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Daily berth planning in a tidal port with channel flow control

Lu Zhen,[1*] Zhe Liang, [2] Dan Zhuge, [3] Loo Hay Lee, [4] Ek Peng Chew [4]

[1] *School of Management, Shanghai University, Shanghai, China*
[2] *School of Economic and Management, Tongji University, Shanghai, China*
[3] *Department of Logistics and Maritime Studies, Hong Kong Polytechnic University, Hong Kong, China*
[4] *Department of Industrial and System Engineering, National University of Singapore, Singapore*

Abstract: This paper studies an operational-level berth allocation and quay crane assignment problem (daily berth planning) with the consideration of the tides and channel flow control constraints. An integer programming model is proposed for this problem. Then a column generation solution approach is developed on a set partitioning based reformulation of the original model. Computational study is conducted on 30 test cases constructed from the real-world data to validate the efficiency of the proposed solution approach. The results show that this simple but practical method can optimally solve the daily berthing planning problem instances with up to 80 vessels, 40 berths, and 120 quay cranes within one hour, which is reasonable and acceptable for the real-world applications. The proposed decision model and the solution method could be potentially useful for some tidal ports with (or without) navigation channels.

Keywords: Port operations; berth allocation; column generation; tide; container ports.

1. Introduction

Due to the offshoring of manufacturing activities in Asia (particularly in China), the amount of container transportation has been growing by about three times the world's GDP growth during the past three decades (Meng et al., 2014). The indicator of the actual throughputs in ports has grown even faster as more and more containers are transshipped in mega-ports of the world (Fransoo and Lee, 2012; Lee and Song, 2017). It is an urgent task to increase the efficiency of port operations so as to maximize the throughput of ports. Because port operators are usually paid by a handling charge per container, the indicator of throughput is essential for the port operators' revenue. The port operators usually have great interest in berth planning since it is the start point of the port operations planning. The planned berth locations for vessels

* Corresponding author. E-mail: lzhen@shu.edu.cn. Tel: +86-21-66137925. Fax: +86-21-66134284.

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are subsequently used as the key input to yard storage, personnel, and equipment deployment planning.

The berth planning process can be categorized into three different levels based on their planning horizon. (1) *Monthly berth planning*: vessels' monthly arrival plans (e.g., estimated import and export throughput, estimated port stay) and physical characteristics are sent from shipping lines to a port operator; then they are fed into the CITOS (Computer Integrated Terminal Operation System) of the port operator. (2) *Weekly berth planning*: the estimated arrival time and departure time of vessels is updated by the shipping lines. The port operator assigns a berth number to each vessel without the exact berthing start time and end time. Based on the assigned berth numbers, the yard planning can be conducted. (3) *Daily berth planning*: the shipping lines send the relatively accurate time of arrival and departure and actual import and export throughput to the port operator, who will decide the actual berthing position and the start and end berthing time. In addition, the quay crane (QC) assignments for vessels are also decided in this critical step. The left part of Figure 1 shows the above three levels of berth planning activities before mooring a vessel.

Among the three levels of berth planning, port operators are most interested in the daily berth planning because this problem is based on relatively accurate information. Therefore, in this study we investigate the daily berth planning process and propose the solution methods to improve the berthing efficiency. The above described daily berth planning is usually called by 'integrated planning of berth allocation and QC assignment problem' in the related literature (Bierwirth and Meisel, 2010 and 2015). However, most of the current studies overlook the factors of the tide and the navigation channel flow control when solving the berth planning problems. Some mega-ports (e.g., Port of Shanghai, Port of Antwerp, and Port of Hamburg) are tidal ports. For an example in Port of Shanghai, the water depth in the Waigaoqiao area is about 12.5 m, which leads to that mega-vessels can only navigate the route when tide is sufficiently high (SHMSA, 2016). For another example in Port of Hamburg, a vessel with a draft of more than 12.8 m needs to consider the tidal factor when it passes through the navigation channel (Port of Hamburg, 2016). In the port of Antwerp, around 70% of arriving vessels were influenced by tide fluctuations before the dredging of the Scheldt River in 2010 (Du et al., 2015). Although berths and port basins of these mega-ports are deep enough to moor mega-ships, the navigation channels are relatively shallow. The tide in a port fluctuates following some pattern as shown in the bottom-right part of Figure 1. The mega-ships need to take advantage of the tide so as to pass through the channel, and the berthing and departure time of these mega-ships depends on the tide pattern. Therefore, the tide pattern is usually critical for making the daily berth planning decision. As shown in the bottom-right part of Figure 1, the feasible tidal time windows for each vessel can be determined in advance according to the predicted tide pattern and the drafts of the vessels.

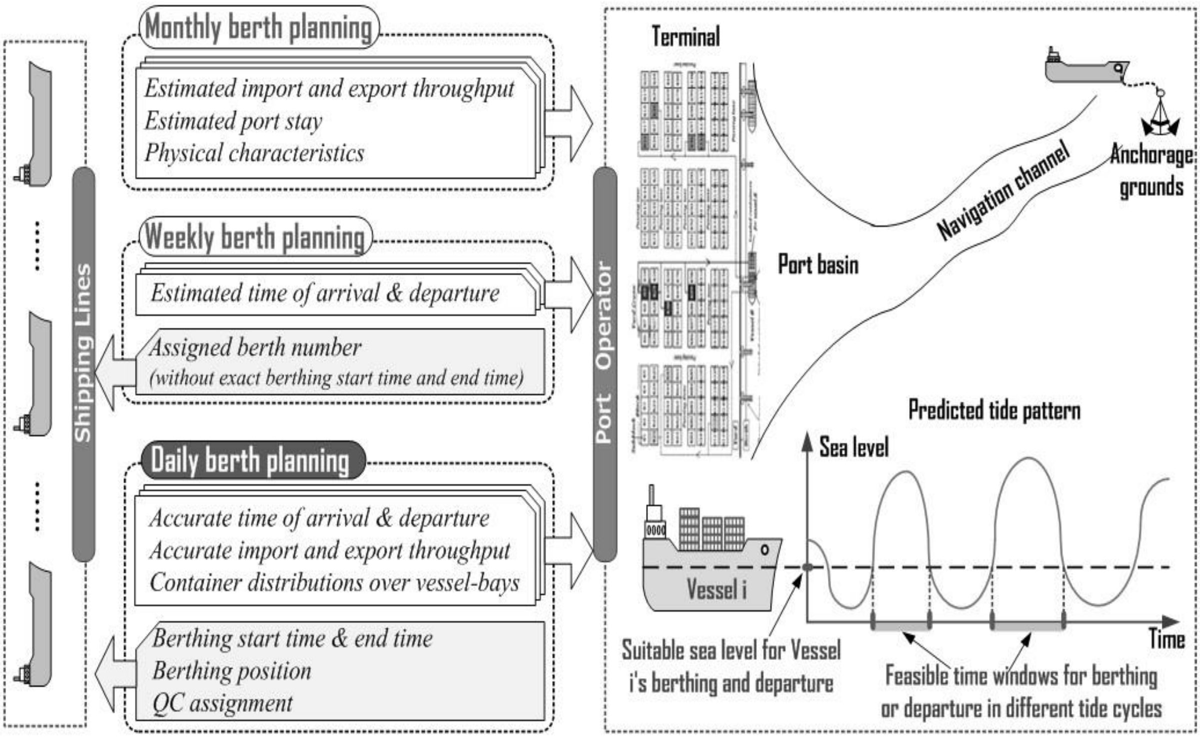

Figure 1: An illustration on daily berth planning in a tidal port

Another critical factor that affects the berth planning is the navigation channel, which is usually surrounded by islands, archipelagos, and hidden reefs. For the safety concern, the pilot station of a port has strict regulations for vessels' sailing in the channel. Vessels are usually guided by some pilot / pilot ships so as to guarantee the safe sailing routes and speed. The daily berth planning has to consider the navigation channel flow control or channel restriction, which may stem from (i) bottleneck resources such as a limit number of the pilots / pilot ships, (ii) locks of channels, e.g., in Port of Antwerp, (iii) spatial conditions like the depth, length, and width of the channels (or rivers connecting a port and the open sea, e.g., in Port of Hamburg), (iv) channel sharing with some neighbor terminals. All of the above channel restrictions may impact the berth allocation in a terminal.

Based on the traditional daily berth planning, the factor of the tide imposes some feasible berthing and departure time windows for vessels; while due to the factor of the channel flow control, the pilot station also proposes some additional berthing and departure time constraints for the incoming and outgoing vessels. Therefore, an intuitive improvement is to integrate the above issues and to optimize them simultaneously. The problem proposed in this study is 'the integrated problem on berth allocation and QC assignment with the consideration of tide and navigation channel'. In this paper we first present an integer programming model, in which the decisions on berth, QC, tide windows, and service time are represented by different variables. However, we cannot obtain even a feasible solution for the test cases with up to 15 vessels and 8 berths within a reasonable time, because there are a large number of big-M constraints and binary variables. Therefore, we propose a set-partitioning based model, in which the variable represents a feasible plan for a vessel. Then a column generation based solution method is suggested to solve the proposed model. Numerical experiments are also conducted to validate the effectiveness and efficiency of the proposed solution method.

The remainder of this paper is organized as follows. Section 2 reviews the related works. In Section 3, we provide the background of the daily berth planning in a tidal port. Section 4 presents an integer programming model. In Section 5, a column generation based solution approach is developed to solve the problem. Section 6 reports the numerical results and management implications based on the experiments using some sets of real world like instances. Section 7 discusses the extension of our method from a discrete berth allocation problem to a continuous berth allocation problem. Closing remark and summary are then outlined in the last section.

2. Related works

For a comprehensive overview on container terminal operations and maritime logistics, see the review work given by Vis and de Koster (2003), Steenken et al. (2004), Stahlbock and Voß (2008), Fransoo and Lee (2013). This study is related to the berth allocation problem (BAP), which is very important for ports' operation management and is also the basis for making other plans on container scheduling decisions by shipping liners. BAP has attracted great attention in academia in the last two decades. Imai et al. (1997) addressed the static BAP (SBAP) in commercial ports. Imai et al. (2001) extended the SBAP to dynamic BAP (DBAP), based on which Monaco and Sammarra (2007) proposed a compact reformulation. BAP can be classified into two types, discrete and continuous, depending on whether vessels' berthing is performed in a continuous or a discrete space (Imai et al., 2005). As to the solution methodology for the continuous BAP, Kim and Moon (2003) proposed a simulated annealing method. Park and Kim (2002) employed a sub-gradient optimization method. Nishimura et al. (2001) proposed a genetic algorithm for BAP to obtain a good solution with small computational effort. Imai et al. (2007) investigated BAP for the indented berths, where mega-containerships could be served from two sides. Cordeau et al. (2005) studied BAP in some specific quay which consists of variable berths. For tactical level BAP, Moorthy and Teo (2006) studied a berth template planning problem, which maximizes the service level and minimizes the connectivity cost related to the transshipment container groups. Cordeau et al. (2007) studied a tactical level service allocation problem arising in the Gioia Tauro transshipment hub.

Another stream of the BAP studies is about the integrated planning of the BAP, the QC assignment, and even yard space allocation. Park and Kim (2003) developed a two-phase solution procedure for a BAP with QC assignment. Meisel and Bierwirth (2009) treated the BAP-QC assignment as a multi-mode resource constrained project scheduling problem. Imai et al. (2008) considered the constraint that QCs cannot pass or bypass from one side to the other side of a vessel whose containers are being handled. Giallombardo et al. (2010) investigated the tactical discrete BAP and QC assignment problem. A novel concept 'QC-profile' was proposed to facilitate the combination of BAP and QC assignment problem. For the above BACAP (berth allocation with crane assignment problem), Vacca et al. (2013) proposed an exact branch and price algorithm, which can solve problem cases up to 20 ships and five berths. Türkoğulları et al. (2014) proposed an exact solution method for a BACAP with continuous berth layout; while the QC assignment for each vessel is assumed to be invariant. Then Türkoğulları et al. (2016) relaxed that assumption on the time-invariant QC assignment and proposed an exact solution method for a BACAP with time-variant QC assignment. Iris et al. (2015) also developed an exact solution method for a continuous BACAP based on some novel set-partitioning formulations. These excellent related works paved the way for this study to develop some method for solving a BACAP with the consideration of more realistic factors. By following the study of Giallombardo et al. (2010), Zhen et al. (2011) integrated the berth allocation, QC assignment, and yard space allocation, for which Jin et al. (2015) designed a column generation based solution method. Similar to the 'QC-profile', a concept of 'YC-profile' was proposed by Jin et al. (2016) and applied in yard management. In the fields of BAP with the consideration of yard issues, Hendriks et al. (2013) conducted studies for container ports and bulk ports, respectively. Meisel and Bierwirth (2013) proposed a framework for aligning all decisions of BAP, QC assignment, and QC scheduling problems in an integrative manner. Liu et al. (2016) designed a bi-objective model on tactical berth allocation and yard assignment.

