Supply chain cost minimization by collaboration between liner shipping companies and port operators

Abstract

The container handling rates at ports are input for container shipping operations planning by shipping lines. The handling rates are unilaterally determined by port operators. This paper points out that it may be possible for port operators to provide higher handling rates at some additional costs. The higher handling rates will enable ships to have more time sailing at sea, leading to less fuel consumption. The reduction in fuel costs for shipping lines may be more significant than the additional costs incurred by port operators. We therefore propose a practical and easy-to-implement collaborative mechanism between shipping lines and port operators, where the shipping lines compensate the port operators for their additional costs. As a result, the overall efficiency of container transportation is improved.

Key Words

Maritime transportation; Container liner shipping; Shipping lines; Port operators

1. Introduction

Shipping lines and port operators are two interacting players in maritime container transportation. Container shipping lines transport containers between ports using dedicated containerships. Port operators provide berthing, container handling, refueling, and maintenance services to shipping lines. The joint efforts between shipping lines and port operators enable a large amount of goods to be transported (Yarusavage 2013; Wang et al. 2014; Zhang and Lam 2014; Zhen and Wang 2015). As reported by UNCTAD (2014), the total container trade volume amounted in 160 million twenty-foot equivalent units (TEUs) in 2013.

Shipping lines aim to transport as many containers as possible using their ships. A ship creates value only when it is sailing, and the time spent at ports is non-productive. Consequently, shipping lines wish to shorten the time their ships spend at ports. However, the time at a port, to a large extent, is controlled by the port operator. In addition to factors such as the volume of the containers to be handled and the storage of the containers onboard, the main determining factor of the port time is the number of quay cranes deployed on the ship. More deployed quay cranes lead to a shorter handling time, albeit not in a proportional manner.

In container shipping operations planning, port operators will provide shipping lines an average productivity value, e.g., 100 container moves per hour. Based on the port productivity and the number of containers to be handled, shipping lines estimate the time their ships spend at ports and design the number of ships to deploy and the sailing speed of the ships. In this process, the port productivity is unilaterally determined by the port operators. In general, port operators would like to achieve the highest container handling rates for ships. However, sometimes port operators may spare some quay cranes to serve other ships. As a result, the highest port productivity is not achieved.

It is hence possible for port operators to provide a higher productivity than they normally do, at some costs, to shorten the port time of ships. We argue that the cost reduction for shipping lines from higher productivity at ports may be more significant than the additional costs of port operators. We therefore aim to design a collaborative mechanism between shipping lines and port operators to achieve such a lower overall cost. The mechanism should be easy to implement in practice and ready to be accepted by both shipping lines and port operators.

Existing studies on container liner shipping operations planning either assume that the time a ship spends at a port is fixed, for example, in network design (Brouer et al. 2014), container assignment (Shibasaki et al. 2005, 2007; Bell et al. 2011, 2013), and fleet deployment (Fagerholt 2004), or is proportional to the number of containers handled (e.g., Wang and Meng, 2012). For an overview on container liner shipping, we refer to Christiansen et al. (2013) and Meng et al. (2014). Some liner shipping studies focus on how to optimize the fuel consumption (e.g., Ronen 2011; Psaraftis and Kontovas 2013) to balance the tradeoff between ship operating cost, bunker cost and inventory cost of cargoes in the containers. These studies have assumed that the total sailing time on all of the legs of a service is equal to the turnaround time minus the constant total time spent at all of the ports of call. The central decisions are how to allocate the total sailing time to each leg. Therefore, the sailing speed planning in these studies is simply determined by the shipping line without any involvement of port operators. There are also studies that investigate berth allocation and quay crane scheduling (e.g., Bierwirth and Meisel 2010; Imai et al. 2013; Zhang et al. 2014; Zhen 2015;

Zhen et al. 2016). However, these studies aim to optimize operating plans from the viewpoint of port operators. The results are the optimal port times that are provided for shipping lines, which the shipping lines must accept. Meanwhile, these studies generally aim to improve the port efficiency at the operational level, whereas our paper focuses on tactical-level planning decisions by considering collaboration between shipping lines and port operators. Yang et al. (2013) used a simulation approach to analyze the impact of a given schedule, while our paper designs a schedule using optimization approaches. In sum, to the best of our knowledge, there is no research that investigates the possibility of a collaborative mechanism under which port operators provide shorter port times, shipping lines compensate the port operators, and the overall cost for container transportation is reduced.

