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Collaborative mechanisms for berth allocation ☆

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ABSTRACT

This paper proposes two collaborative mechanisms between container shipping lines and port operators to facilitate port operators to make proper berth allocation decisions. In the first mechanism, assuming no transshipment, a shipping line needs to provide the port operator with the utilities associated with the start operation days of each liner route. The total utilities for all start operation days must be 0. A higher bunker and inventory cost for the shipping line means a lower utility. The port operator compensates the shipping line if its ship is scheduled on a day with negative utility and charges additional fees if the ship is scheduled on a day with positive utility. The second mechanism accounts for the utilities related to the inventory cost of transshipment containers. These two mechanisms ensure that shipping lines have no incentive to overstate or undervalue the utilities. The utilities estimated by shipping lines are much more accurate than those estimated by port operators. Hence, models for the tactical berth allocation problem incorporating the utilities provided by shipping lines lead to more efficient and equitable berth allocation plans. The utilities provided by shipping lines can also guide the decisions on operational berth allocation.

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1. Introduction

Container shipping is vital to international trade: around 80 per cent of global trade by volume and over 70 per cent by value is carried by sea, and among all the sea cargos, 52 per cent in dollar terms are containerized [37]. There are two major players in container shipping: container shipping lines and container port operators [36]. Shipping lines transport containers from their origin ports to their destination ports [1,2,28,29,30,26,51]. Port operators provide services for containerships, such as container handling and storage, refueling, replenishment of consumables and maintenance. The fast growth of international container trade and the time-consuming and costly port capacity expansion have enabled port operators to seek efficient operations planning tools, which are a subject of extensive academic studies, see Vis and de Koster [38], Steenken et al. [35], Stahlbock and Voss [34], Bierwirth and Meisel [3].

Port operations are of utmost concern by maritime and port authorities and poor planning would result in serious economic, safety, and/or environmental issues [32,33,44]. They mainly consist of the quay-side operations and yard-side operations [15,16,5,45,48,46,47,17]. The berth allocation problem (BAP), which is the assignment of quay space and service time to vessels for container loading and unloading, is one of the essential quay-side decision problems faced by port operators. The BAP can be classified according to different criteria. First, there are discrete BAP (DBAP) where each berth can serve one ship at a time, and continuous BAP (CBAP) with a long straight quay and how many ships can be accommodated at the same time depends on the sizes of the ships. Second, BAP can be classified as being either static (SBAP) or dynamic (DynBAP). In SBAP, all ships are already in the port when the berth allocation is planned, whereas in DynBAP some ships are still on the voyage to the port when the port operator allocates berths. The SBAP is applicable when the port is highly congested, and is not the focus of our study. Third, BAP can occur at the operational level (OBAP), or tactical level (TBAP). The OBAP covers a planning horizon of usually at most one week and the TBAP aims to support port operators to negotiate with shipping lines. If TBAP accounts for the periodicity of vessel schedules, e.g., weekly arrival patterns of containerships, then if a vessel is serviced at a berth on day 7 and day 8, other vessels cannot use the berth on day 1, because day 8 and day 1 correspond to the same day in a week. The time horizon of this type of TBAP is a cylinder whose circumference equals 1 week. Hence, the resulting models (see [31,50] are significantly different from OBAP. If in

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the TBAP vessels do not arrive periodically, the time horizon is simply a rectangle with an open end and the models are very similar to OBAP models.

Besides determining the berthing time and location, some studies on DynBAP (either DBAP or CBAP and either TBAP or OBAP) also integrate other decision issues such as quay crane assignment, quay crane scheduling, container storage planning at yard, and yard truck scheduling. The models on DynBAP all aim at providing berthing and other related services at minimum cost (cost associated with quay cranes and yard trucks). However, different models have different definitions for service. Most studies assume that each ship has a preferred arrival time. Giallombardo et al. [9] is an exception in that it examined a TBAP and assumed that there is no difference for shipping lines when their ships are scheduled to arrive. The objective is to minimize the container handling time of ships by choosing quay crane assignment profiles.