Recently, the bunker fuel consumption and emission has become a more and more popular factor considered in some BAP related studies. Du et al. (2011) proposed a mixed-integer second-order cone programming model for a BAP considering the fuel consumption and vessel emissions. Hu et al. (2014) further involved the QC allocation into the BAP and also considered the fuel consumption and emissions from vessels. A mixed-integer second-order cone programming model was developed. Besides the above studies that are mainly based on mathematical programming, some studies have employed the discrete event simulation approach, e.g., Legato and Mazza (2001). Moreover, the simulation optimization technique is recently utilized to optimize the tactical and operational BAP decisions in an integrated way (Legato et al., 2014). Randomness in discharge/loading operations and QC assignment were also considered in Legato et al. (2014). For a comprehensive overview on the BAP, see the review work given by Bierwirth and Meisel (2010, 2015).

Although there are abundant BAP related studies, there are very few studies that have considered the factor of tide. Barros et al. (2011) studied a BAP in a tidal bulk port in Brazil.

In their study, the decision on the berthing position of vessels can be neglected because of the homogenous berths assumed in the study. Xu et al. (2012) studied both the static and the dynamic cases of the daily berth planning problems in a tidal port in China. These two studies considered the tidal impact on the water depth in berths; while the realistic situation is that the tides mainly influence the water depth of the navigation channels. This realistic factor is recently taken into account in a BAP study by Du et al. (2015), which is a major breakthrough in the fields of BAP. Their study borrowed the idea of virtual arrival policy to mitigate the tidal impacts. Qin et al. (2016) evaluated the solution performance of the integer programming and the constraint programming for BAP with time-varying water depth. Different from the study by Du et al. (2015), this study further considers the factors of navigation channel flow control and QC assignment decisions. In addition, this study focuses on the daily berth planning—a more realistic decision problem than the generic BAP. In the daily berth planning, a detailed process of berthing and sailing activities is taken into account and is formulated in the proposed mathematical model.

The main contribution of this study may contain the following points: (1) it proposes a new BAP model on the basis of a more comprehensive consideration on the vessels' berthing and sailing activities; (2) besides the berth allocation, the QC assignment decision as well as the tidal factor and the navigation channel flow control are taken into account; (3) a column generation based solution approach is developed to solve the large-scale problem instances (up to 80 vessels) to optimality within an hour.

3. Problem background

3.1 Description of vessels' port stays in the daily berth planning

Before presenting the mathematical formulation, we first elaborate on the detailed process of the daily berth planning and the practical requirements and restrictions involved in the process. Figure 2 illustrates the important events (activities) contained in a vessel's port stay.

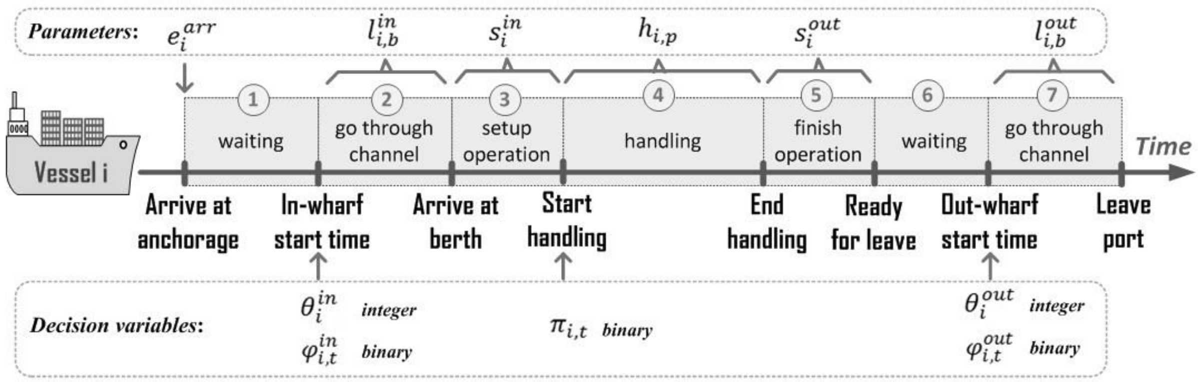

Figure 2: Important events and time points for the daily berth planning

As shown in Figure 2, Vessel i arrives at the anchorage of the port at time denoted by e_i^{arr}, which is often called by ETA (expected time of arrival) and is usually sent from the shipping line of Vessel i to the port operator in advance. Then Vessel i is parked and waits for in-wharf permission. When permission is granted, Vessel i goes through the navigation channel; the time for Vessel i to move from the anchorage to Berth b is denoted as $l_{i,b}^{in}$. When Vessel i arrives at its assigned berth (i.e., Berth b), there are some berthing and handling setup operations (e.g., docking, tying ropes, removing twist locks) that need to be conducted before QCs start handling for Vessel i. The length of the time for performing the setup operations for Vessel i is denoted by s_i^{in}. Then containers are loaded or unloaded during the planned handling interval. The length of the handling time interval for Vessel i depends on the QC resources assigned to the vessel. As shown in Figure 2, the length of the handling time is denoted by $h_{i,p}$; here the subscript p denotes the index of a QC-arrangement plan (i.e., 'QC-profile' defined later) assigned to Vessel i. When the terminal completes the container loading/unloading activities, there is also a time interval for finishing and departure setup operations, which last for a length s_i^{out} of the time. Then the out-wharf process starts; and the vessel travels back to the anchorage. As shown in Figure 2, $l_{i,b}^{out}$ denotes the length of time when Vessel i goes through the navigation channel from its moored Berth b to the open sea. Finally, Vessel i leaves the port.

In the upper part of Figure 2, the parameters are input data for this decision problem. Part of the decision variables, defined by Greek letters, is shown in the lower part of Figure 2. Section 4 illustrates a complete list of the parameters and variables, based on which the time points of the key events during the daily berthing process can be connected.

3.2 Objective of the daily berth planning

The objective of the berth planning is related to two parts: the waiting time of vessels and the delay of vessels' departure.

(1) *Waiting time*: The waiting time of a vessel is the time elapsed between the arrival time at the anchorage and the start time of the in-wharf activity (i.e., period ① illustrated in Figure 2). Different countries/ports have different standards to measure the waiting time. For example, in Singapore a vessel is said to be *berthed-on-arrival* (BOA) if the in-wharf activity commences within two hours upon arrival. The BOA statistic is often used as a proxy to gauge the quality of service provided by the port operator (Moorthy and Teo, 2006). Reducing the waiting time of vessels also has its practical meaning. Even for a vessel that leaves the port without delay, a long waiting time may also reduce the vessel's perceived service quality of the port operator. The liner of the vessel may feel that if they knew their vessel waited outside the port for a long time, they would have slowed down the vessel during the previous voyage for potentially reducing fuel consumption. It is necessary for port operators to reduce the waiting time for vessels so as to improve the quality of the service. Therefore, in this study we minimize the weighted sum of all the vessels' waiting time, i.e., $\sum_{i\in V} r_i^w(\theta_i^{in} - e_i^{arr})$. Here V is the set of all vessels; r_i^w denote the priority (weight) of Vessel i with respect to their waiting time. If a vessel has a higher priority r_i^w, more attention should be paid to reducing its waiting time.

(2) *Delay of departure*: As shown in Figure 2, the actual departure delay of Vessel i can be calculated by $(\theta_i^{out} + l_{i,b}^{out} - e_i^{dep})^+$, in which e_i^{dep} represents the vessel's expected time of departure (ETD). The operator '$(\cdot)^+$' means: if $x \geq 0$, $(x)^+ = x$; otherwise, $(x)^+ = 0$. ETD is usually requested by the shipping line operating Vessel i, and the delay after ETD could disrupt the vessel's following schedule. Give r_i^d as the priority (importance) of Vessel i with respect to their delay of departure, the weighted sum of all the vessels' delay, i.e., $\sum_{i\in V} r_i^d(\theta_i^{out} + l_{i,b}^{out} - e_i^{dep})^+$, should be minimized.

It should be noted that the factor of 'delay of departure' is more important than the factor of 'waiting time for in-wharf' in realistic port management. Thus we could set a larger weight for the former factor than the weight for the latter factor.

3.3 Feasible tidal time windows for berthing and departure

A decision maker of berth planning needs to ensure each vessel's berth stay interval should be within a single-tide-cycle or a multiple-tide-cycle. As shown in Figure 3, a single-tide-cycle berth stay means a short turnaround time for a tide-dependent vessel, which may require more QCs to quicken the loading/unloading activities. On the contrary, a double-tide-cycle even a triple-tide-cycle may require fewer QCs but increase the length of stay of the vessel in the port, resulting in the berth not efficiently used. Moreover, the multiple-tide-cycle berth stay may result in departure tardiness of the subsequent vessels. Therefore, it is a challenging task to find the most efficient schedule when considering the effect of tide.

In this study, we define $[\underline{w}_{i,k}^{in}, \overline{w}_{i,k}^{in}]$ and $[\underline{w}_{i,k}^{out}, \overline{w}_{i,k}^{out}]$ as the berthing and departing time window for Vessel i passing through the channel in the k^{th} tide cycle, respectively. The in-wharf/out-wharf process of any vessel (i.e., period ②/⑦ illustrated in Figure 2) should be within one of the feasible berthing time windows.

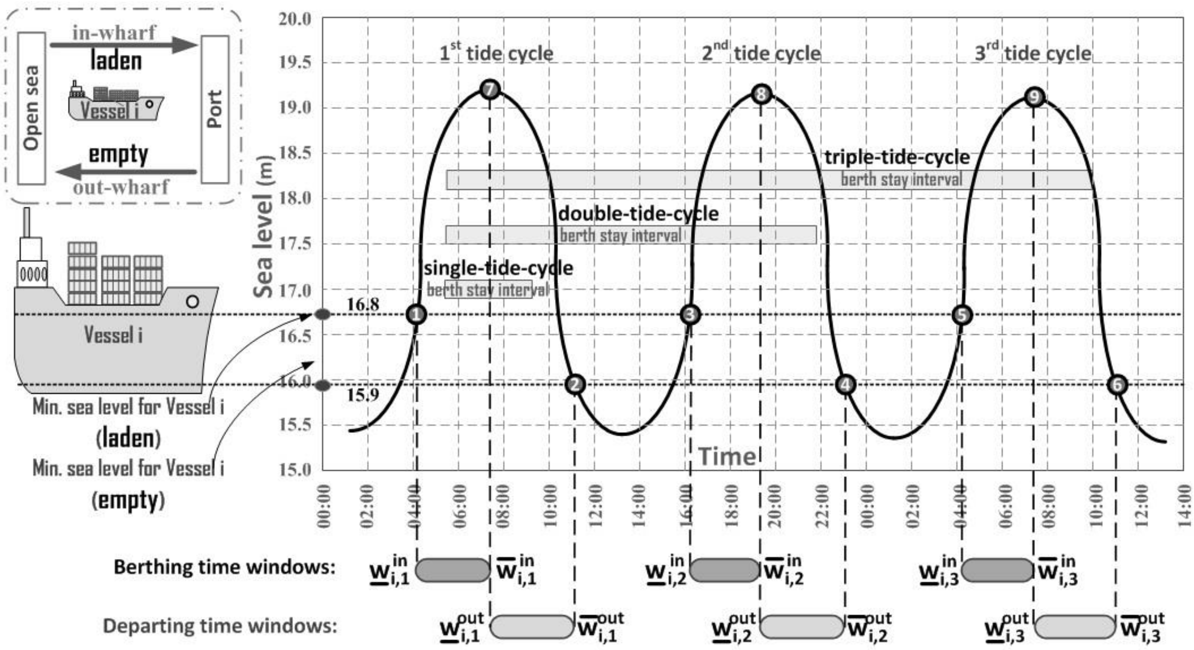

Figure 3: An example on feasible berthing and departing time windows for a tide-dependent vessel

For the example in Figure 3, we describe the process of determining the feasible berthing and departing time windows. The solid curve in Figure 3 (i.e., the sea level) is mainly drawn according to the historical data of the sea level at the port. The diagram of tidal sea level is usually posted on the wall in the planning room of the port operator; and it acts as an important basis for this berth planning problem. For Vessel *i* in the example of Figure 3, we assume it is a relatively laden status when it enters the port, while it is a relatively empty status when it leaves the port. By considering the draft of the vessel, the minimum sea level for the in-wharf process and the out-wharf process is 16.8 m and 15.9 m, respectively. As shown in Figure 3, six intersections between the two horizontal dashed lines and the solid curve are marked by the points 1, 2, 3, 4, 5, and 6 in Figure 3. Their coordinates are (4:10, 16.8), (11:15, 15.9), (16:10, 16.8), (23:15, 15.9), and etc. Moreover, an in-wharf process would better occur during the rising tides; while an out-wharf process would better occur during the falling tides. The reason is that during the rising tides, the sea water flows from the out ocean to the port basin, which can facilitate the vessels' in-wharf process; on the contrary, during the falling tides, the sea water flows from the port basin to the out ocean, which can facilitate the vessels' out-wharf process. For the climaxes of the curve (i.e., the points 7, 8, and 9 in Figure 3), their coordinates are (7:20, 19.2), (19:20, 19.2), and etc. Then we can obtain the feasible berthing time windows are [4:10, 7:20], [16:10, 19:20], and etc.; while the feasible departing time windows are [7:20, 11:15], [19:20, 23:15], and etc.