Container liner shipping services are generally weekly. Given the number of ships deployed on the service, the turnaround time, which consists of sailing time at sea and port time, equals 7 days multiplied by the number of ships deployed. Therefore, if the port time is shortened, the sailing time could be increased, which leads to a lower sailing speed. Because the daily fuel consumption is approximately proportional to the speed cubed, and the bunker fuel price is very high, slow steaming is prevalent in liner shipping for saving fuel. Therefore, we investigate how shipping lines and port operators could collaborate in container handling by reducing port time to save bunker fuel. The problem is a tactical-level decision that is initiated by shipping lines. This paper takes the initiative to propose a practical and easy-to-implement collaborative mechanism that could improve the overall efficiency of container transportation. The key idea of the collaborative mechanism is, instead of providing just one option of productivity to shipping lines, the port operator provides several options. Some of these options are more costly for the port operator as they involve more resource commitment;

at the same time, these options are beneficial to the shipping lines. Shipping lines need to compensate the port operator if they choose more productive options, which is possible if the compensation is smaller than the fuel cost savings for the shipping lines. As a result, neither the shipping lines nor the port operator incurs a loss with such a mechanism. We conduct an illustrative example based on a trans-Pacific service and find that the proposed collaborative mechanism could lead to a saving of 100,000 USD per week for such a service, or equivalently, 5 million USD per year. This number of savings is significantly for shipping lines, especially in the current environment of shipping capacity oversupply and low profit margins.

The contribution of the paper is three-fold. First, we propose a collaborative mechanism that is applicable to many supply chains settings other than just the maritime supply chain; for instance, a supplier could provide different lead times to customers and customers could choose a suitable lead time and compensate the supplier accordingly. Second, we develop a mixed-integer nonlinear optimization model for shipping lines and propose a global optimization algorithm based on Karush-Kuhn-Tucker conditions and bi-section search. Third, the proposed collaborative mechanism could considerably reduce the cost of the maritime supply chain. Our illustrative example shows a saving of 5 million USD per year for a liner service.

2. Collaborative Mechanism and Its Formulation

Consider a ship route such as the Central China Express (CCX) service operated by Orient Overseas Container Line (OOCL) shown in Fig. 1. It can be represented by its port calling sequence - $1 \to 2 \to \cdots \to N \to 1$, where the number 1 denotes its first port of call and

N is the number of ports of call. These ports of call are grouped into a set $I := \{1, 2, \cdots, N\}$. The voyage between two consecutive ports of call on the liner ship route is referred to as a *leg*. The i^{th} leg is defined as the voyage from the i^{th} port of call to the $(i+1)^{\text{th}}$ port of call when $i = 1, 2, \cdots, N-1$ and the N^{th} leg is from the N^{th} port of call to the 1^{st} port of call.

On the CCX ship route, if we define Qingdao as the first port of call, then the port calling sequence is: Qingdao (1) → Ningbo (2) → Shanghai (WGQ) (3) → Shanghai (YAN) (4) → Pusan (5) → Los Angeles (6) → Oakland (7) → Pusan (8) → Qingdao (1). Note that the port of Pusan is visited twice in a round-trip journey: both the fifth and the eighth ports of call are Pusan.

<Figure 1>

The voyage distance of leg i is denoted by L_i (n mile). If the sailing time on the leg is t_i (h), then the sailing speed v_i (knot) is L_i / t_i. Suppose that the time spent at the i^{th} port of call is τ_i (h), we have:

$$\text{turnaround time} = \sum_{i \in I} (t_i + \tau_i) \tag{1}$$

The company deploys a total of m ships on the ship route. For simplicity we assume that m is fixed. However, the model and method to be developed can easily be modified to accommodate the case where m is a decision variable. The weekly frequency of the service implies that:

$$\sum_{i \in I} (t_i + \tau_i) = 168m \tag{2}$$

where 168 is the number of hours in a week.