The studies considering the preference of ship arrival times can be classified into four different lines, which are briefly summarized as follows. The first line aims to minimize the total service time (turnaround time) of all ships, including waiting time for berths and container handling time, or total weighted service time where different ships have different weights, for example, Imai et al. [18,19,22,21], Cordeau et al. [7], Moorthy and Teo [31], Golias et al. [11,12], Lee et al. [24]. Note that if the handling time is constant, minimizing the service time is equivalent to minimizing the waiting time. Similarly, Imai et al. [20] required that if a ship's waiting time exceeds a certain limit, the ship must be served at an external terminal, and minimized the total service time of ships at the external terminal. Golias et al. [10] considered two objectives: minimizing the total service time of preferential customers, and minimizing the total service time of all vessels.

The second line minimizes the total tardiness cost, which is the finish operation time (real departure time) minus the expected departure time if the former is larger, and 0 otherwise, for instance, Kim and Moon [23], Chang et al. [4], Zhen et al. [50]. In addition, Han et al. [14] proposed a proactive approach for a BAP with quay crane scheduling and stochastic arrival and handling time. They took into account the expected value and standard deviation of the total service time and weighted tardiness of all ships. Chen et al. [6] minimized the maximum relative tardiness of all ships, which depends on the arrival time, the expected departure time, and the finish operation time, respectively.

The third line formulates the penalty for earliness and tardiness in greater details. Meisel and Bierwirth [27] investigated a CBAP with quay crane allocation. They considered a cost function that is related to the ships' expected arrival time, earliest start operation time, expected finish operation time, latest allowed finish operation time, start operation time and finish operation time. Zhen et al. [49] developed an integrated model for the TBAP with yard operations planning. The model minimized the weighted sum of deviation from vessels' expected turnaround time intervals and the operations cost associated with transshipment containers. Both early arrival and late arrival were penalized.

The fourth line incorporates the bunker cost of the vessels in the models. Golias et al. [13] considered the following elements in the objective function: (i) the total service time, (ii) the tardiness, and (iii) the emissions and fuel cost for all vessels while in transit to their next port of call. By contrast, Du et al. [8] incorporated the tardiness and the fuel cost for all vessels while in transit from their current positions to the focal port of the BAP.

All of the above studies optimize container terminal operations from the viewpoint of port operators while taking into account the requirement from shipping lines. With the exception of a few works that minimize the total service time, all models need more input regarding the ships than the most essential ones such as which containers to discharge and which containers to load. For instance, to minimize the weighted total service time, one needs to know the weight of each ship's service time; to minimize the tardiness, the expected departure time is necessary; studies in the third and fourth lines require even more inputs from shipping lines. In reality, shipping lines may be reluctant to share the information because of confidentiality. Moreover, wrong information may be delivered to port operators, for example, shipping lines may exaggerate the severity of the delay of their ships. Consequently, port operators have to estimate the parameters based on the importance of the shipping line, the size and container handling volume of the ship, and subjective judgment. We conjecture that this is also the reason why considerably more mathematical models fall into the first and second lines of research that needs much fewer parameters than the third and fourth lines.

Therefore, the objective of this study is to propose collaborative mechanisms between shipping lines and port operators for TBAP. Such mechanisms ensure that shipping lines have the incentive to provide true and accurate information for berthing to port operators. The information is aggregate and hence does not contain any confidential data. Port operators will take advantage of the information to allocate berths in an efficient and equitable manner.

The remainder of the paper is organized as follows. Section 2 proposes a collaborative mechanism for ships without container transshipment. Section 3 designs a collaborative mechanism for ships with container transshipment and formulates a mathematical model for BAP with collaborative mechanisms. Section 4 reports a case study. Finally, Section 5 concludes this paper and points out future research directions.

2. Collaborative mechanism without transshipment

2.1. A simple example of the impact of different start operation times

We first use a simple example to demonstrate the impact of different start operation times on shipping lines. We assume that ships arrive on a weekly pattern as in reality most shipping lines provide weekly liner shipping services [42,43].

Example 1. Consider the BAP at Pusan with a weekly liner service route that includes Savannah, Pusan, and Qingdao sequentially, among others, see Fig. 1. A string of 5000-TEU (twenty-foot equivalent units) ships are deployed on this route and visit each port of call on the same day every week. Suppose that ships on the route leave Savannah on Sunday (day 0), and arrive at Qingdao on Tuesday 4 weeks later (day 30). A ship spends 2 day at Pusan for container handling and the shipping line needs to negotiate with Pusan about what day of a week its ships should visit Pusan.

