The shipping demands at each port of call are shown in Table 2. The total number of containers loading and discharging at each port of call $q_i^{ld}$ and the number of containers transported on each leg $q_i$ can be calculated by the data from Table 2. Tables 3 and 4 show the container handling times and costs at each port.

The proposed model is implemented with YALMIP toolbox in MATLAB by calling IBM ILOG CPLEX 12.8.0 on the personal computer with Intel Core i5 2.5 GHz CPU and 16 GB RAM. The test can be completed within 5 seconds. The optimal number of ships deployed on the designed is 2, and the optimal sailing speed and kind of container handling rate are shown in Table 5.
Table 1. Parameters in the case study.

| Port ID | Port           | Waiting time (h) | Length (nm) |
|---------|----------------|------------------|-------------|
| 1       | Manila North   | 5                | 10.80       |
| 2       | Manila South   | 10               | 1,166.70    |
| 3       | Shanghai       | 15               | 187.20      |
| 4       | Ningbo         | 10               | 1,057.40    |

Table 2. Port-to-port shipping demands (in TEUs).

| Port       | Manila(N) | Manila(S) | Shanghai | Ningbo |
|------------|-----------|-----------|----------|--------|
| Manila(N)  | -         | -         | 250      | 150    |
| Manila(S)  | -         | -         | 300      | 180    |
| Shanghai   | 300       | 400       | -        | -      |
| Ningbo     | 200       | 300       | -        | -      |

Table 3. Container handling times at each port (m/TEU).

| Port       | 1  | 2  | 3  |
|------------|----|----|----|
| Manila(N)  | 2.5| 2  | 1.5|
| Manila(S)  | 2.5| 2  | 1.5|
| Shanghai   | 1.2| 1  | 0.8|
| Ningbo     | 1.2| 1  | 0.8|

Table 4. Container handling times at each port (m/TEU).

| Port       | 1  | 2  | 3  |
|------------|----|----|----|
| Manila(N)  | 45 | 50 | 55 |
| Manila(S)  | 45 | 50 | 55 |
| Shanghai   | 50 | 55 | 60 |
| Ningbo     | 50 | 55 | 60 |

Table 5. Optimal sailing speed and handling rates.

| Port       | Speed (knots) | Kind of handling rate |
|------------|---------------|-----------------------|
| Manila(N)  | 10.80         | 3                     |
| Manila(S)  | 11.78         | 3                     |
| Shanghai   | 11.70         | 1                     |
| Ningbo     | 12.30         | 1                     |

We subsequently investigate how the variation of bunker price influences the optimal sailing speed and container handling rate. We set the bunker price from US$100 to US$700, and calculate the corresponding optimal solutions, which are shown in Table 6. We can see that the bunker price significantly affects the ship sailing speed, container handling time, and thereby affects container handling rate. With the increase of bunker price, a higher container handling rate with a higher container handling cost is needed to reduce bunker consumption.

Table 6. Optimal solutions with different bunker prices.

| Bunker price (US$/t) | Average sailing speed (knots) | Total container handling time (h) | Fleet size |
|----------------------|-------------------------------|-----------------------------------|------------|
| 100                  | 14.50                         | 128.27                            | 2          |
| 300                  | 11.99                         | 93.60                             | 2          |
| 500                  | 11.99                         | 93.60                             | 2          |
We move to analyze the effect of the variations of the unit inventory cost on the optimal solutions. We set the unit inventory cost as 0.5, 1, 1.5, 2 respectively, and the results of 4 experiments are shown in Table 7. When the unit inventory cost rises, the number of ships deployed remains unchanged, while both the average sailing speed and total container handling time increase. This indicates that when ships transport containers of higher value, they should sail at a higher sailing speed, and carriers need to adopt a higher container handling rate.

5. Conclusions and implications
This study focus on jointly optimizing ship sailing speed and container handling rate for a near-sea liner service route with the objective of minimizing the sum of the vessel operating cost, fuel cost, container handling cost, and inventory cost. A mixed integer linear programming model is formulated and further applied to a real-world case study involving SITC Container Lines. We further investigate the effect of bunker price variations on the optimal solutions. Results show that when the bunker price, carriers have to adopt a higher container handling rate to reduce the total cost. Finally, we examine the effect of the variations of the unit inventory cost on the optimal solutions. Results indicate that when higher value goods are shipped, ships should sail at a higher sailing speed, and carriers also need to adopt a higher container handling rate.

In future studies, we will take into account the uncertainties in wait time at ports, which is more practical to the near-sea liner shipping industry.

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References
[1] Christiansen, M., et al. (2013) Ship routing and scheduling in the new millennium. European Journal of Operational Research, 228:467-483.
[2] Meng, Q., et al. (2014) Containership Routing and Scheduling in Liner Shipping: Overview and Future Research Directions. Transportation Science, 48:265-280.
[3] Tran, N.K. and H. Haasis. (2015) Literature survey of network optimization in container liner shipping. Flexible Services and Manufacturing Journal, 27:139-179.
[4] Agarwal, R. and O. Ergun. (2008) Ship Scheduling and Network Design for Cargo Routing in Liner Shipping. Transportation Science, 42:175-196.
[5] Wang, S. and Q. Meng. (2012) Sailing speed optimization for container ships in a liner shipping network. Transportation Research Part E: Logistics and Transportation Review, 48:701-714.
[6] Wang, S., A. Alharbi and P. Davy. (2014) Liner ship route schedule design with port time windows. Transportation Research Part C: Emerging Technologies, 41:1-17.
[7] Wang, S., A. Alharbi and P. Davy. (2015) Ship Route Schedule Based Interactions Between Container Shipping Lines and Port Operators. In: Chung-Yee, L., Qiang, M. (Eds.), Handbook of Ocean Container Transport Logistics: Making Global Supply Chains Effective. Springer International Publishing, Cham. 279-313.
[8] Du, G., C. Sun and J. Weng. (2016) Liner Shipping Fleet Deployment with Sustainable Collaborative Transportation. Sustainability, 8:165.

[9] Zhen, L., et al. (2019) Integrated planning of ship deployment, service schedule and container routing. Computers and Operations Research, 104:304-318.

[10] Mulder, J., W. van Jaarsveld and R. Dekker. (2019) Simultaneous Optimization of Speed and Buffer Times with an Application to Liner Shipping. Transportation science, 53:365-382.

[11] Wang, Y., Q. Meng and H. Kuang. (2018) Jointly optimizing ship sailing speed and bunker purchase in liner shipping with distribution-free stochastic bunker prices. Transportation research. Part C, Emerging technologies, 89:35-52.

[12] Zhuge, D., et al. (2020) Schedule design for liner services under vessel speed reduction incentive programs. Naval research logistics, 67:45-62.

[13] Zhao, Y., et al. (2020) Sailing Speed Optimization Model for Slow Steaming Considering Loss Aversion Mechanism. Journal of advanced transportation, 2020:1-11