The bunker cost is an important variable cost in such a setting. Since the fuel burned by the auxiliary engine of a ship is almost constant, we only consider the fuel consumed by the main engine that drives the propeller. The bunker consumption function on the i^{th} leg, denoted by $g_i(v_i)$ (tons/n mile), is mainly dependent on the sailing speed v_i, and has the following form:

$$g_i(v_i) = a_i(v_i)^{b_i}, \forall i \in I \tag{3}$$

where $a_i > 0$, $b_i > 1$ are two parameters calibrated from historical operating data (Wang and Meng, 2012). Fuel consumption further determines carbon emission. Note that the ship speed can generally be freely adjusted as there is little traffic in the open sea, in contrast to road transportation in which the speed is mainly determined by the traffic condition (Suzuki 2008, 2011; Suzuki and Dai 2012; Qu et al. 2015; Riemann et al. 2015). Represent by α (USD/ton) the bunker price. As $v_i = L_i / t_i$, the total bunker cost can be calculated as follows:

$$\text{total bunker cost} = \alpha \sum_{i \in I} L_i a_i (v_i)^{b_i} = \alpha \sum_{i \in I} L_i a_i \left(\frac{L_i}{t_i}\right)^{b_i} = \alpha \sum_{i \in I} a_i (L_i)^{b_i+1} (t_i)^{-b_i} \tag{4}$$

2.1 Conventional Planning Approach

The conventional planning approach to determine the optimal sailing speeds on voyage legs at the tactical level by the shipping line is as follows:

Step 1: Before launching a ship route, the shipping line informs all the port operators on the ship route the ship related information (in particular, length and draft of the ships) and the approximate number of containers to be handled.

Step 2: Each of the operator of port of call $i \in I$ informs the shipping line the approximate container handling rate.

Step 3: Based on the container handling rates and the numbers of containers to be handled at all the ports, the shipping line estimates the port time τ_i at each port of call $i \in I$. The shipping line then makes decisions on the sailing speeds on all voyage legs according to the expected port times τ_i. As the sailing speeds are determined, the arrival time at each port of call could be calculated and such arrival times are announced in the website of the shipping line.

The above process occurs at the tactical level rather than at the operational level. In Step 3, the shipping line determines the optimal sailing speed, or equivalently, the optimal sailing time t_i, on each leg, by solving the following optimization model:

[Conventional]
$$\min_{t_i} \alpha \sum_{i \in I} a_i (L_i)^{b_i+1} (t_i)^{-b_i} \tag{5}$$

subject to:

$$\sum_{i \in I} t_i = 168m - \sum_{i \in I} \tau_i \tag{6}$$

$$t_i \geq 0, i \in I \tag{7}$$

The objective function (5) minimizes the total bunker cost. Constraint (6) imposes weekly frequency. Constraint (7) defines nonnegative variables.

2.2 Collaborative Mechanism

The conventional planning model (5) indicates that a longer sailing time leads to a lower cost. Therefore, if a port operator provides a shorter container handling time by deploying more quay cranes, less fuel will be consumed. In particular, the bunker cost reduction for the shipping line may outperform the cost increase for the port operator. We therefore provide the following collaborative mechanism between shipping lines and port operators. Such a collaborative mechanism is initiated by the shipping line. It benefits the shipping line and does not harm the port operators:

Step 1: Before launching a ship route, the shipping line informs all port operators on the ship route the ship related information (in particular, length and draft of the ships) and the approximate number of containers to be handled.

Step 2: Each of the operators the ports of call informs the shipping line the approximate container handling rate.

Step 3: The shipping line enquires each port operator (i) whether it is possible to increase the handling rate; and (ii) if it is possible for a port operator to increase the handling rate, what new handling rates are possible, and how much additional costs the shipping line needs to pay the port operator.

Step 4: Based on the possible handling rates provided by port operators, the shipping line determines which container handling rate to adopt at each port of call, and compensates the port operators. According to the chosen container handling rates and the numbers of containers to be handled at all the ports, the shipping line estimates the port time at each port of call $i \in I$. The shipping line then makes decisions on the sailing speeds on all voyage legs based on the expected port times. As the sailing speeds are determined, the arrival time at each port of call could be calculated and such arrival times are announced in the website of the shipping line.