We assume that the shipping line is concerned about the bunker cost and the inventory cost of the containers. A lower sailing speed implies a lower bunker cost because daily bunker consumption is approximately proportional to the speed cubed. At the same time, a lower speed means a longer transit time, and thereby a higher inventory cost of the cargos in containers. Suppose that the bunker consumption (ton/n mile) is 0.001 times the sailing speed squared, and the bunker price is $500/ton. The highest sailing speed of the

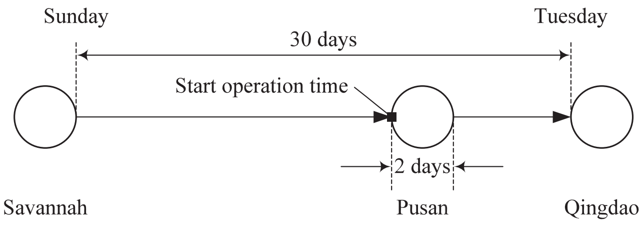

Fig. 1. Pusan and its previous and subsequent ports of call.

ships is 25 knots. Suppose further that the inventory cost rate is \$0.5/(TEU h) and 4500 TEUs are carried from Savannah to Pusan (the distance is 9678 n miles) and 3500 TEUs are carried from Pusan to Qingdao (the distance is 467 n miles). □

For Example 1, we calculate the effect of different start operation days (SODs) at Pusan on the total costs for the shipping line. Suppose that the SOD is Sunday, as the departure day from Savannah is Sunday (day 0), the ships can sail for 7 days, 14 days, 21 days, or 28 days from Savannah to Pusan. (i) If the ship arrives at Pusan on day 7, the sailing speed of the ship from Savannah and Pusan, denoted by v (knots), is

$$v = \frac{\text{sailing distance}}{\text{sailing time}} = \frac{9678}{7 \times 24} \approx 57.6,$$

which is greater than the maximum speed 25 knots. Hence, the ship cannot arrive at Pusan on day 7. (ii) If the ship arrives at Pusan on day 14,

$$v = \frac{\text{sailing distance}}{\text{sailing time}} = \frac{9678}{14 \times 24} \approx 28.8,$$

which is greater than the maximum speed 25 knots. Hence, the ship cannot arrive at Pusan on day 14. (iii) If the ship arrives at Pusan on day 21,

$$v = \frac{\text{sailing distance}}{\text{sailing time}} = \frac{9678}{21 \times 24} \approx 19.2$$

The sailing time from Pusan to Qingdao is 30 days minus the 21 days for sailing from Savannah to Pusan, and then minus the 2 days for container handling at Pusan, equal to 7 days. The sailing speed of the ship between Pusan and Qingdao, denoted by v' (knots), is

$$v' = \frac{\text{sailing distance}}{\text{sailing time}} = \frac{467}{(30 - 21 - 2) \times 24} \approx 2.7.$$

Since both v and v' are smaller than the maximum speed, it is possible for the ship to arrive at Pusan on day 21. The total costs, including the bunker cost and the inventory cost, on the two legs, can be calculated by

$$\begin{aligned}
\text{Total costs} = {} & \text{Bunker cost on the first leg} \\
& + \text{Inventory cost on the first leg} \\
& + \text{Bunker cost on the second leg} \\
& + \text{Inventory cost on the second leg} \\
= {} & 500 \times 9678 \times 0.001 \times v^2 + 0.5 \times 4500 \times (21 \times 24) \\
& + 500 \times 467 \times 0.001 \times v'^2 + 0.5 \times 3500 \times [(30 - 21 \\
& - 2) \times 24] \\
\approx {} & 3.21 \times 10^6.
\end{aligned}$$

(iv) If the ship arrives at Pusan on day 28, then the sailing time from Pusan to Qingdao is 0, which is impossible.