It should be noted that not all the visiting vessels are influenced by tides. Some vessels may be tide-independent. When jumbo vessels are tide-independent for a port, the tidal restrictions mentioned in this section need not be considered. In addition, this study mainly considers the tides influence the water level at the navigation channel, and assumes the operations of a vessel at a berth will not be interrupted at low tide windows.

3.4 Flow control in navigation channel

The capacity of channel flow control is usually ignored in the literature of BAP. However, this issue exists in many ports, not only the tidal ports. A pilot station of a port usually defines the channel capacity as the maximum number of vessels that can use the channel at the same time. Any potential violation with the capacity or incompliance with the safety will result in the plan revision.

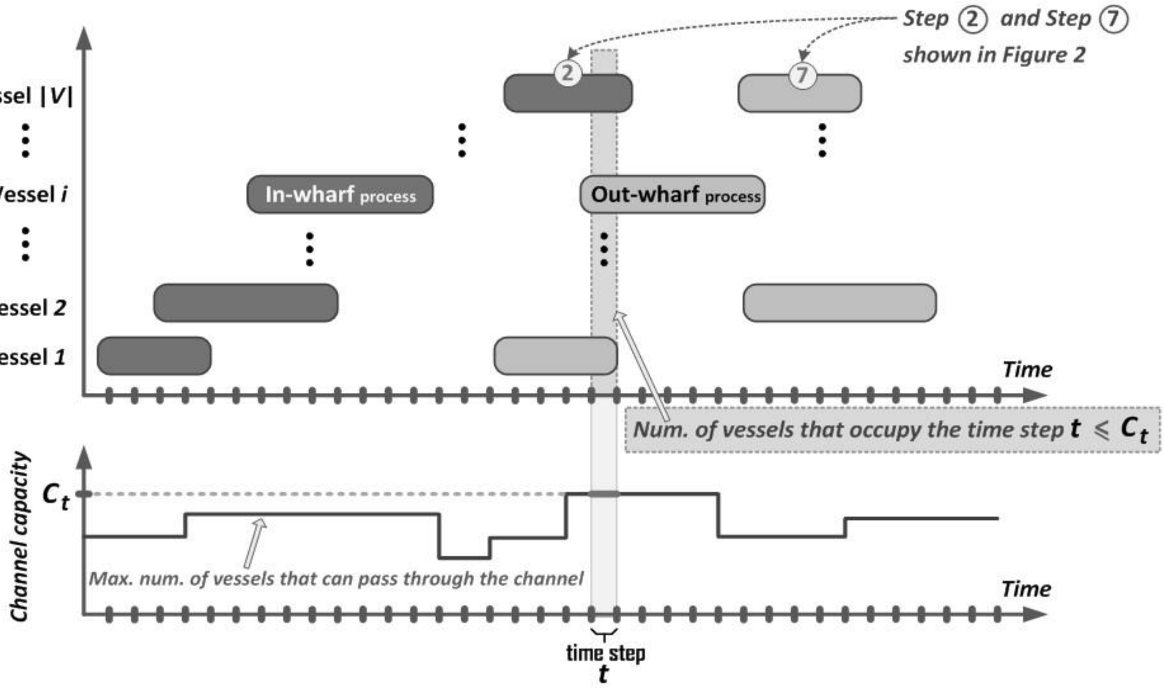

Figure 4: Flow control of navigation channel in daily berth planning.

The rectangles in the upper part of Figure 4 represent the in-wharf and the out-wharf processes of each vessel. Because the water level of a channel could be different at different time, in this study we define C_t as the maximum number of vessels that can pass through the navigation channel simultaneously at the time step t, as shown in Figure 4. The setting of C_t could also depend on the weather condition of the channel, the limitation number of the pilot ships, and the possible sharing of the channel with some neighbor terminals. The berth planning is related with the traffic flows of vessels in the channel. Given a berth plan, the number of the vessels in the channel should be no greater than C_t at any time step t as shown in Figure 4.

3.5 Berth allocation and QC assignment

The core decisions of the daily berth planning are the berth allocation and QC assignment. Figure 5 shows an example of the discrete berth allocation as well as the QC assignment. Vessels are allocated to four berths. For each berth, two additional dummy vessels $o(b)$ and $d(b)$ are also illustrated in this figure by small rectangles with dashed lines. The $o(b)$ and $d(b)$ are used to denote the starting time and ending time for each berth's occupation. The definition of the dummy vessels was proposed in a classic BAP model (Cordeau, et al., 2005), which has acted as the basis for plenty of further studies on the discrete BAP models. Each large rectangle denotes a vessel, for which the length of the rectangle denotes the handling time, i.e., the step ④ shown in Figure 2.

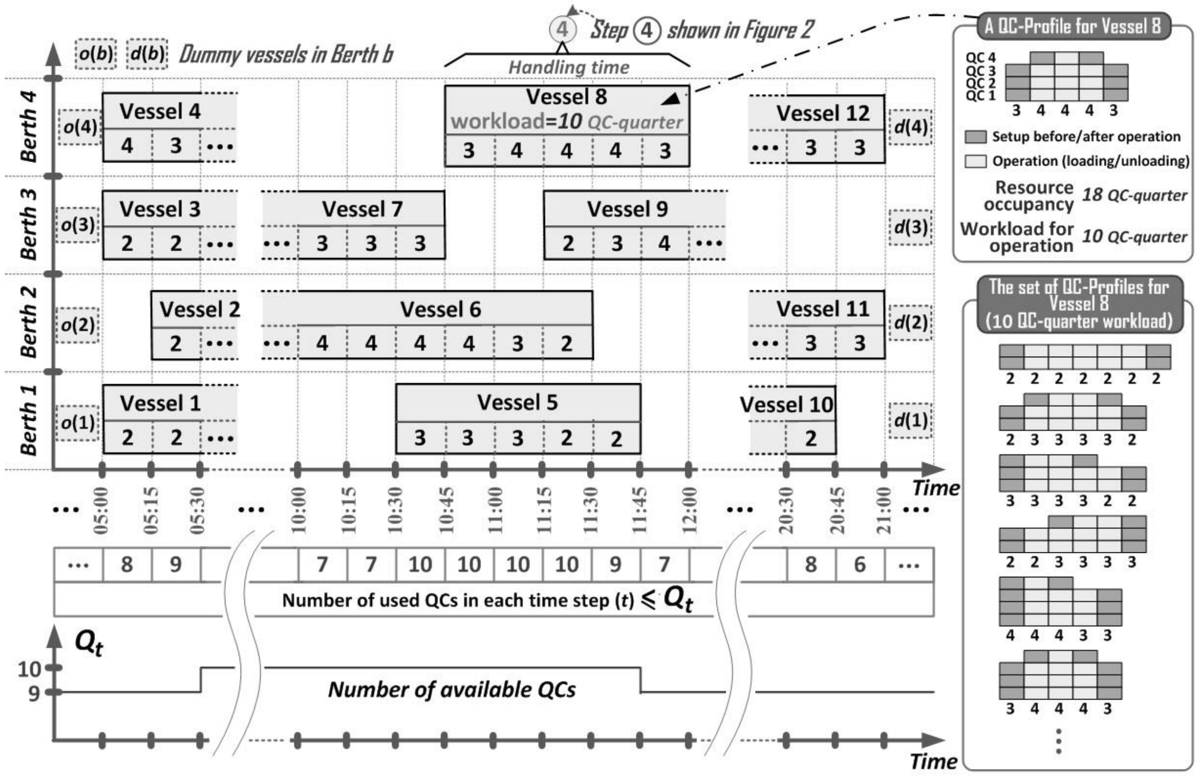

Figure 5: An example of berth allocation and QC assignment plan

Different from some BAP studies, the handling time of vessels is variant and depends on the QC assignment. When handling the QC assignment in the berth allocation planning, this study applies the concept of ‘QC-profile’, which was proposed by Giallombardo et al. (2010). The QC-profile denotes the number of QCs assigned for the berthed vessel in each time step. Shipping lines inform the port operator about the workload of each vessel, i.e., the number of QC-quarters (if the time step is one quarter). Then a set of QC-profiles can be generated for each vessel. The upper-right corner of Figure 5 shows the details of the QC-profile used by Vessel 8 and an example of the set of QC-profiles for Vessel 8, whose workload is ten QC-quarters. In the illustration of QC-profiles, a small rectangle with dark color denotes the setup time before or after a QC’s operation, which is assumed to be one quarter in this study. It should be noted that the number of QC-quarters needed by a vessel is not equal to the number of QC-quarters occupied by the vessel due to the consideration of QC setup time. The set of QC-profiles for a vessel is generated according to the vessel’s handling workload, which is the number of QC-quarters needed by the vessel; while in the mode formulation, the number of QCs occupied by a vessel in each quarter (marked in vessels’ rectangles in Figure 5) is considered in the QC-profile related constrains. When generating the possible QC-profiles for a vessel, there are some operational constraints. First, the number of QCs used on each time-step should be within the reasonable range; second, the allowed variation of the number of QCs between two adjacent time steps should be limited, so that the distribution of QCs is as regular as possible when serving a vessel. For simplicity, the example in Figure 5 does not consider the productivity loss incurred by QCs interference (Meisel and Bierwirth, 2009). However, this factor of productivity loss can be taken into account when preparing QC-profile sets for vessels.

Here we make more explanation on adopting the method of 'QC-profile assignment' in our model. We admit the BAP with QC-profile assignment is different from the traditional BACAP. If we do not enumerate all the QC-profiles for each vessel, the BAP with QC-profile assignment may lose the optimality for the BACAP. However, the method of QC-profile assignment (Giallombardo et. al., 2010) is a very practical way for the BACAP decision and can reduce the solution space significantly, because the decision on 'determining how many QCs are used during each time period for each vessel (in the BACAP)' is simplified to the decision on 'determining which QC-profile is chosen for each vessel (in the BAP with QC-profile assignment)'. As aforementioned, when generating the set of QC-profiles for Vessel 8 (its workload is ten QC-quarter), we could set some restrictions such as the limit of QC number changing during two consecutive quarters. For example, a QC assignment plan '4QC-1QC-4QC-1QC in four quarters' may not be practical in realistic port operations, because the number of QC changing during two consecutive quarters is a bit large. Such plan is a possible solution for the traditional BACAP, but may not be included in the set of QC-profiles for the vessel in the BAP with QC-profile assignment. Therefore, from the academic perspective, the method of 'QC-profile assignment' may lose some optimality for the traditional BACAP, but it may be a practical way and also has been used by other scholars in recent studies (Liu et al., 2016).

Given a berth allocation plan, the number of used QCs in each time-step can be computed, as illustrated in the bottom part of Figure 5. The total number of QCs should not be greater than the number of available QCs in each time-step denoted by Q_t (shown in Figure 5). Given the QC capacity Q_t and the set of QC-profiles for each vessel, it is a very difficult to decide the assignment of a QC profile and the starting handling time $\pi_{i,t}$ for each vessel with respect to the QC capacity.

In this study, the decisions on berth allocation and QC assignment are further combined with the constraints of the tide time windows and the channel flow control. Thus, determining a good daily berthing plan is a challenging optimization problem from the mathematical modeling perspective.

4. Basic model formulation

In this section, a basis model for the problem is presented. Some nonlinear forms in the objective of the model are also linearized. This basic integer programming model is the basis for the further investigations.

4.1 Notations

Before presenting the mathematical model, the notations on the parameters and the variables used in the model are listed in the following parts. For the convenience of understanding the notations, we use the Latin letters and the Greek letters to denote the parameters (indices, sets) and the decision variables, respectively, in this section.

Indices and sets:

B the set of the berths, indexed by b.

V the set of the vessels, indexed by i and j.

$o(b)$ the dummy vessel denoting the first one in the sequence of vessels that moor at Berth b.

$d(b)$ the dummy vessel denoting the last one in the sequence of vessels that moor at Berth b.

T the set of the time-steps, indexed by t.

P_i the set of the QC-profiles vessels feasible for Vessel i, indexed by p.

K the set of the tide cycles, indexed by k.

Parameters:

r_i^w the priority (weight) of Vessel i with respect to its waiting time.

r_i^d the priority (weight) of Vessel i with respect to its delay of departure.

e_i^{arr} the expected arrival time of Vessel i.

e_i^{dep} the expected departure time of Vessel i.

$l_{i,b}^{in}$ the length of time for Vessel i to move from the anchorage to Berth b through the navigation channel.

$l_{i,b}^{out}$ the length of time for Vessel i to move from Berth b to the anchorage through the navigation channel.

s_i^{in} the length of time for Vessel i docking and handling setup operations.

s_i^{out} the length of time for Vessel i handling finish operations and departing the wharf.

$h_{i,p}$ the length of handling time if Vessel i uses the QC profile p.

$q_{i,p,u}$ the number of utilized QCs in the u^{th} time-step of QC-profile p, which serves Vessel i; here u is from one.