Similar to the conventional planning approach, the above collaborative mechanism occurs at the tactical level rather than at the operational level. To formulate the shipping line's decisions in Step 4, we define the following notation. τ_i^k is the possible port times at port of call $i \in I$, $k = 0,1,2,\cdots,K_i$, where $K_i + 1$ is the number of possible port times at port of call i (including the index 0); $\tau_i^0 > \tau_i^1 > \cdots > \tau_i^{K_i}$; τ_i^0 is the same as the port time τ_i in the conventional planning approach. c_i^k is the additional cost the shipping line needs to pay the operator of port of call $i \in I$ if the port time τ_i^k is provided; $c_i^0 = 0 < c_i^1 < \cdots < c_i^{K_i}$. The shipping line has the following decisions: x_i^k is a binary variable which equals 1 if and only if the shipping line requests port time τ_i^k to be provided at port of call $i \in I$; t_i is the sailing time on leg $i \in I$. The optimization model for the shipping line under the collaborative mechanism is:

[Collaborative] $$\min_{x_i^k, t_i} \alpha \sum_{i \in I} a_i (L_i)^{b_i+1} (t_i)^{-b_i} + \sum_{i \in I} \sum_{k=0}^{K_i} c_i^k x_i^k \qquad (8)$$

subject to:

$$\sum_{i \in I} t_i + \sum_{i \in I} \sum_{k=0}^{K_i} \tau_i^k x_i^k = 168m \qquad (9)$$

$$\sum_{k=0}^{K_i} x_i^k = 1, i \in I \qquad (10)$$

$$x_i^k \in \{0,1\}, i \in I, k = 0,1,2,\cdots,K_i \qquad (11)$$

$$t_i \geq 0, i \in I \qquad (12)$$

The objective function (8) minimizes the sum of bunker costs and compensation costs for port operators. Constraint (9) imposes weekly frequency. Constraint (10) enforces that exactly one port time at each port of call is requested. Constraint (11) defines binary variables. Constraint (12) defines nonnegative variables.

Since the shipping line will compensate the port operators for their potential losses, the collaborative mechanism (8) benefits the shipping line and does not harm the port operators.

3. Solution Method

The model [Collaborative] is a mixed-integer nonlinear optimization model. We can see that it actually aims to find the optimal tradeoff between the total sailing time and the total port time. Since the turnaround time $168m$ is constant, we can define T as the total sailing time, $\hat{T}$ as the total port time, and decompose the model.

The model [Collaborative] can be reformulated as a speed optimization model, a port time optimization model, and linking constraints:

[Speed]

$$\min_{t_i} \alpha \sum_{i \in I} a_i (L_i)^{b_i+1} (t_i)^{-b_i} \tag{13}$$

subject to:

$$\sum_{i \in I} t_i = T \tag{14}$$

$$t_i \geq 0, i \in I \tag{15}$$

[Port time]

$$\min_{x_i^k} \sum_{i \in I} \sum_{k=0}^{K_i} c_i^k x_i^k \tag{16}$$

subject to:

$$\sum_{i \in I} \sum_{k=0}^{K_i} \tau_i^k x_i^k \leq \hat{T} \tag{17}$$

$$\sum_{k=0}^{K_i} x_i^k = 1, i \in I \tag{18}$$

$$x_i^k \in \{0,1\}, i \in I, k = 0,1,2,\cdots,K_i \tag{19}$$

[Linking constraints] $$T + \hat{T} = 168m \tag{20}$$

$$T \geq 0, \hat{T} \geq 0 \tag{21}$$

In Eq. (17), we use "≤" rather than "=" because x_i^k are discrete decision variables.

Now we can develop the following global optimization method:

Step 1: Discretize T from 0 to $168m$ (e.g., in terms of 1 hour).

Step 2: For each of the discretized values of T, solve model [Speed], and solve model [Port time] by fixing $\hat{T} = 168m - T$. We will elaborate on how to solve the two models in the next two subsections. If model [Port time] is infeasible, we can set its objective value at infinity.

Step 3: Find the value of T that leads to the minimal total objective value of the two models [Speed] and [Port time], and the corresponding optimal decisions.

The model [Speed] can be solved based on its Karush-Kuhn-Tucker conditions and the model [Port time] has a pseudo-polynomial solution algorithm based on the well-known knapsack problem. The details of how to solve the two models can be found in Appendix 1 and Appendix 2.