Based on the above calculations, when the SOD is Sunday, the total bunker and inventory costs are $\$3.21 \times 10^6$, and the ship visits Pusan on day 21. Using this approach, we calculate the total costs for each SOD, and the results are shown in Fig. 2 and Table 1. The most desirable SOD is Saturday. The total cost changes nonlinearly with the deviation from the most desirable day. For instance, if the SOD is changed from Saturday to Friday, the total cost is slightly increased by $\$9 \times 10^3$. However, if the start operation day is changed to Sunday, the cost will increase by $\$5.5 \times 10^5$.[1]

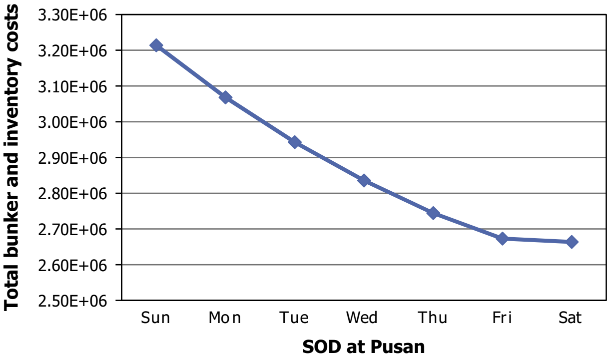

Fig. 2. The sum of bunker cost and inventory cost (\$) associated with different SODs.

Table 1
The total costs ($\$10^6$) associated with different SODs.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
3.21	3.07	2.94	2.84	2.74	2.67	2.66

The above calculation already demonstrates that a number of parameters are needed for port operators to properly address the BAP. Considering that different shipping lines have significantly different cost structures, it is hardly possible for port operators to obtain all the cost parameters from the shipping lines.

2.2. Collaborative mechanism

We thus propose a collaborative mechanism to address this problem, which is similar to congestion pricing in road transportation [25]. In the collaborative mechanism, the port operator requires that a shipping line must provide a utility value u_{it} (\$) if its ship i starts operation on day t, where $t \in W$ and $W := \{0, 1, 2, \ldots, 6\}$ means Sunday (0), Monday (1), through to Saturday (6), respectively. For instance, letting c_{it} be the total cost (\$) associated with SOD $t \in W$ (the values shown in Table 1), the shipping line may propose the following values of u_{it}:

$$u_{it} = \frac{\sum_{\tau \in W} c_{i\tau}}{7} - c_{it}, t \in W \tag{1}$$

The values of u_{it} are shown in Table 2 for the example in Fig. 2. If $u_{it} > 0$, then u_{it} is the additional fee that the shipping line would like to pay if the port operator plans the start operation time on day t; else if $u_{it} < 0$, then $-u_{it}$ is the amount of compensation payable to the shipping line as the port operator schedules the ships on an undesirable day t. To ensure fairness, the port operator requires that the utilities must satisfy:

$$\sum_{t \in W} u_{it} = 0 \tag{2}$$

Hence, if a day t is desirable, the shipping line will set a positive u_{it} and if a day t is undesirable, the shipping line will set a negative u_{it}. The values of u_{it} calculated by Eq. (1) satisfy the relation in Eq. (2).

A congested port could only provide limited flexibility to the shipping lines, which means ships must be prepared to arrive on

Table 2
The utility ($\$10^3$) for each of the seven days defined by Eq. (1).

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
−337	−191	−65	42	133	204	214

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[1] In reality, if the port operator imposes ships must arrive on Sunday (and served on Sunday and Monday for container handling), then the shipping line will adjust the arrival times at Savannah and Qingdao. Hence, the cost increase would be less than $\$5.5 \times 10^5$.

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any day of a week. By contrast, if the port has sufficient capacity, it may give more flexibility to shipping lines. For example, it may require that each ship can choose the start operation time from any 5 days of a week, and the sum of the u_{it} over these 5 days is 0. In the example in Fig. 2, the shipping line will choose Tuesday, Wednesday, Thursday, Friday and Saturday because Sunday and Monday are the least preferable. Pusan must ensure that a berth is available on these five days. The values of u_{it} in this context can be calculated by the following equation

$$u_{it} = \frac{c_{i2} + c_{i3} + c_{i4} + c_{i5} + c_{i6}}{5} - c_{it}, t \in W \setminus \{0, 1\} \qquad (3)$$

and are reported in Table 3.