Q_t the number of available QCs in Time-step t.

C_t the maximum number of vessels that can pass through the navigation channel simultaneously in Time-step t.

M a sufficiently large positive number.

$[\underline{w}_{i,k}^{in}, \overline{w}_{i,k}^{in}]$ berthing time window for Vessel i passing through the navigation channel in the k^{th} tide cycle.

$[\underline{w}_{i,k}^{out}, \overline{w}_{i,k}^{out}]$ departing time window for Vessel i passing through the navigation channel in the k^{th} tide cycle.

Decision variables:

$\beta_{i,b}$ a binary variable, equals one if Vessel i is allocated to Berth b, and zero otherwise.

$\gamma_{i,p}$ a binary variable, equals one if QC-profile p is assigned to Vessel i, and zero otherwise.

θ_i^{in} an integer variable, represents the in-wharf start time of Vessel i.

θ_i^{out} an integer variable, represents the out-wharf start time of Vessel i.

$\sigma_{i,j,b}$ a binary variable, equals one if Vessel j is scheduled immediately after Vessel i at Berth b, and zero otherwise.

$\pi_{i,t}$ a binary variable, equals one if the handling time interval of Vessel i starts in Time-step t, and zero otherwise.

$\eta_{i,p,t}$ a binary variable, equals one if QC-profile p is assigned to Vessel i and the handling time interval starts in Time-step t, and zero otherwise; $\eta_{i,p,t} = \gamma_{i,p} \cdot \pi_{i,t}$.

$\varphi_{i,t}^{in}$ a binary variable, equals one if the in-wharf start time of Vessel i is Time-step t, and zero otherwise; so we have $\theta_i^{in} = \sum_{t \in T} t \cdot \varphi_{i,t}^{in}$.

$\varphi_{i,t}^{out}$ a binary variable, equals one if the out-wharf start time of Vessel i is Time-step t, and zero otherwise; so we have $\theta_i^{out} = \sum_{t \in T} t \cdot \varphi_{i,t}^{out}$.

$\zeta_{i,k}^{in}$ a binary variable, equals one if the in-wharf start time of Vessel i is in the berthing time window of the k^{th} tide cycle, and zero otherwise.

$\zeta_{i,k}^{out}$ a binary variable, equals one if the out-wharf start time of Vessel i is in the departing time window of the k^{th} tide cycle, and zero otherwise.

4.2 Mathematical model:

Based on the above definition on the parameters and variables, a mathematical model is formulated as follows.

$$[\textbf{BAP}]\ \mathit{Min}\ \sum_{i \in V} \left[r_i^w \left(\theta_i^{in} - e_i^{arr} \right) + r_i^d \left(\theta_i^{out} + \sum_{b \in B} \beta_{i,b} l_{i,b}^{out} - e_i^{dep} \right)^+ \right] \tag{1}$$

Subject to:

$$\sum_{b \in B} \beta_{i,b} = 1 \qquad \forall i \in V \tag{2}$$

$$\sum_{p \in P_i} \gamma_{i,p} = 1 \qquad \forall i \in V \tag{3}$$

$$\sum_{t \in T} \pi_{i,t} = 1 \qquad \forall i \in V \tag{4}$$

$$\sum_{t \in T} \varphi_{i,t}^{in} = 1 \qquad \forall i \in V \tag{5}$$

$$\sum_{t \in T} \varphi_{i,t}^{out} = 1 \qquad \forall i \in V \tag{6}$$

$$\beta_{i,b} = \sum_{j \in V \cup \{d(b)\}} \sigma_{i,j,b} \qquad \forall i \in V, \forall b \in B \tag{7}$$

$$\sum_{j \in V \cup \{d(b)\}} \sigma_{o(b),j,b} = 1 \qquad \forall b \in B \tag{8}$$

$$\sum_{i \in V \cup \{o(b)\}} \sigma_{i,d(b),b} = 1 \qquad \forall b \in B \tag{9}$$

$$\sum_{j \in V \cup \{d(b)\}} \sigma_{i,j,b} = \sum_{j \in V \cup \{o(b)\}} \sigma_{j,i,b} \qquad \forall i \in V, \forall b \in B \tag{10}$$

$$\theta_i^{out} \le \theta_j^{in} + l_{j,b}^{in} + (1 - \sigma_{i,j,b})M \qquad \forall i,j \in V, \forall b \in B \tag{11}$$

$$\theta_i^{in} \geq e_i^{arr} \qquad \forall i \in V \tag{12}$$

$$\theta_i^{in} + \sum_{b \in B} \beta_{i,b} l_{i,b}^{in} + s_i^{in} + \sum_{p \in P_i} \gamma_{i,p} h_{i,p} + s_i^{out} \leq \theta_i^{out} \qquad \forall i \in V \tag{13}$$

$$\theta_i^{in} \geq \underline{w}_{i,k}^{in} - (1 - \zeta_{i,k}^{in})M \qquad \forall i \in V, \forall k \in K \tag{14}$$

$$\theta_i^{in} + \sum_{b \in B} \beta_{i,b} l_{i,b}^{in} \leq, \overline{w}_{i,k}^{in} + (1 - \zeta_{i,k}^{in})M \qquad \forall i \in V, \forall k \in K \tag{15}$$

$$\theta_i^{out} \geq \underline{w}_{i,k}^{out} - (1 - \zeta_{i,k}^{out})M \qquad \forall i \in V, \forall k \in K \tag{16}$$

$$\theta_i^{out} + \sum_{b \in B} \beta_{i,b} l_{i,b}^{out} \leq \overline{w}_{i,k}^{out} + (1 - \zeta_{i,k}^{out})M \qquad \forall i \in V, \forall k \in K \tag{17}$$

$$\sum_{k \in K} \zeta_{i,k}^{in} = 1 \qquad \forall i \in V \tag{18}$$

$$\sum_{k \in K} \zeta_{i,k}^{out} = 1 \qquad \forall i \in V \tag{19}$$

$$\theta_i^{in} + \sum_{b \in B} \beta_{i,b} l_{i,b}^{in} + s_i^{in} = \sum_{t \in T} \pi_{i,t} t \qquad \forall i \in V \tag{20}$$

$$\eta_{i,p,t} \geq \gamma_{i,p} + \pi_{i,t} - 1 \qquad \forall i \in V, \forall p \in P_i, \forall t \in T \tag{21}$$

$$\sum_{i \in V} \sum_{p \in P_i} \sum_{u=max\{1; t-h_{i,p}+1\}}^{t} q_{i,p,(t-u+1)} \eta_{i,p,u} \leq Q_t \qquad \forall t \in T \tag{22}$$

$$\theta_i^{in} = \sum_{t \in T} \varphi_{i,t}^{in} t \qquad \forall i \in V \tag{23}$$

$$\theta_i^{out} = \sum_{t \in T} \varphi_{i,t}^{out} t \qquad \forall i \in V \tag{24}$$

$$\sum_{i \in V} \left(\sum_{u=max\{1; t-l_{i,b}^{in}+1\}}^{t} \varphi_{i,u}^{in} + \sum_{u=max\{1; t-l_{i,b}^{out}+1\}}^{t} \varphi_{i,u}^{out} \right) \leq C_t \quad \forall t \in T \tag{25}$$

$$\beta_{i,b} \in \{0,1\} \qquad \forall i \in V, \forall b \in B \tag{26}$$

$$\gamma_{i,p} \in \{0,1\} \qquad \forall i \in V, \forall p \in P_i \tag{27}$$

$$\sigma_{i,j,b} \in \{0,1\} \qquad \forall i, j \in V, \forall b \in B \tag{28}$$

$$\pi_{i,t} \in \{0,1\} \qquad \forall i \in V, \forall t \in T \tag{29}$$

$$\varphi_{i,t}^{in} \in \{0,1\} \qquad \forall i \in V, \forall t \in T \tag{30}$$

$$\varphi_{i,t}^{out} \in \{0,1\} \qquad \forall i \in V, \forall t \in T \tag{31}$$

$$\eta_{i,p,t} \in \{0,1\} \qquad \forall i \in V, \forall p \in P_i, \forall t \in T \tag{32}$$

$$\zeta_{i,k}^{in}, \zeta_{i,k}^{out} \in \{0,1\} \qquad \forall i \in V, \forall k \in K \tag{33}$$

$$\theta_i^{in}, \theta_i^{out} \in \mathbb{Z}^+ \qquad \forall i \in V, \forall b \in B \tag{34}$$

Objective (1) contains two parts: the first part is the weighted sum of all vessels' waiting time for in-wharf activity, and the second part is the weighted sum of the tardiness with respect to the vessels' expected departure time e_i^{dep}. Specifically, θ_i^{out} is the out-wharf start time of Vessel i; $\sum_{b\in B}\beta_{i,b}l_{i,b}^{out}$ is the duration of the out-wharf process, in which Vessel i goes through the navigation channel from Berth b to the open sea, and leaves the port. Thus $\theta_i^{out}+\sum_{b\in B}\beta_{i,b}l_{i,b}^{out}$ represents the vessel's actual departure time. It should be noted that the cost of QC operations is not considered in the objective. The cost of QC operations for all the vessels during the planning horizon is independent to berthing plans because the total of all vising vessels' workload may be a constant with respect to QC-quarters.

The constraints of the model are mainly classified into the following six parts. Some of them are based on the models proposed by existing studies.

(i) Basic restrictions on core decisions:

Constraints (2) and (3) are about the two core decisions of the problem: berth allocation and QC assignment. Constraints (2) state that each vessel is allocated to exact one berth. Constraints (3) ensure one QC-profile is assigned to each vessel. Constraints (4)−(5) ensure the feasibility of the binary variables $\pi_{i,t}$, $\varphi_{i,t}^{in}$, $\varphi_{i,t}^{out}$ that denote the key time points of berthing activities (shown at the bottom part of Figure 2).

(ii) Classical constraints on discrete BAP (ref. Cordeau, et al., 2005):

Constraints (7)−(13) are the typical constraints for the discrete BAP model (Cordeau, et al., 2005), which was modeled as an MDVRPTW (multi-depot vehicle-routing problem with time windows). Constraints (7) link the variable $\sigma_{i,j,b}$ of sequencing vessels in each berth and the variable $\beta_{i,b}$ of allocating vessels to berths. Constraints (8) and (9) ensure the sequence of ships in each berth has one origin node and one destination node, respectively. Constraints (10) state that Vessel i has both a predecessor and a successor in the vessel sequence for Berth b, if Vessel i is allocated to Berth b. Constraints (11) ensure the precedence relation between the out-wharf start time θ_i^{out} of Vessel i and the berth arrival time $\theta_j^{in}+l_{j,b}^{in}$ of Vessel j if Vessel i is immediately followed by Vessel j at Berth b. θ_i^{in} represents the actual in-wharf start time of Vessel i. The time cannot be earlier than the expected arrival time e_i^{arr} of the vessel because of Constraints (12).

(iii) Constraints connecting time points of stages in Figure 2 (this study):

Constraints (13) state the relationship among the key time points illustrated in Figure 2. For Vessel i, its in-wharf start time θ_i^{in} plus the duration of passing through channel $\sum_{b\in B}\beta_{i,b}l_{i,b}^{in}$, plus the setup duration for preparing operations s_i^{in}, plus the duration of container handling (loading/unloading) activities $\sum_{p\in P_i}\gamma_{i,p}h_{i,p}$, and plus the setup duration for ending operations s_i^{out}, is not later than the vessel's out-wharf start time θ_i^{out}. The gap between them is the possible waiting time for the vessel's out-wharf activity. It should be noted that the vessel needs to stay at the berth during this waiting stage.

(iv) Constraints on tidal factors (this study):

Constraints (14)−(19) are about the factor of tide cycles. Constraints (14), (15), and (18) ensure that the in-wharf process should be located in one of the time window $[\underline{w}_{i,k}^{in}, \overline{w}_{i,k}^{in}], \forall k = 1,2,\cdots,|K|$. Similarly, Constraints (16), (17), (19) ensure that the out-wharf process should be located in one of the time window $[\underline{w}_{i,k}^{out}, \overline{w}_{i,k}^{out}], \forall k = 1,2,\cdots,|K|$.

(v) Constraints on QC and channel capacity (ref. Giallombardo, et al., 2005):

Constraints (20)−(22) are about the capacity constraints for QCs (Giallombardo, et al., 2005). Constraints (22) state that the number of used QCs in Time-step t should not exceed QC capacity Q_t. The calculation on the number of the QCs used by all the vessels needs a binary variable $\eta_{i,p,t}$ which equals the product of two other binary variables, i.e., $\eta_{i,p,t} = \gamma_{i,p}\pi_{i,t}$, and is linearized in Constraints (21). Another binary variable $\pi_{i,t}$, which is related to the starting QC handling time for a vessel, is connected with the previous mentioned variables through Constraints (20).