4. Illustrative Example

To investigate the effectiveness of the proposed collaboration mechanism, we apply it to the CCX ship route shown in Fig. 1, a real route operated by OOCL. Five 5000-TEU ships are deployed on the ship route. The bunker price $\alpha = 500$ USD/ton. The relation (3) between sailing speed and bunker consumption per nautical mile is (Wang and Meng 2012; Xiao et al. 2012; Fransoo and Lee 2013):

$$g_i(v_i) = \frac{0.02 \times (v_i)^3}{24 v_i} \approx 0.00083 \times (v_i)^2, i \in I$$

We define Qingdao as the first port of call. The distance of each voyage leg (n mile), the possible port times provided by each port of call (h) and the corresponding additional costs (USD) are shown in Table 1. The port of Pusan (which is called twice in a round-trip journey) and the port of Los Angeles provide more than one possible port time.

<Table 1>

In the conventional planning approach, the shipping line accepts the port times τ_i^0, and the optimal speed on the ship route is 21.12 knots. The total bunker cost is 2.236×10^6 USD. In the collaborative mechanism, the shipping line accepts the port time of 36 hours at the 5th port of call, 48 hours at the 6th port of call, and 24 hours at the 8th port of call. As a result, the optimal speed on the ship route is reduced to 20.47 knots, and the total bunker cost is decreased to 2.101×10^6 USD. At the same time, the shipping line needs to pay the port operators $26,000$ USD. Therefore, in the collaborative mechanism the shipping line has a total cost of 2.127×10^6 USD, which is 1.09×10^5 USD smaller than that in the conventional planning approach.

4.1 Impact Analysis of the Tightness of the Schedule

The schedule of a ship route might be "tight" in the sense that ships sail at a high speed and as a result, in case of delay there is little room for the ships to speed up. Liner shipping companies design a tight schedule for several reasons. First, if the operating cost of a ship is high, then a tight schedule is preferable as fewer ships are required to maintain a weekly frequency. Note that the operating cost of a ship is high if the crew wages are high and the time charter rate of ships is high. Second, when there are not sufficient ships to deploy, a tight schedule is necessary.

We investigate how the tightness of the schedule affects the collaboration mechanism. To this end, we conduct experiments by changing the number of ships to deploy from 4, 5 through to 8. We report in Table 2 the accepted port times (hours) at the three ports of call (the 5th port of call Pusan, the 6th port of call Los Angeles, and the 8th port of call Pusan) under the collaboration mechanism and cost reduction over the conventional planning approach. We can see that when the schedule is tighter (fewer ships deployed), shipping lines will accept shorter port times, and although shipping lines have to pay more to the port operators, the cost reduction due to less fuel burned is more significant. This finding has two implications: shipping lines should push port operators harder to reduce the port time in case of tighter schedule, and port operators can charge higher compensation if the shipping lines' schedule are tighter.

<Table 2>

4.2 Influence of the Bunker Price

The bunker price is mainly determined by the crude oil price in the international market and may change rapidly due to political factors. We analyze how the bunker price affects the collaboration mechanism by changing the bunker price from 200 USD/ton, 300 USD/ton through to 700 USD/ton. We report in Table 3 the accepted port times (hours) at the three ports of call (the 5th port of call Pusan, the 6th port of call Los Angeles, and the 8th port of call

Pusan) under the collaboration mechanism and cost reduction over the conventional planning approach. We can see that when the bunker price is higher, shipping lines will accept shorter port times, and although shipping lines have to pay more to the port operators, the cost reduction due to less fuel burned is more significant. Therefore, shipping lines should push port operators harder to reduce the port time in case of higher bunker price, and port operators can charge higher compensation if the bunker price is higher.

<Table 3>

4.3 Results of Different Compensation Prices at Los Angeles

Port operators may aim to obtain more compensation for reducing the port time. We analyze how the compensation price at Los Angeles for the shorter port time of 36 hours affects the collaboration mechanism. We change the compensation price from 80,000, 85,000 through to 100,000 USD and report in Table 4 the accepted port times (hours) at the three ports of call (the 5th port of call Pusan, the 6th port of call Los Angeles, and the 8th port of call Pusan) under the collaboration mechanism and cost reduction over the conventional planning approach. We can see that when the compensation required by Los Angeles is higher than 85,000 USD, shipping lines will not accept the shorter port time of 36 hours as it is too expensive. When the compensation required by Los Angeles is lower than 80,000 USD, shipping lines will accept the shorter port time. This means if the additional cost for providing the shorter port time at Los Angeles is lower than 80,000 USD, the Los Angeles port operator may charge 80,000 USD for shipping lines to use the shorter port time.