2.3. Advantages of the collaborative mechanism

Such a collaborative mechanism has four advantages. First, shipping lines calculate the impact of different start operation days and they do not need to disclose confidential information about how u_{it} is calculated to port operators. The accuracy of u_{it} depends on the efforts of the shipping lines. They may try to obtain an accurate u_{it}, or just give a rough estimation. Nevertheless, even a rough estimation is highly desirable because (i) a rough estimation by the shipping line is much more accurate than the estimation based on the subjective judgment of the port operator; (ii) the *perceived* service quality is high: if the shipping line overestimates the utility of a particular day and the port operator schedules the arrival on that day, then the shipping line is still happy because *in its opinion* that day has high utility.

Second, Eq. (2) ensures that shipping lines will try to report the real values of u_{it}. It does not make sense for shipping lines to overstate or undervalue the utility of a particular day. That is the novelty of the mechanism. In reality, we believe that at the beginning as shipping lines are not familiar with the mechanism, they may tend to underreport the value of $|u_{it}|$ if it is too large in order to avoid paying too high fees to the port operator (or simply set $u_{it} = 0$). As port operators are also not familiar with the mechanism, they may set an upper limit for $|u_{it}|$ so that they do not need to compensate too much to the shipping lines.

Third, port operators can prioritize ships according to their real sensitivity to start operation times, rather than e.g. according to the importance of the shipping lines. This will lead to a more equitable and efficient berth allocation plan.

Fourth, although the collaborative mechanism is designed for TBAP, it may also guide the decisions on OBAP. For instance, consider two ships i and j. Their planned start operation times are both Sunday with $u_{i0} = u_{j0} = 1000$. In a particular week both ship arrive on Saturday and it happens that the port has exactly one available berth. If $u_{i6} = 3000$ and $u_{j6} = 4000$, then the port operator should serve ship j at the berth and let ship i wait.

3. Collaborative mechanism with transshipment

In Section 2, we do not consider the impact of container transshipment. In reality, ships frequently transship containers especially in hub-and-spoke networks.

Table 3
The utility ($\$10^3$) for each of the five days.

Tuesday	Wednesday	Thursday	Friday	Saturday
−171	−64	28	99	108

Example 2. Suppose that in Example 1 there is another liner route that provides a weekly feeder service connecting Pusan and Dalian (the distance is 526 n miles) using one 1000-TEU ship. The ship spends one day at Dalian and one day at Pusan. It transfers 900 TEUs to the 5000-TEU ships on the mainline service in Fig. 1, and receives 700 TEUs from the 5000-TEU ships. For simplicity, we assume that the port of Dalian is always available for berthing. Therefore, the SOD at Pusan does not affect the bunker and inventory costs on the feeder route. Suppose that the 5000-TEU ships in Fig. 1 are scheduled to visit Pusan on Saturday (and are berthed on Saturday and Sunday), and containers can be transshipped between ships if their berthing times have at least one day overlap. □

If the 1000-TEU ship is berthed on Saturday, the 900 TEUs will stay at Pusan for 2 days (the time interval from the arrival of the incoming ship to the departure of the outgoing ship), and the 700 TEUs will stay at Pusan for 1 day. If the 1000-TEU ship is berthed on Thursday, the 900 TEUs must be stored in the yard until Saturday when the 5000-TEU ship arrives (4 days' inventory from Thursday to Sunday), and the 700 TEUs must be stored in the yard until next Thursday when the 1000-TEU ship arrives (6 days' inventory from Saturday to Thursday). The inventory cost of the transshipment containers can be calculated by

$$\begin{aligned} &\text{Inventory cost of transshipment containers} \\ &\quad = 0.5 \times 900 \times (4 \times 24) + 0.5 \times 700 \times (6 \times 24) = 93600. \end{aligned}$$

The inventory costs of the transshipment containers associated with different SOD of the 1000-TEU ship at Pusan are reported in Fig. 3 (given that the SOD at Pusan for the mainline service in Fig. 1 is Saturday). Sunday is the most desirable SOD with a total inventory cost of \$27,600.