Constraints (23)−(25) are about the capacity limitation of the navigation channel. This factor is newly considered in this study, but their formulation borrows the idea from the above QC capacity related constraints (Giallombardo, et al., 2005). Constraints (25) ensure that the number of the incoming and outgoing vessels through the navigation channel during Time-step t should not exceed channel capacity C_t. The calculation on the number of the incoming and outgoing vessels needs binary variables $\varphi_{i,t}^{in}$ and $\varphi_{i,t}^{out}$, respectively. They are connected with the previous mentioned variables through Constraints (23)−(24). It should be noted that we can further consider the difference of vessels' size with respect to the capacity of the channel

(Lalla-Ruiz, et al., 2016). A new parameter (e.g., v_i) can be defined to represent the size of Vessel i; C_t is redefined as the channel capacity with the same unit as the parameter 'v_i'. Then the left part of the inequality (25) is revised to '$\sum_{i\in V} v_i(\cdots)$' accordingly.

(vi) Constraints defining variables: Constraints (26)−(34).

4.3 Linearization for Objective (1)

There is a nonlinear form '$(\cdot)^+$' in Objective (1). For linearizing it, we define two nonnegative variables ϱ_i^+ and ϱ_i^-, and add a constraint '$\theta_i^{out} + \sum_{b\in B} \beta_{i,b} l_{i,b}^{out} - e_i^{dep} = \varrho_i^+ - \varrho_i^-$, $\forall i \in V$'. Then the nonlinear form '$\left(\theta_i^{out} + \sum_{b\in B} \beta_{i,b} l_{i,b}^{out} - e_i^{dep}\right)^+$' in Objective (1) is replaced by ϱ_i^+. The objective of the above model becomes linear, i.e., *Minimize* $\sum_{i\in V}\left[r_i^w\left(\theta_i^{in} - e_i^{arr}\right) + r_i^d \varrho_i^+\right]$. Here it is noted that ϱ_i^+ and ϱ_i^- can be defined as two non-negative continuous variables (not necessary integers). As in the objective, ϱ_i^+ should be as less as possible, ϱ_i^+ will be zero, if '$\theta_i^{out} + \sum_{b\in B} \beta_{i,b} l_{i,b}^{out} - e_i^{dep}$' is negative; while ϱ_i^+ will equal 'ϱ_i^+ will equal '$\theta_i^{out} + \sum_{b\in B} \beta_{i,b} l_{i,b}^{out} - e_i^{dep}$' if its value is non-negative.

5. A column generation based approach

The BAP model contains a large number of binary variables and big-M constraints. The branch-and-bound (B&B) procedure used to find the optimal IP solution is very time-consuming. For example, we found that more than 10^5 B&B nodes are explored to obtain the optimal IP solution for a very small test case with only five berths and ten vessels. To overcome this difficulty, we propose a set partitioning based formulation (Iris et al., 2015), in which each variable represents a specific vessel plan.

Formally, a feasible vessel plan includes detailed information about the in-wharf time, the berth used to unload/upload containers, the QC-profile selected, and the out-wharf time. The time information of the plan is set properly so that the vessel can enter/leave the channel within feasible tidal time windows. Define the set of feasible vessel plans for Vessel i as D_i. Define the cost of vessel Plan d as c_d. Therefore, for a given Plan d of Vessel i at Berth b, the cost of the plan can be computed as $c_d = r_i^w\left(\theta_i^{in} - e_i^{arr}\right) + r_i^d\left(\theta_i^{out} + l_{i,b}^{out} - e_i^{dep}\right)^+$. Each vessel plan consumes three types of resources, navigation channel, berth, and cranes, at different time steps. Define binary parameters ψ_{dt}^{in} such that $\psi_{dt}^{in} = 1$ if vessel Plan $d \in D_i$ uses the navigation channel to enter the berths at Time-step t, and $\psi_{dt}^{in} = 0$ otherwise. Similarly, define binary parameters ψ_{dt}^{out} such that $\psi_{dt}^{out} = 1$ if Plan $d \in D_i$ uses the navigation channel to exit the berth at Time-step t, and $\psi_{dt}^{out} = 0$ otherwise. Define binary parameters β_{bdt} such that $\beta_{bdt} = 1$ if Plan d occupies Berth b at Time-step t. Define non-negative integer parameters q'_{dt} as the number of QCs used by Plan d at Time-step t. Define the binary variable x_d such that $x_d = 1$ if Plan d is selected in the solution and $x_d = 0$ otherwise. Given the above notations, we can formulate the problem as a set partitioning based model as follows.

[**MP**] *Min* $\sum_{i \in V} \sum_{d \in D_i} c_d x_d$ (35)

Subject to:

$$\sum_{d \in D_i} x_d = 1 \qquad \forall i \in V \qquad (36)$$

$$\sum_{i \in V} \sum_{d \in D_i} \psi_{dt}^{in} x_d + \sum_{i \in V} \sum_{d \in D_i} \psi_{dt}^{out} x_d \leq C_t \qquad \forall t \in T \qquad (37)$$

$$\sum_{i \in V} \sum_{d \in D_i} \beta_{bdt} x_d \leq 1 \qquad \forall b \in B, \forall t \in T \qquad (38)$$

$$\sum_{i \in V} \sum_{d \in D_i} q'_{dt} x_d \leq Q_t \qquad \forall t \in T \qquad (39)$$

$$x_d \in \{0, 1\} \qquad \forall d \in D_i, \forall i \in V \qquad (40)$$

Objective (35) minimizes the total cost of the selected vessel plans. Constraints (36) ensure that one plan is selected for each vessel. Constraints (37) guarantee that at any time-step t the total number of the vessels going through the navigation channel is less than or equal to the capacity of the channel. Constraints (38) state that at most one vessel is using a berth at any time. Constraints (39) ensure that the number of the QCs used by all the vessels at any time is less than the total number of available QCs.

The set partitioning based model only contains $|V| + 2|T| + |B||T|$ number of constraints. However, the number of feasible vessel plans is huge. Therefore, it might be impractical and intractable to enumerate all the vessel plans. Also, it is normally not necessary to enumerate all the feasible vessel plans because the optimal solution usually only contains a very small portion of the entire vessel plans. Therefore, we propose a column generation algorithm to generate good vessel plans. Column generation algorithm has been widely and successfully applied to many large-scale, real-life optimization problems in the areas such as transportation (Barnhart et al., 1998, Baldacci et al., 2011, Liang et al. 2014, Meng et al. 2015), machine scheduling (Van den Akker et al. 1999, Chen et al. 1999), bioinformatics (Chou et al., 2015), to name but a few. In column generation, when the number of variables in a LP model is too large to enumerate explicitly, a subset of feasible variables is constructed first. The restricted linear master problem is then solved, and the dual cost of each constraint is calculated. To improve the restricted linear master problem (i.e., generating more profitable variables), we solve the pricing subproblems based on the dual information. These variables are then added to the restricted linear master problem, and the updated restricted linear master problem is resolved. This iterative procedure is repeated until no new profitable variables are found, which implies the current LP relaxation is optimal.

To facilitate our discussion, we define the following additional parameters and variables for the pricing problems. The elements of the column associated to a vessel Plan d in the master problem become variables in the pricing subproblem, where we look for a vessel plan with negative reduced cost, i.e. for a profitable column to be added to the restricted master problem.

Parameters (newly defined):

α_i the dual variable for Constraints (36). Because the = sign can be replaced by the $\geq$ sign without increasing the objective value, we know $\alpha_i \geq 0$.

δ_t the non-positive dual variable for Constraints (37).

ε_{bt} the non-positive dual variable for Constraints (38).

λ_t the non-positive dual variable for Constraints (39).

Variables (newly defined or redefined):

ψ_{dt}^{in} the binary variable such that $\psi_{dt}^{in} = 1$ if vessel enters the channel at Time-step t and $\psi_{dt}^{in} = 0$ otherwise.

ψ_{dt}^{out} the binary variable such that $\psi_{dt}^{out} = 1$ if vessel leaves the channel at Time-step t and $\psi_{dt}^{out} = 0$ otherwise.

β_{bdt} the binary variable such that $\beta_{bdt} = 1$ if vessel occupies Berth b at Time-step t, and $\beta_{bdt} = 0$ otherwise.

Given the above notations, the reduced cost of vessel Plan d for Vessel i allocated to Berth

b can be written as follows:

$$Z' = c_d - \alpha_i - \sum_{t\in T} \psi_{dt}^{in}\delta_t - \sum_{t\in T} \psi_{dt}^{out}\delta_t - \sum_{t\in T} \beta_{bdt}\varepsilon_{bt}$$
$$- \sum_{t\in T, p\in P_i} \eta_{ipt}(\sum_{u=t}^{t+h_{ip}-1} q_{ip(u-t+1)}\lambda_u) \tag{41}$$

In the above formula, $c_d = r_i^w(\theta_i^{in} - e_i^{arr}) + r_i^d\left(\theta_i^{out} + l_{ib}^{out} - e_i^{dep}\right)^+$

The last part of Eq.(41) computes the accumulated shadow cost contributed by the QCs profile p starting from Period t to Period '$t + h_{ip} - 1$'. It is noted that if the QC profile p and the start time t are fixed, '$\sum_{u=t}^{t+h_{ip}-1} q_{ip(u-t+1)}\lambda_u$' can be computed directly. For simplicity, we define $\lambda_{pt} = \sum_{u=t}^{t+h_{ip}-1} q_{ip(u-t+1)}\lambda_u$.

The pricing subproblem of the column generation is to find a vessel plan with negative Z'. Therefore, all the parameters and variables associated to a vessel plan d, such as ψ_{dt}^{in}, ψ_{dt}^{out}, β_{bdt}, and η_{ipt}, become decision variables in the pricing subproblem. In the following sections, we present two different pricing subproblem methods using mathematical programming and enumeration. In the computational study section, we also present the computational performance of these two different subproblem methods.

5.1 Pricing subproblem by mathematical programming

The pricing subproblem can be formulated as a mathematical programming problem as follows. The pricing subproblem (42)−(60) is to find the vessel plan with minimum reduced cost for a fixed vessel $i \in V$ and a fixed berth $b \in B$.

[PP$_{\mathbf{ib}}$]

$$Min\ \ r_i^w(\theta_i^{in} - e_i^{arr}) + r_i^d\left(\theta_i^{out} + l_{ib}^{out} - e_i^{dep}\right)^+ - \sum_{t\in T} \delta_t\psi_{dt}^{in} - \sum_{t\in T} \delta_t\psi_{dt}^{out}$$
$$- \sum_{t\in T} \varepsilon_{bt}\beta_{bdt} - \sum_{t\in T, p\in P_i} \lambda_{pt}\eta_{ipt} \tag{42}$$

Subject to:

$$\theta_i^{in} + l_{ib}^{in} + s_i^{in} + \sum_{t\in T, p\in P_i} \eta_{ipt}h_{ip} + s_i^{out} + \xi_{ib} \geq \theta_i^{out} \tag{43}$$

$$\theta_i^{in} \geq \underline{w}_{i,k}^{in} - \left(1 - \zeta_{ik}^{in}\right)M \qquad \forall k \in K \tag{44}$$

$$\theta_i^{in} + l_{ib}^{in} \leq \overline{w}_{i,k}^{in} - \left(\zeta_{ik}^{in} - 1\right)M \qquad \forall k \in K \tag{45}$$

$$\theta_i^{out} \geq \underline{w}_{i,k}^{out} - (1 - \zeta_{ik}^{out})M \qquad \forall k \in K \tag{46}$$

$$\theta_i^{out} + l_{ib}^{out} \leq \overline{w}_{i,k}^{out} - (\zeta_{ik}^{out} - 1)M \qquad \forall k \in K \qquad (47)$$

$$\sum_{k\in K} \zeta_{ib}^{in} = 1 \qquad (48)$$

$$\sum_{k\in K} \zeta_{ib}^{out} = 1 \qquad (49)$$

$$\sum_{t\in T} \sum_{p\in P_i} \eta_{ipt} = 1 \qquad (50)$$

$$\theta_i^{in} \leq t - (\psi_{dt}^{in} - 1)M \qquad \forall t \in T \qquad (51)$$

$$\theta_i^{in} + l_{ib}^{in} \geq t - (1 - \psi_{dt}^{in})M \qquad \forall t \in T \qquad (52)$$

$$\theta_i^{out} \leq t - (\psi_{dt}^{out} - 1)M \qquad \forall t \in T \qquad (53)$$

$$\theta_i^{out} + l_{ib}^{out} \geq t - (1 - \psi_{dt}^{out})M \qquad \forall t \in T \qquad (54)$$

$$\theta_i^{in} + l_{ib}^{in} \leq t - (\beta_{dbt} - 1)M \qquad \forall t \in T \qquad (55)$$

$$\theta_i^{out} \geq t - (1 - \beta_{bdt})M \qquad \forall t \in T \qquad (56)$$

$$\theta_i^{in}, \theta_i^{out} \in \mathbb{Z}^+ \qquad (57)$$

$$\psi_{dt}^{in}, \psi_{dt}^{out}, \beta_{bdt} \in \{0,1\} \qquad \forall t \in T \qquad (58)$$

$$\eta_{ipt} \in \{0,1\} \qquad \forall t \in T; \forall p \in P_i \qquad (59)$$

$$\zeta_{ik}^{in}, \zeta_{ik}^{out} \in \{0,1\} \qquad \forall k \in K \qquad (60)$$

Objective (42) minimizes the total reduced cost of the vessel plan. Constraints (43) ensure the out-wharf time is properly computed. Constraints (44)−(47) ensure that the vessel goes through the channel within a feasible time windows caused by tides. Constraints (48) and Constraints (49) ensure that only one feasible tide time window is selected for vessel to *enter* and *exit* the channel, respectively. Constraints (50) ensure that only one QC profile is selected and only one start handling time is selected. Constraints (51)−(52) ensure that $\psi_{dt}^{in} = 1$ if the vessel enters the channel at Time-step t and $\psi_{dt}^{in} = 0$ otherwise. Similarly, Constraints (53)−(54) ensure that $\psi_{dt}^{out} = 1$ if the vessel leaves the channel at Time-step t and $\psi_{dt}^{out} = 0$ otherwise. Constraints (55)−(56) state that $\beta_{bdt} = 1$ if the vessel occupies Berth b at Time-step t, and $\beta_{bdt} = 0$ otherwise. Constraints (57)−(60) define variables.