<Table 4>

5. Implications

The proposed collaborative mechanism works best for liner services with tight schedules, meaning that a slight reduction of port time will lead to considerable fuel cost savings. For example, when the fuel price is low and the supply of shipping capacity is insufficient, ships will sail at high speeds with little buffer time and the proposed collaborative mechanism could dramatically benefit shipping lines. When shipping capacity is sufficient and shipping lines slow steam, the advantage of shorter port time is not as evident as when liner services have tight schedules.

When a port has extra quay cranes, which was the case for many ports in 2008 (Port Finance International 2015), then it is straightforward for the port operator to estimate the extra cost of deploying more quay cranes, which is the extra overtime compensation for the crane operators. When a port has limited number of quay cranes and/or crane operators, which is the case for e.g. Canadian ports (Canada Visa 2015) and the Port of Hong Kong (Wong 2014), deploying more quay cranes for one vessel means reducing the productivity for other vessels. As a result, a trade-off has to be balanced. The key question for the port operator is to identify which vessels have more buffer time on their next leg and therefore do not incur too much extra fuel costs if their port time is increased.

One potential problem associated with the collaborative mechanism is how to maintain the relation between the port operator and the shipping lines. Currently, suppose that the port operator promises an average productivity of e.g. 120 container moves per hour. In practice, even if the real productivity is 110 moves/h, shipping lines would not seek compensation because they want to maintain a good relation with the port operator. However, if a shipping line pays extra and the port operator promises an average productivity of e.g. 140 moves/h, but in reality the productivity is only 120 moves/h, then there is no reason to believe that the shipping line would not seek compensation from the port operator. Neither the port operator nor the shipping line wants to see this situation.

Another potential problem is the fairness between shipping lines. Suppose that two ships S1 and S2 of similar size are operated by two shipping lines; at most 6 quay cranes can be deployed on a ship. Suppose that the port has 10 quay cranes and the shipping line of S2 pays extra and the port promises to deploy 6 quay cranes for S2. Suppose that S1 is berthed first and S2 is still on its way to the port. The port will deploy 6 quay cranes for S1. When S2 arrives, the port will deploy the remaining 4 quay cranes for S2 and move 2 quay cranes from S1 to S2. The shipping line of S1 might be very uncomfortable and unsatisfied that S2 has a higher priority over S1, seeing that 2 quay cranes are moved from S1 to S2, even though the shipping line of S2 pays extra. Consequently, before implementing the collaborative mechanism, seeking opinions from port operators and shipping lines and analyzing the qualitative factors are essential.

6. Conclusions

The container handling rates at ports are input for container shipping operations planning by shipping lines. In conventional planning approaches, the handling rates are unilaterally determined by port operators. This paper pointed out that it may be possible for port operators to provide higher handling rates at some additional costs. The higher handling rates will reduce the costs for shipping lines, which may be more significant than the additional costs incurred by port operators. We therefore proposed a practical and easy-to-implement collaborative mechanism between shipping lines and port operators, where the shipping lines compensate the port operators for their additional costs. We further developed solution methods for finding the optimal planning decisions under such a collaborative mechanism. An illustrative example based on a trans-Pacific ship route operated by OOCL demonstrates that considerable cost reductions for the shipping line could be achieved and no loss is incurred to port operators.

The proposed mechanism may also be applied on an ad-hoc basis when a ship falls behind schedule. In such a situation, the shipping line might be interested to know whether it makes sense to offer the terminal an extra fee for faster service or to operate at higher speed in order to return to schedule. The optimal tradeoff between the extra terminal fee and the extra bunker cost can be analyzed in a similar manner.

An important component in the collaborative mechanism is how port operators estimate the handling times. The handling time depends on factors including the number of containers to be handled, the number of quay cranes to be deployed which is constrained by the number of available ones and the length of the ship, and the storage of containers on the ship. These factors could be modelled in future studies.