Fig. 3 highlights that the inventory cost of transshipment containers changes nonlinearly with the deviation from the most desirable day. Moreover, the inventory cost of transshipment containers is related to the *difference* of the start operation days of the two ships. For example, there is no difference in the inventory cost of transshipment containers whether the 5000-TEU ships arrive on Saturday and the 1000-TEU ship arrives on Sunday, or the former arrive on Thursday and the latter arrives on Friday. Hence, let i be the mainline ship that visits the port on day t_i, and j be the feeder ship that visits on day t_j. The total inventory cost of transshipment containers, denoted by $c_{ij}^{(t_i - t_j)\mathrm{mod}7}$, is shown in Table 4 and is the same as Fig. 3.

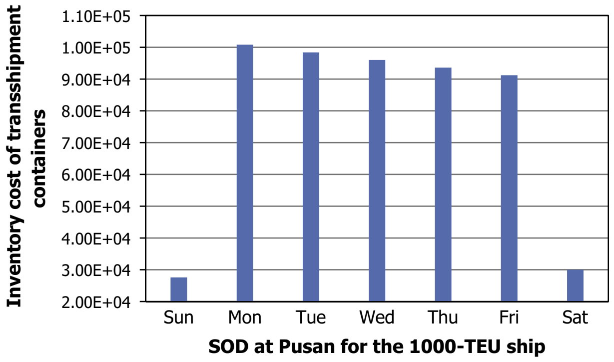

Fig. 3. Inventory cost (\$) of transshipment containers for each SOD of the 1000-TEU ship.

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3.1. Collaborative mechanism

Similarly, a collaborative mechanism can be proposed for port operators to obtain the inventory cost (service requirement) of the shipping lines in transshipment connection. We assume that (i) the liner service routes are classified as mainline and feeder routes, (ii) a mainline route may transship containers with more than one feeder route, and (iii) a feeder route must transship containers with exactly one mainline route and the shipping lines are not concerned about the absolute SOD of the feeder routes (in the above example, as Dalian is always ready for berthing, when the feeder route starts operation at Pusan makes no difference if transshipment containers are excluded). We will discuss how to relax these assumptions later. The collaborative mechanism is as follows. For each mainline route i, the shipping line proposes its utilities of different start operation days that satisfy Eq. (2). For each feeder route j, the shipping line proposes utilities $u_{ij}^{(t_i-t_j)\mathrm{mod}7}$ with regard to the difference of the start operation days t_i and t_j. The utilities $u_{ij}^{(t_i-t_j)\mathrm{mod}7}$ must also satisfy:

$$\sum_{\Delta t=0}^{6} u_{ij}^{\Delta t} = 0 \tag{4}$$

For a shipping line, the calculation of $u_{ij}^{(t_i-t_j)\mathrm{mod}7}$ is similar to Eq. (1) and the result of Example 2 is shown in the last row of Table 4.

The port operator may also provide shipping lines the flexibility to choose $(t_i - t_j)$ mod 7 from e.g. 5 values rather than from the set $\{0, 1, 2, 3, 4, 5, 6\}$. If a shipping line has N liner service routes, it needs to provide $7N$ utility values to the port operator.

In a more general setting, a feeder route has its own preference for the start operation day (in the above example, if Dalian is not always available, the start operation day at Pusan will affect the bunker cost and inventory cost between Dalian and Pusan), and there may be transshipment containers between any two liner service routes [39,40,41]. In this case, the shipping line needs to define u_{it} for each liner service route, and $u_{ij}^{(t_i-t_j)\mathrm{mod}7}$ for each combination of two liner service routes. Therefore, a shipping line with N liner service routes needs to provide at most $7N + 7N(N-1)/2$ parameters to the port operator. It may be difficult for shipping lines to provide such a large number of parameters, especially at the early stage of the implementation of the collaborative mechanisms.