We can always solve this pricing sub-problem model for each combination of vessel and berth. Hence, we need to solve $|V||B|$ subproblems in each iteration of the column generation to prove the optimality of the LP relaxation.

We analyze the time complexity for solving the above subproblem. From Figure 2, it is obvious that if we fix θ_i^{in}, the start handling time can be fixed accordingly. If both θ_i^{in} and

QC profile is fixed, η_{ipt} and the "ready to leave" time, which is computed as $\theta_i^{in} + l_{ib}^{in} + s_i^{in} + \sum_{t \in T} \sum_{p \in P_i} \eta_{ipt} h_{ip} + s_i^{out}$, can be fixed accordingly. Again, if the out-wharf start time θ_i^{out} is fixed (and the waiting time before θ_i^{out} is fixed), the rest of all variables can be decided uniquely. By definition, we know that $0 \leq \theta_i^{in} < \theta_i^{out} \leq |T|$. It is obvious that solution space of the subproblem formulation is at most $\frac{1}{2}|T|^2|P_i|$. Therefore, the time complexity for solving the subproblem is $O(|T|^2|P_i|)$.

5.2 Pricing subproblem by enumeration

Intuitively, there are three essential decisions made in the subproblem formulation, waiting time before entering the channel (denoted by $\theta_i^{in} - e_i^{arr}$), the QC-profile, and the waiting time before leaving the channel (denoted by $\theta_i^{out} - (\theta_i^{in} + l_{ib}^{in} + s_i^{in} + \sum_{p \in P_i} \gamma_{ip} h_{ip} + s_i^{out})$) as shown in Figure 2). Given these three decisions, we can directly decide the feasibility of the vessel plan and compute the corresponding reduced cost. Since the number of possible delay time for entering or leaving channel is at most $|T|$, and the number of QC-profile is $|P_i|$, the complexity of finding minimum reduced cost is $|T|^2|P_i|$, which is in polynomial time. Thus, we can always enumerate and compute the reduced cost of all the possible vessel plans.

5.3 Solution Procedure

The flow chart of the column generation is shown in Figure 6. In the first step, we simply use a greedy delay heuristic to find a set of feasible vessel plan for each vessel. Then we solve the restricted linear master problem, and obtain the dual cost of each constraint (Section 5.1). Then we solve the pricing subproblem using two proposed methods (Section 5.2 and 5.3), and the reduced costs of generated columns are computed. Specifically, we add at most 100 columns (vessel plans) for each fixed vessel and berth combination in every column generation iteration, so that the total number of variables added to the restricted master problem is not too large. From our preliminary computational study, we find that the IP solutions provided by the set of variables from the column generation are optimal or near optimal. Therefore, after obtaining the optimal solution to the LP relaxation of the master problem, we directly solve an IP problem with the set of variables from column generation without using branch-and-price.

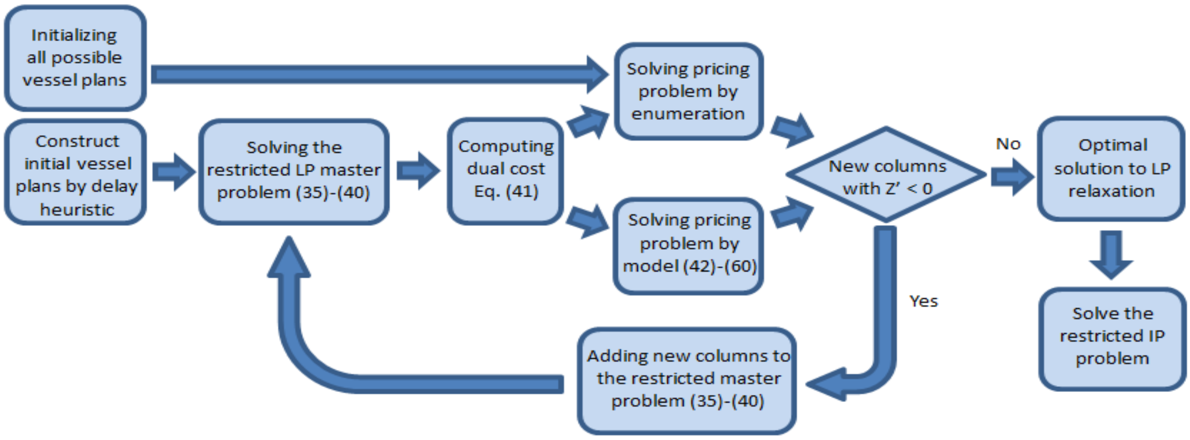

Figure 6: Flow chart of the proposed column generation

6. Numerical experiments

6.1 Generation of test cases

The daily berth planning is made for one day, but the planning horizon used in the proposed model is usually set as 48 hours because the dwelling time interval of some vessels may span two days. The unit of time step is set as a quarter (i.e., 15 minutes). Then the planning horizon is divided into 192 time steps. For determining the number of vessels considered in the instances, we collected the real records of vessel arrival and departure in the six terminals (Guandong, Hudong, Mindong, Pudong, Shengdong, Zhendong) of Shanghai Port from July to September in 2015. The data was provided by the SIPG (Shanghai International Port Group Co. Ltd.). The average number of vessels visiting a terminal in a day is about 13. The average daily total throughput in a terminal is about 25000 TEUs. If the daily berth planning is made for the six terminals in Shanghai Port as a whole, the number of visiting vessels considered in the model could reach about 80. In this study, we consider three classes of instances:

- 10 vessels, 5 berths, 15 QCs;
- 40 vessels, 20 berths, 60 QCs;
- 80 vessels, 40 berths, 120 QCs;

For vessels, we distinguish between three classes, namely feeder, medium, and jumbo (Meisel and Bierwirth, 2009; Zhen et al., 2011). These classes of vessels differ in technical specifications as shown in Table 1. For generating QC-profiles for these classes of vessels, the parameter ranges are listed in Table 1. In experiments, we generate about 200 QC-profiles on average for each vessel. In this study, we set the draft '12.5 m' as the critical point to distinguish a vessel is either tide-dependent or not (Du et al., 2015). More specifically, all the feeders are tide-independent. For tide-independent medium vessels, their drafts follow the uniform distribution U[7, 12.5]; while for tide-dependent medium vessels, their drafts follow the distribution U[12.6, 14]. For tide-independent and tide-dependent jumbo vessels, their drafts follow the distributions U[9,12.5] and U[12.6, 15], respectively. The tidal windows are calculated based on vessel draft and a SINE curve '2.25Sin(πt/6+2π/3)+2.75', which simulates the tidal fluctuation (Phillips 1999; Taylor 2007).

Table 1: Technical specifications for different vessel classes

			QC-Profile				
Class	Percent	Draft (m)	Range of QCs	Range of handling time (quarters)	Avg. handling time (quarters)	Range of workload (QC-quarters)	Avg. workload (QC-quarters)
Feeder	1/3	5–11	1–3	16–32	24	20–80	50
Medium	1/3	7–14	2–4	24–40	32	50–150	100
Jumbo	1/3	9–15	3–5	32–48	40	100–220	160

For validating whether the above experiment setting follows the reality, we estimate the berth utilization and QC utilization for each instance group. Table 2 shows the details.

(1) Estimating the berth utilization:

In Table 1, for the three classes of vessels, the average handling time is 24, 32, and 40 quarters, respectively. Moreover, we assume the average setup time ($s_i^{in} + s_i^{out}$) for a vessel is four quarters. Then the average vessel uses [(24+4)+(32+4)+(40+4)]/3 = 36 berth-quarters.

If the number of vessels is N, 'N×36' is the number of 'berth-quarters' that are used by the vessels in the planning horizon. The fourth column 'N×36' in Table 2 shows the details.

If the number of berths is B, 'B×96' is the number of available 'berth-quarters' in the planning horizon (i.e., one day, 96 quarters). The fifth column 'B×96' in Table 2 shows the details.

The ratio of 'N×36' to 'B×96' is the berth utilization.

(2) Estimating the QC utilization:

According to Table 1, for the three classes of vessels, the average workloads are 50, 100, and 160 QC-quarters, respectively. Then the average vessel uses (50+100+160)/3 = 103.3 QC-quarters.

If the number of vessels is N, 'N×103.3' is the number of 'QC-quarters' that are used by the vessels in the planning horizon. The seventh column 'N×103.3' in Table 2 shows the details.

If the number of QCs is Q, 'Q×96' is the number of available 'QC-quarters' in the planning horizon (i.e., one day, 96 quarters). The eighth column 'Q×96' in Table 2 shows the details.

The ratio of 'N×103.3' to 'Q×96' is the QC utilization.

The berth utilization rate and QC utilization rate of the six classes of instances are listed in Table 2. These two types of utilization rates are both about 72−75%, which closely reflects reality. For each combination of vessel, berth, and QCs, we randomly create three test cases. Therefore, we have altogether 30 test cases and each case is named by pattern 'N-B-Q-#', in which 'N' is the number of vessels, 'B' is the number of berths, 'Q' is the number of QCs, and '#' is the index of cases.

6.2 Computational settings

In this section, we explain the computational experience in detail. We first present the computational results when we solve the BAP model directly by using the CPLEX solver. After that, we present the computational performance of set partitioning model. For the pricing problem that generates columns for the set partitioning model, this study proposes two different approaches: one is the traditional column generation and the other is the column enumeration, which are presented in Section 5.1 and 5.2, respectively.

All the experiments are implemented and performed on a Lenovo ThinkStation P900 workstation with two Xeon E5- 2680 V4 CPUs (28 cores) of 2.4 GHz processing speed and 256 GB of memory running Windows 7. Computational time reported in the next section is obtained from the workstation internal timing calculations. All mathematical modeling and algorithms are implemented in C#. Each LP or IP problem is solved through the concert CPLEX library version 12.7 with the default setting. When the CPLEX solver searches the B&B tree, it can use maximally 56 threads provided by the workstation. However, we do not parallelize our computer program for column enumeration and column generation.

Table 2: The berth and QC utilization rates of the instances in experiments

Num. of vessels (N)	Num. of berths (B)	Num. of QCs (Q)	Used berth-quarters ($N \times 36$)	Available berth-quarters ($B \times 96$)	Berth utilization	Used QC-quarters ($N \times 103.3$)	Available QC-quarters ($Q \times 96$)	QC utilization
10	5	15	360	480	75%	1033	1440	72%
40	20	60	1440	1920	75%	4132	5760	72%
80	40	120	2880	3840	75%	8264	11,520	72%

Notes: In the first row, '36' and '103.3' mean that the average vessel uses 36 berth-quarters and 103.3 QC-quarters, which are calculated according to Table 1; '96' means one day has 96 quarters.

6.3. Computational results of solving the BAP model directly

Table 3 shows the computational results when we use the CPLEX solver to solve the BAP model directly. In particular, we demonstrate the details on the problem size and the solution quality of 30 instances. The information on the problem size includes the number of variables (# of Var.), the number of binary variables (# of Binary Var.), the number of constraints (# of Constr.), the number of big-M constraints (# of Big-M Constr.), and the number of non-zeros in the problem matrix. In the solution quality part, we present the LP relaxation value, the number of B&B nodes searched by CPLEX, the IP value, the IP time, IP-LP gap. We set the maximum CPU time to be three hours.

As we can see from Table 3, if we solve the BAP model directly using CPLEX solver, we can only obtain the feasible solutions for ten out of 30 test cases within three hours computational time, and among them only six solutions (to case 10- 5-15-1, 10-5-15-3, 10-5-15-4, 10-5-15-5, 10-5-15-6, and 10-5-15-8) are optimal. As the majority of the variables are binary, and there are a large number of big-M constraints, the LP relaxation of the BAP model is poor. A huge number of B&B nodes need to be searched to find good solutions, which is very time-consuming.