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Appendix 1: A Bi-Section Search Based Approach for Sailing Speed Optimization

To address the model [Speed], we derive its Karush-Kuhn-Tucker (KKT) conditions (Wang et al. 2016). Let λ and π_i be the Lagrangian multiplier associated with Eqs. (14) and (15), respectively. The optimal solution to [Speed] must satisfy the KKT conditions below:

[KKT]

$$\alpha a_i(-b_i)(L_i)^{b_i+1}(t_i)^{-b_i-1} + \lambda - \pi_i = 0, \forall i \in I \tag{22}$$

$$\pi_i t_i = 0, \forall i \in I \tag{23}$$

$$\pi_i \geq 0, \forall i \in I \tag{24}$$

$$\sum_{i \in I} t_i = T \tag{25}$$

$$t_i \geq 0, \forall i \in I \tag{26}$$

where Eq. (22) is the KKT equations, Eq. (23) is the complementary slackness conditions, Eq. (24) is the nonnegativity constraints on Lagrangian multipliers, and Eqs. (25) and (26) impose feasibility of the solution.

Evidently, at the optimal solution we must have $t_i > 0, i \in I$. Therefore, the complementary slackness conditions (23) imply that $\pi_i = 0, i \in I$. As a result, Eq. (22) becomes:

$$t_i = L_i \left(\frac{\lambda}{\alpha a_i b_i} \right)^{-\frac{1}{b_i+1}}, \forall i \in I \tag{27}$$

Eq. (27) means that all the $t_i, i \in I$ strictly decreases with λ. Therefore, an efficient way to address model [Speed] is to use bi-section search on λ and then check whether constraint (25) is satisfied. More exactly, due to numerical errors, constraint (25) should be replaced by

$$\sum_{i \in I} t_i \le T \tag{28}$$

The bi-section search based method is:

Step 1: Define a lower bound for λ, denoted by $\underline{\lambda}$, and an upper bound for λ, denoted by $\overline{\lambda}$. $\underline{\lambda}$ should be sufficiently small and $\overline{\lambda}$ should be sufficiently large.

Step 2: Set $\lambda = (\underline{\lambda} + \overline{\lambda})/2$. Compute t_i by Eq. (27). If Eq. (28) is satisfied, set $\overline{\lambda} \leftarrow (\underline{\lambda} + \overline{\lambda})/2$; otherwise set $\underline{\lambda} \leftarrow (\underline{\lambda} + \overline{\lambda})/2$.

Step 3: If $\overline{\lambda} - \underline{\lambda}$ is smaller than a pre-specified tolerance, stop and output the values of t_i. Otherwise go to Step 2.

Appendix 2: A Dynamic Programming Based Approach for Port Time Optimization

The model [Port time] has a nice structure that is similar to the well-known knapsack problem. This structure leads to the following dynamic programming based pseudo-polynomial solution algorithm.

We assume that $\hat{T}$ and all τ_i^k are integers (integer number of hours). Then, in the dynamic programming method, there are N stages, which correspond to the visit of the N ports of call. The number of states in stage $i \in I$ is $K_i \hat{T}$: we can represent a state in stage $i \in I$ by (k,t), where $k = 0,1,2,\cdots,K_i$ and $t = 1,2,\cdots,\hat{T}$. The state (k,t) in stage $i \in I$ means the port time at port of call i is τ_i^k and the total port time at ports of call $i, i+1, i+2, \cdots, N$ does not exceed t. We can define $S_i(k,t)$ as the minimum total costs that the shipping line should pay the port operators at ports of call $i, i+1, i+2, \cdots, N$ at the state (k,t) in stage $i \in I$. At the state (k,t) in stage $i-1$, the decision is which handling port time at port of call i to adopt. If port time $\tau_i^{k'}$ is adopted, then the state will become $(k', t-\tau_{i-1}^k)$ in stage i. The recursive relation is:

$$S_N(k,t) = \begin{cases} c_N^k, \text{ if } \tau_N^k \le t \\ +\infty, \text{ otherwise} \end{cases} \tag{29}$$

$$S_{i-1}(k,t) = c_{i-1}^k + \min_{k'=0,1,2,\cdots,K_i} S_i(k', t-\tau_{i-1}^k), i = 2,3,\cdots,N \tag{30}$$

The optimal objective value of model [Port time] is

$$\min_{k=0,1,2,\cdots,K_1} S_1(k,\hat{T}) \tag{31}$$

Since in reality K_i and $\hat{T}$ are not large (e.g., K_i may be smaller than 4 and $\hat{T}$ may be smaller than 1000), model [Port time] could be efficiently solved.

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