3.2. Mathematical model

We develop an optimization model to demonstrate how to incorporate the parameters provided by shipping lines under the collaborative mechanisms in BAP. We consider a general setting where any two ships may exchange containers and use the example of DBAP where the set of berths is B. A total of N ships need to be berthed and the values of u_{it} and $u_{ij}^{(t_i-t_j)\mathrm{mod}7}$ are already provided by shipping lines. We define parameters $u_{ij}^{t_i t_j} := u_{ij}^{(t_i-t_j)\mathrm{mod}7}$ to facilitate model development. We further define a binary parameter δ_{it}^{τ} which equals 1 if ship i that starts operation on day $t \in W$ needs to be berthed on day $\tau \in W$. For example, if the port time of ship i is two days, then $\delta_{i6}^{6} = \delta_{i6}^{0} = 1$ and $\delta_{i6}^{1} = \delta_{i6}^{2} = \delta_{i6}^{3} = \delta_{i6}^{4} = \delta_{i6}^{5} = 0$. Consistent with the literature, we define a cost parameter $c_{ij}^{b_1 b_2}$ (\$) which is the transportation cost of transshipment containers if ship i is berthed at $b_1 \in B$ and ship j is berthed at $b_2 \in B$. $c_{ij}^{b_1 b_2} = 0$ if there is no transshipment containers between the two ships. Note that $c_{ij}^{b_1 b_2}$ is the cost related to port operations, and hence the port operator could estimate it.

Let x_{ibt} be the a binary decision variable which equals 1 if ship $i = 1, 2, \cdots, N$ starts operation at berth $b \in B$ on day $t \in W$ and 0 otherwise. Let x_{it} be the a binary decision variable which equals 1 if and only ship i starts operation on day $t \in W$ and x_{ib} be the a binary decision variable which equals 1 if and only ship $i = 1, 2, \cdots, N$ is served at berth $b \in B$. The BAP can be formulated as

$$[\mathrm{P}] \quad \max_{x_{ibt}, x_{it}, x_{ib}} \sum_{i=1}^{N} \sum_{t \in W} u_{it} x_{it} + \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} \sum_{t \in W} \sum_{\tau \in W} u_{ij}^{t\tau} x_{it} x_{j\tau} - \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} \sum_{b_1 \in B} \sum_{b_2 \in B} c_{ij}^{b_1 b_2} x_{ib_1} x_{jb_2} \tag{5}$$

subject to:

$$x_{it} = \sum_{b \in B} x_{ibt}, i = 1, 2, \ldots, N, t \in W \tag{6}$$

$$x_{ib} = \sum_{t \in W} x_{ibt}, i = 1, 2, \ldots, N, b \in B \tag{7}$$

$$\sum_{b \in B} \sum_{t \in W} x_{ibt} = 1, i = 1, 2, \ldots, N \tag{8}$$

$$\sum_{i=1}^{N} \sum_{t \in W} \delta_{it}^{\tau} x_{ibt} \leqslant 1, b \in B, \tau \in W \tag{9}$$

$$x_{ibt} \in \{0, 1\}, i = 1, 2, \ldots, N, b \in B, t \in W \tag{10}$$

The objective function (5) maximizes the utility of the shipping lines (which corresponds to revenues of the port operators) minus the transportation cost of transshipment containers. Constraints (6) and (7) define x_{it} and x_{ib}, respectively. Constraint (8) imposes that a ship must start operation at one berth on one day of a week. Constraint (9) enforces that a berth can only serve one ship each day. Constraint (10) defines x_{ibt} as a binary decision variable. Note that x_{it} and x_{ib} take either 0 or 1 automatically due to the constraints (6), (7), (8) and (10).

If we consider a simple setting where ships on feeder routes are only concerned about the inventory cost of transshipment containers, then we can set $u_{jt} = 0, t \in W$, for feeder ship j. If the shipping lines can choose, for example, that ship i does not start operation on Sunday or Monday (day 0 or day 1), then we can set $x_{i0} = 0$ and $x_{i1} = 0$ in model [P].

4. Case study

We carry out two case studies to demonstrate the applicability of the proposed mechanisms. In the first case study, we do not consider the inventory cost of transshipment containers, and in the second case study, we consider the inventory cost of transshipment containers.

Table 4
Inventory cost (\$$10^3$) related to transshipment containers.

$t_j (t_i = \text{Sat})$	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
$(t_i - t_j)\mathrm{mod}7$	6	5	4	3	2	1	0
$c_{ij}^{(t_i-t_j)\mathrm{mod}7}$	27.6	100.8	98.4	96.0	93.6	91.2	30.0
$u_{ij}^{(t_i-t_j)\mathrm{mod}7}$	49.2	−24.0	−21.6	−19.2	−16.8	−14.4	46.8

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Table 5
The utility ($\$10^3$) defined by Eq. (1) for the two services.