Table 3: Scales of problem instances and the results of solving the BAP model directly by the CPLEX solver

Problem instances	Some key features of the instance scale					LP Relaxation	IP			Quality of IP solution	
	# of Var.	# of Binary Var.	# of Constr.	# of Big M Constr.	# of Non-zeros	OBJ_{LR}	# of B&B Node	Solution OBJ_{IP}	CPU Time	IP-LP Gap	Optimality Gap
10-5-15-1	467,424	467,303	460,579	3,990	8,715,047	0	20,918	0	1296 s	0.00%	0.00%
10-5-15-2	470,854	470,733	463,974	3,990	9,509,887	0	35,320	120	> 3 h	100.00%	30.83%
10-5-15-3	493,786	493,665	486,672	3,990	9,813,012	0	18,516	0	1162 s	0.00%	0.00%
10-5-15-4	455,762	455,641	449,036	3,990	9,122,704	0	14,921	70	1261 s	100.00%	0.00%
10-5-15-5	461,544	461,423	454,759	3,990	9,239,597	0	11,786	0	872 s	0.00%	0.00%
10-5-15-6	465,366	465,245	458,542	3,990	9,098,033	0	13,178	0	3778 s	0.00%	0.00%
10-5-15-7	446,942	446,821	440,306	3,990	8,989,249	0	41,513	72	> 3 h	100.00%	2.78%
10-5-15-8	493,786	493,665	486,672	3,990	9,816,660	10	8,643	10	845 s	0.00%	0.00%
10-5-15-9	447,138	447,017	440,500	3,990	8,588,021	0	40,518	140	> 3 h	100.00%	99.29%
10-5-15-10	493,786	493,665	486,672	3,990	9,982,321	0	88,710	114	> 3 h	100.00%	100.00%
40-20-60-1	1,956,789	1,955,108	1,928,569	17,760	55,812,191	0	34,411	Cannot	> 3 h	N.A.	
40-20-60-2	1,954,829	1,953,148	1,926,629	17,760	55,493,975	0	14,054	obtain any	> 3 h		
40-20-60-3	1,956,789	1,955,108	1,928,569	17,760	56,462,470	0	15,888	solution	> 3 h		
40-20-60-4	1,872,705	1,871,024	1,845,343	17,760	51,896,748	0	46,509		> 3 h		
40-20-60-5	1,936,895	1,935,214	1,908,878	17,760	54,855,745	0	43,747		> 3 h		
40-20-60-6	1,836,543	1,834,862	1,809,550	17,760	51,672,146	11.81	55,924		> 3 h		
40-20-60-7	1,947,185	1,945,504	1,919,063	17,760	56,021,138	1.73	32,320		> 3 h		
40-20-60-8	1,917,295	1,915,614	1,889,478	17,760	54,478,945	0	3,051		> 3 h		
40-20-60-9	2,008,141	2,006,460	1,979,397	17,760	56,233,764	0	9,324		> 3 h		
40-20-60-10	1,915,531	1,913,850	1,887,732	17,760	54,466,006	0	34,815		> 3 h		
80-40-120-1	4,103,483	4,096,922	4,047,050	40,320	224,912,432	Cannot solve			> 3 h	N.A.	
80-40-120-2	4,046,643	4,040,082	3,990,790	40,320	221,797,208				> 3 h		
80-40-120-3	3,945,311	3,938,750	3,890,492	40,320	215,377,227				> 3 h		
80-40-120-4	3,936,981	3,930,420	3,882,247	40,320	216,126,639				> 3 h		
80-40-120-5	4,117,595	4,111,034	4,061,018	40,320	224,019,849				> 3 h		
80-40-120-6	4,140,037	4,133,476	4,083,231	40,320	224,945,148				> 3 h		
80-40-120-7	4,017,635	4,011,074	3,962,078	40,320	217,946,779				> 3 h		
80-40-120-8	3,970,203	3,963,642	3,915,130	40,320	217,242,804				> 3 h		
80-40-120-9	3,951,583	3,945,022	3,896,700	40,320	217,049,396				> 3 h		
80-40-120-10	4,111,813	4,105,252	4,055,295	40,320	225,865,137				> 3 h		

Notes: '#' denotes the total numbers; 'Var.' denotes the variables; 'Constr.' denotes the constraints; 'Non-zeros' denotes the total number of non-zero entries for the problem matrix. 'IP-LP Gap' is computed by $(OBJ_{IP} - OBJ_{LR}) / OBJ_{IP}$. 'Optimality Gap' is reported by the CPLEX solver.

6.4 Computational results of the column generation based method

In this section, we first present the results by enumerating all the possible columns (vessel plans); then, we show the computational results of the proposed column generation method. We also compare the performance of these two methods at the end of this section.

6.4.1 Set-Partitioning model based on enumerating all the possible columns

In Table 4, we present the solution results of the set partitioning model by enumerating all the possible columns (vessel plans). Different from the traditional column generation procedure, this method does not 'generate' new columns in iterations, but enumerates all the columns at first and then solves the master problem based on the set of all the columns. For this method, we show the total number of vessel plans, the plan enumeration time, the total number of constraints, the total number of non-zeros in the problem matrix, the LP value and time, the IP value and time, the IP-LP Gap, the optimality gap, and the total solution time.

As we can see from Table 4, the enumeration based solution approach can obtain optimal solutions within three hours. From these test cases, we can see that the set partitioning model provides very tight LP relaxation. In fact, for 26 out of 30 test cases, the IP-LP gaps are zero. It is not surprising that the set-partitioning based model provides very tight LP relaxations. Similar observations have been reported in many other applications using set-partitioning based model, such as crew pairing problem (Barnhart et al., 2003), aircraft routing problem (Barnhart et al., 1998), aircraft conflict resolution problem (Liang et al., 2014), parallel machine scheduling problem (van den Akker et al. 1999), to name but a few.

However, as the problem size increases, the number of possible vessel plans increases from less than half a million to more than 24 million. We calculate the total computation time for each instance by adding the 'Colum. Enum. Time' for enumerating columns and the 'IP Time' for solving the IP model in each row of Table 4. The total computation time for the enumeration method to solve some large-scale instances exceed three hours because of a large number of variables. In addition, it is worth mentioning that when solving the IP model, the CPLEX IP solver uses up to 56 threads in the B&B process as mentioned in Section 6.2.

Table 4: Results of column enumeration based solution approach

Problem instances	Scales of master problem based on column enumeration								
	# of all Colum.	Colum. Enum. Time(s)	# of Constr.	# of Non-zeros	LP Relaxation OBJ_{LR}	IP OBJ_{IP}	IP-LP Gap	Optimality Gap	IP Time (s)
10–5–15–1	401,580	101	689	14,931,740	0	0	0.00%	0.00%	13
10–5–15–2	406,380	85	689	15,826,924	108	108	0.00%	0.00%	20
10–5–15–3	400,000	91	689	15,616,000	0	0	0.00%	0.00%	18
10–5–15–4	356,880	92	689	13,349,376	70	70	0.00%	0.00%	17
10–5–15–5	401,040	95	689	16,104,880	0	0	0.00%	0.00%	10
10–5–15–6	397,800	89	689	15,608,240	0	0	0.00%	0.00%	21
10–5–15–7	382,500	86	689	15,597,000	71.25	72	1.04%	0.00%	22
10–5–15–8	400,000	94	689	15,712,000	10	10	0.00%	0.00%	18
10–5–15–9	455,312	102	689	17,628,017	48.67	49	0.67%	0.00%	32
10–5–15–10	367,000	93	689	14,109,000	28.63	36	20.47%	0.00%	23
40–20–60–1	5857,880	1612	2174	232,558,284	208	208	0.00%	0.00%	384
40–20–60–2	6219,080	1684	2174	250,594,784	108	108	0.00%	0.00%	382
40–20–60–3	5963,380	1643	2174	243,698,992	74	74	0.00%	0.00%	456
40–20–60–4	6069,900	1750	2174	235,912,996	174	174	0.00%	0.00%	725
40–20–60–5	6301,080	1933	2174	255,110,364	85.83	91	5.68%	0.00%	986
40–20–60–6	6168,350	1842	2174	247,599,920	151	151	0.00%	0.00%	332
40–20–60–7	6135,700	2058	2174	250,815,948	322	322	0.00%	0.00%	732
40–20–60–8	6309,640	1902	2174	257,226,840	0	0	0.00%	0.00%	810
40–20–60–9	6230,000	1872	2174	244,259,000	18	18	0.00%	0.00%	445
40–20–60–10	6008,112	1996	2174	241,170,997	140	140	0.00%	0.00%	407
80–40–120–1	24,497,151	8102	4154	1000,347,956	503	503	0.00%	0.00%	2888
80–40–120–2	24,180,580	7446	4154	985,734,868	528	528	0.00%	0.00%	1532
80–40–120–3	24,397,160	8432	4154	988,353,708	289	289	0.00%	0.00%	3058
80–40–120–4	23,730,080	7857	4154	958,670,188	381	381	0.00%	0.00%	2218
80–40–120–5	24,791,390	7490	4154	996,181,512	333	333	0.00%	0.00%	1700
80–40–120–6	24,771,900	7344	4154	989,139,940	178	178	0.00%	0.00%	2322
80–40–120–7	24,561,311	7815	4154	982,797,231	570	570	0.00%	0.00%	2551
80–40–120–8	23,836,960	7181	4154	964,053,920	286	286	0.00%	0.00%	1684
80–40–120–9	23,058,480	7502	4154	939,899,438	293	293	0.00%	0.00%	2564
80–40–120–10	24,421,580	8440	4154	1006,345,016	399	399	0.00%	0.00%	2320

Notes: '# of all Colum.' denotes the total number of all the possible columns; 'Colum. Enum. Time' is the time for enumerating all the columns, the unit is in second. 'IP-LP Gap' is computed by $(OBJ_{IP} - OBJ_{LR}) / OBJ_{IP}$.

6.4.2 A traditional column generation based solution procedure

In our preliminary study, we first test two different pricing subproblem methods: mathematical programming model presented in Eqs. (42) −(60) and the enumeration of the vessel plan. The two ways are shown in Fig. 6. The computational results show that the mathematical programming model performs poorly because only one column (vessel plan) can be obtained after solving each subproblem model. Therefore, a large number of column generation iterations are needed to obtain the optimal LP solution. On the other hand, by using enumeration subproblem method (as presented in Section 5.2), in every iteration we add at most 100 columns (vessel plans) for each vessel and berth combination. As a result, the number of column generation iterations is greatly reduced. When we obtain the optimal LP solution of the set partitioning model, we just solve a restricted IP model based on the existing columns.

In Table 5, we present the solution information of the column generation method. We show the number of columns (vessel plans) generated, the column generation time, the IP value, IP-LP gap, and the optimality gap reported by the CPLEX solver.

We calculate the total computation time for each instance by adding the 'Column Generation Time' for generating columns and the 'IP Time' for solving the IP model in each row of Table 5. Results in Table 5 show that the column generation can obtain the optimal solutions for all the 30 test cases within an hour, which is acceptable in the real-life situation. The number of column generation iterations ranges from one to four. The total number of generated vessel plans is less than 150,0 0 0 for all the test cases. Specifically, for 23 out of 30 test cases, we obtain the optimal solutions using only the initial set of the vessel plans. For the rest cases, the number of vessel plans obtained by column generation is much less than the initial set of vessel plans. As the total number of the vessel plans is not large, the restricted IP can be solved quickly.

According to Tables 4 and 5, we summarize the comparison of the two different set partitioning methods: column enumeration and column generation. Both of them can solve the cases to optimality but the latter one is much faster than the former one. Column generation only generates about 0.5% of all the possible columns on average to obtain optimal IP solutions.

For some test cases in Table 5, it takes three or four iterations for column generation to prove the optimal LP solution; whereas for others, it only takes one or two iterations. Therefore, we further investigate the factors that affect the number of iterations in two experiments. The results of these two experiments are listed in Tables 6 and 7, respectively. In the first experiment, we have ten vessels and seven berths. Because the number of berths is relatively large, there is always some berth available to service the vessel. By adjusting the number of QC from 16 to 13, we find the utilization rate of QC increases from 0.70 to 0.85; while the number of the column generation iterations increases from one to three as shown in Table 6.

In the second experiment, we have ten vessels and 18 QCs so that there are enough QCs to serve vessels at any time. By reducing the number of berths from seven to four, the utilization of the berth increases from 0.54 to 0.92, and the number of column generation iterations increases from one to three accordingly as shown in Table 7.

As we can see from Tables 6 and 7, the number of column generation iterations is highly affected by the utilization of the berths and QCs. It means the computation time of column generation depends not only on the scale of the instance (e.g., the number of resources such as berths and QCs), but also on the utilizations of these resources significantly.