Service	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
S1	−337	−191	−65	42	133	204	214
S2	280	−398	−216	−71	32	146	227

4.1. Case study without transshipment

Suppose that there is only one berth at the Port of Pusan. There are two shipping lines L1 and L2, providing services S1 and S2, respectively. S1 is identical to the one in Example 1. S2 visits Los Angeles, Pusan, and Tianjin. The distance from Los Angeles to Pusan is 5230 n miles, and Pusan to Tianjin 688 n miles. The ships on S2 leave Los Angeles on Wednesday and must arrive at Tianjin in 20 days. The time spent at Pusan is also 2 days. The number of containers carried from Los Angeles to Pusan is 3500 TEU, and from Pusan to Tianjin 5000 TEUs. The fuel consumption rate and the inventory cost rate are the same as S1.

The utilities for different SODs at Pusan for the two services are shown in Table 5. S1 has the highest utility when the SOD is Saturday, and Sunday is the most preferable SOD for S2. Since there is only one berth, and both S1 and S2 need two days for container handling, it is impossible for both services to visit Pusan on their most desirable SODs. In the optimal solution, the SOD for S1 is Friday, and the SOD for S2 is Sunday. The total utility provided for the two shipping lines is 204 + 280 = 484.

In the conventional berth allocation planning approach, if the port considers that S1 is more important, then it may satisfy S1 first by allocating Saturday as its SOD. Then the port has to let S2 arrive on Thursday. Hence, the total utility for the two shipping lines is only 214 + 32 = 246.

4.2. Case study with transshipment

Consider the case in Section 4.1, except that shipping line L1 further operates S3, which is the feeder service in Example 2. In the optimal solution, the SOD for S1 is Friday, the SOD for S2 is Sunday, and the SOD for S3 is Thursday. The total utility provided for the two shipping lines is 204 + 280 − 14 = 470.

In the conventional berth allocation planning approach, if the port considers that shipping line L1 is more important, then it may satisfy S1 and S3 first by allocating Saturday as the SOD for S1 and Friday as the SOD for S3. Then the port has to let S2 arrive on Wednesday. Hence, the total utility for the two shipping lines is only 214 – 71 − 14 = 129.

These two case studies demonstrate the applicability of the proposed collaborative mechanisms. In particular, shipping lines and port operators may achieve Pareto improvements using the mechanisms, meaning that at least one of the two players (shipping lines and port operators) gains more benefit while no player is hurt.

5. Conclusions and future work

This paper has proposed two collaborative mechanisms between container shipping lines and port operators to facilitate port operators to make more efficient and equitable tactical berth allocation decisions. In the first mechanism, a shipping line needs to provide the utilities associated with the start operation days of a week at the port for liner service routes with no transshipment containers, where a higher bunker and inventory cost means a lower utility. The port operator compensates the shipping line if its ship is scheduled on a day with negative utility and charges additional fees if the ship is scheduled on a day with positive utility. The requirement that the sum of the utilities of a week equals 0 ensures that the mechanism is fair to shipping lines and port operators, and ensures that shipping lines have no incentive to overstate or undervalue the utilities. In the second mechanism, a shipping line needs to provide the utilities associated with the difference of the start operation days of two liner routes with transshipment containers, where the utilities are related to the inventory cost of the transshipment containers.

It is easy to understand that the utilities estimated by shipping lines should be much more accurate than those estimated by port operators. Moreover, utilities estimated by shipping lines reflect the perceived service quality of the shipping lines. The resulting tactical berth allocation model incorporating the utilities provided by shipping lines under the collaborative mechanisms leads to more efficient and equitable berth allocation plans. The utilities provided by shipping lines can also guide the decisions on the operational berth allocation problems.

A natural extension of this work would be mechanism design for collaborations between different terminals at a port if these terminals are operated by different operators. How should they share berthing resources and allocate the additional profit for improved services is a worthwhile research topic. Another extension would be collaborations between different ports. For instance, a number of liner shipping services visit Hong Kong and Yantian sequentially. Hence, it may be advantageous for the port of Hong Kong and the port of Yantian to allocate their berths in a holistic manner to maximize the utilities of shipping lines.

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