Table 5: Results of column generation based solution approach

Problem instances	# of columns generated	Column generation time (s)	# of Iterations	LP relaxation OBJ_{LR}	LP time (s)	IP OBJ_{IP}	IP time (s)	IP-LP Gap	# of B&B nodes	Optimality Gap
10-5-15-1	2005	29	1	0	0.01	0	0.13	0.00%	0	0.00%
10-5-15-2	2360	35	1	108	0.01	108	0.16	0.00%	0	0.00%
10-5-15-3	2000	29	1	0	0.01	0	0.17	0.00%	0	0.00%
10-5-15-4	1810	29	1	70	0.01	70	0.17	0.00%	0	0.00%
10-5-15-5	2005	27	1	0	0.01	0	0.11	0.00%	0	0.00%
10-5-15-6	1985	28	1	0	0.01	0	0.19	0.00%	0	0.00%
10-5-15-7	4278	48	2	71.25	0.03	72	0.31	1.04%	0	0.00%
10-5-15-8	2000	30	1	10	0.01	10	0.09	0.00%	0	0.00%
10-5-15-9	3317	136	3	48.67	0.03	49	0.28	0.67%	0	0.00%
10-5-15-10	4758	99	3	28.63	0.03	36	0.48	20.47%	0	0.00%
40-20-60-1	29,749	412	1	208	0.20	208	3.28	0.00%	0	0.00%
40-20-60-2	31,355	399	1	108	0.11	108	2.07	0.00%	0	0.00%
40-20-60-3	30,147	404	1	74	0.19	74	2.43	0.00%	0	0.00%
40-20-60-4	35,418	699	2	174	0.67	174	3.84	0.00%	0	0.00%
40-20-60-5	37,662	1960	4	85.83	1.67	91	9.95	5.68%	0	0.00%
40-20-60-6	30,946	396	1	151	0.17	151	1.75	0.00%	0	0.00%
40-20-60-7	36,038	852	2	322	0.59	322	4.51	0.00%	0	0.00%
40-20-60-8	31,712	427	1	0	0.22	0	3.60	0.00%	0	0.00%
40-20-60-9	31,285	548	1	18	0.11	18	1.64	0.00%	0	0.00%
40-20-60-10	30,428	573	1	140	0.22	140	2.62	0.00%	0	0.00%
80-40-120-1	123,277	2155	1	503	2.39	503	22.04	0.00%	0	0.00%
80-40-120-2	122,042	1927	1	528	0.90	528	11.98	0.00%	0	0.00%
80-40-120-3	140,836	2998	2	289	5.69	289	25.37	0.00%	0	0.00%
80-40-120-4	120,044	1803	1	381	0.97	381	9.75	0.00%	0	0.00%
80-40-120-5	124,353	2082	1	333	1.01	333	14.84	0.00%	0	0.00%
80-40-120-6	124,511	1799	1	178	1.03	178	10.17	0.00%	0	0.00%
80-40-120-7	124,009	1636	1	570	0.89	570	14.83	0.00%	0	0.00%
80-40-120-8	120,214	1671	1	286	0.76	286	11.87	0.00%	0	0.00%
80-40-120-9	117,423	1744	1	293	1.43	293	16.50	0.00%	0	0.00%
80-40-120-10	123,296	1876	1	399	1.19	399	13.40	0.00%	0	0.00%

Table 6: Influence of QC amount on the number of column generation iterations

Number of QCs	16	15	14	13
Utilization of QC	0.70	0.74	0.81	0.85
Number of columns	1919	1919	2729	3570
Number of iterations	1	1	2	3

Table 7: Influence of berth amount on the number of column generation iterations

Number of berths	7	6	5	4
Utilization of berth	0.54	0.62	0.84	0.92
Number of columns	1903	1650	2241	3838
Number of iteration	1	1	2	3

Table 8: Comparison between the proposed model and an intuitive decision rule (FCFS)

Problem instances	OBJ_{PM}	OBJ_{FCFS}	Gap
15–8–22–1	82	93	11.83%
15–8–22–2	267	289	7.61%
15–8–22–3	42	75	44.00%
15–8–22–4	344	373	7.77%
15–8–22–5	250	276	9.42%
15–8–22–6	37	59	37.29%
15–8–22–7	155	210	26.19%
15–8–22–8	67	70	4.29%
15–8–22–9	220	230	4.35%
15–8–22–10	292	325	10.15%
30–15–45–1	187	201	6.97%
30–15–45–2	235	237	0.84%
30–15–45–3	248	281	11.74%
30–15–45–4	155	266	41.73%
30–15–45–5	208	427	51.29%
30–15–45–6	201	456	55.92%
30–15–45–7	373	488	23.57%
30–15–45–8	144	299	51.84%
30–15–45–9	177	210	15.71%
30–15–45–10	253	368	31.25%
60–30–90–1	305	534	42.88%
60–30–90–2	367	567	35.27%
60–30–90–3	499	987	49.44%
60–30–90–4	509	943	46.02%
60–30–90–5	418	1108	62.27%
60–30–90–6	410	857	52.16%
60–30–90–7	379	867	56.29%
60–30–90–8	280	716	60.89%
60–30–90–9	225	458	50.87%
60–30–90–10	381	734	48.09%
		Avg.	31.93%

Note: 'Gap' is computed by (OBJ_{FCFS}-OBJ_{PM})/OBJ_{FCFS}.

6.5. Experiments on our proposed mathematical model

To validate effectiveness of our proposed decision model, we compare our decision model with an intuitive decision rule, i.e., First Come First Serve (FCFS), which means the port operator assigns arriving vessels to available berths sim- ply according to the vessels' arrival time. In realistic ports, this rule is usually used if all the vessels have the same priority.

According to the experimental results shown in Table 8, we can see that our proposed decision model can outperform the FCFS decision rule by 32% on average with respect to the same criterion, i.e., Objective (1). This comparative result could validate the necessity of proposing the mathematical decision model in this study.

As one of the main contributions in this study is consideration of the tides and channel flow capacity. Sensitivity analysis on some tide related or channel capacity related parameters is conducted. The results are shown in Figs. 7 and 8.

From the results in Fig. 7, we can see that the average length of the tidal time windows for vessels has obvious influence on the final result in the berthing planning. Here the tidal time windows mean the periods, during which tide-dependent vessels can pass through the channel to berths. The horizontal axis in Fig. 7 is from 20 to 96; here 96 quarters represent a case that all the vessels can pass the channel during a whole day. Thus the larger is the value in the horizontal axis, the more significant influence is imposed by the tidal factor on the vessels' berthing activity. The result in Fig. 7 validates the significant influence of the tidal factor, and also implies the necessity of the consideration on the tidal factor in this study.

The result in Fig. 8 demonstrates that the channel capacity also has influence on the final result of the berthing planning. Here the channel capacity denotes the number of vessels that can pass through the channel simultaneously. Along the capacity increasing, the objective value decreases at the first; when the capacity exceeds a certain value (threshold), the objective value converges to a constant. In the experiments shown in Fig. 8, the threshold value is nine. The result implies that the channel capacity needs not be expanded significantly. For the case in Fig. 8, 'four' or 'five' may be a suitable value for the channel capacity; because when the capacity exceeds these values, the final objective is not reduced (or is reduced slightly). In reality, expanding channel capacity is a huge and expensive project. So the above sensitivity analysis in Fig. 8 could support the strategic-level decision on channel capacity planning.

Figure 7: Sensitivity analysis on the average length of the tidal time windows

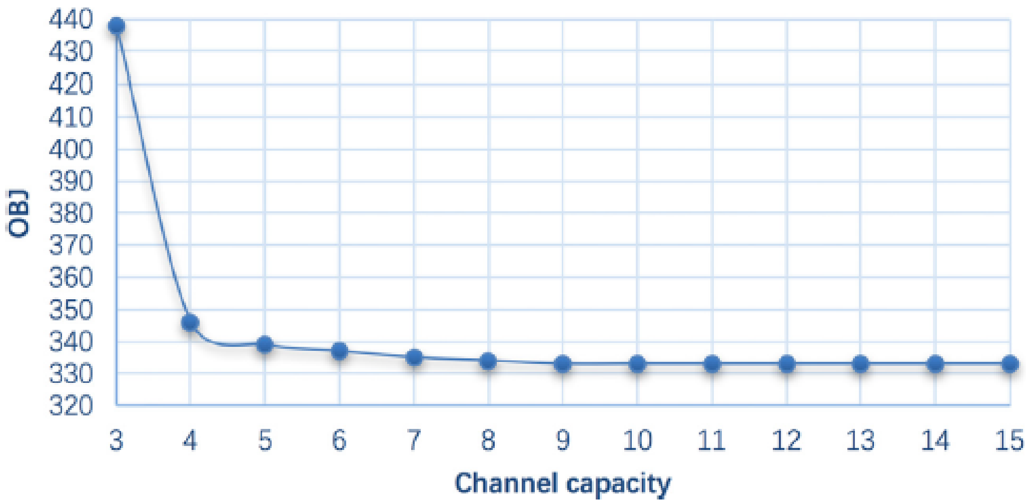

Figure 8: Sensitivity analysis on the channel capacity

7. Extension to the continuous berth allocation problem

In the above study, the decision on berth allocation belongs to the category of discrete BAP, in which the quay of a port is divided into a set of equal berths and each vessel occupies one berth during its stay in the port. However, in the realistic environment, the length of vessels may be significantly different from each other. Therefore, the continuous BAP has become more and more popular in the academia recently. In the continuous BAP, vessels may occupy different lengths of quay space during their stay in a port.

From the perspective of mathematical modeling, the continuous BAP is more complex than the discrete BAP; and the former one may dominate the latter one. According to some recent continuous BAP related studies (Türkogulları et al., 2014, 2016; Iris et al., 2015, 2017), the quayside of a port is divided into a lot of equal-sized units (berth sections). For example (i.e., the following numerical experiments in Table 9), a port's quay is discretized by 90 berth sections; each berth section has a length of 50 m; and a vessel may occupy 3 −9 berth sections. For the continuous berth allocation with QC assignment, the feasible tidal time windows as well as the flow control in navigation channel are considered in this extension. For the column generation based solution approach on the above extended problem, the main change on the basis of the method presented in Section 5 is: when generating columns (vessel plans), a vessel plan occupies multiple adjacent berths (berth sections); while a vessel plan is related to single berth in the previous method.

Table 9 shows the results of numerical experiments on the continuous berth allocation with QC assignment as well as tidal and channel flow control. As the number of berth sections (berths) is much more than the instances on the previous discrete berth allocation context, the computation time in Table 8 is much longer than the time in Tables 4 and 5 for the instances with the same number of vessels. Although the computation time is a bit long, the above experiments validate that our previously proposed model and method can also apply to the cases of continuous berth allocation.

Table 9: Results for the problem under continuous berth allocation setting by using the column enumeration based method

Problem instances	Scales of master problem based on column enumeration				LP Relaxation OBJ_{LR}	IP OBJ_{IP}	IP-LP Gap	Optimality Gap	CPU Time(s)
	# of all colum.	Colum. Enum. Time	# of Constr.	# of Non Zeros					
10-30-15-1	1,105,200	749	3114	159,517,100	17.94	39	54.00%	0.00%	130
10-30-15-2	1,278,600	789	3114	152,754,660	68.6	70	2.00%	0.00%	383
10-30-15-3	1,122,300	711	3114	132,442,700	41.75	51	18.14%	0.00%	193
10-30-15-4	1,269,600	781	3114	142,773,671	5.4	6	10.00%	0.00%	209
10-30-15-5	1,109,100	694	3114	137,117,387	92	92	0.00%	0.00%	131
10-30-15-6	1,145,952	744	3114	150,620,608	0	1	100.00%	0.00%	178
10-30-15-7	1,088,400	731	3114	142,312,891	0	0	0.00%	0.00%	189
10-30-15-8	1,223,400	775	3114	168,252,280	1.33	2	33.50%	0.00%	253
10-30-15-9	1,103,840	829	3114	157,993,160	56	57	1.75%	0.00%	333
10-30-15-10	1,098,600	848	3114	138,194,780	1.33	3	55.67%	0.00%	312
20-60-30-1	4,900,616	3517	6034	692,006,919	1.14	2	43.00%	0.00%	2965
20-60-30-2	5,312,056	3933	6034	763,533,806	88	88	0.00%	0.00%	1333
20-60-30-3	5,397,000	4335	6034	666,461,849	14	14	0.00%	0.00%	1516
20-60-30-4	4,563,880	3678	6034	622,445,520	102	102	0.00%	0.00%	2031
20-60-30-5	4,972,656	3487	6034	606,998,581	0	0	0.00%	0.00%	1038
20-60-30-6	5,072,596	3816	6034	663,082,628	159	159	0.00%	0.00%	1863
20-60-30-7	5,540,100	4117	6034	656,509,421	72	72	0.00%	0.00%	1773
20-60-30-8	4,731,912	3786	6034	590,153,899	102	102	0.00%	0.00%	1555
20-60-30-9	5,019,690	3970	6034	715,347,258	0	0	0.00%	0.00%	2622
20-60-30-10	5,317,220	3941	6034	602,870,964	15	16	6.25%	0.00%	1612
30-90-60-1	10,998,600	7415	8954	1,330,481,158	153	153	0.00%	0.00%	6536
30-90-60-2	12,239,676	8047	8954	1,652,854,483	98	98	0.00%	0.00%	4215
30-90-60-3	11,950,892	9955	8954	1,453,537,436	80	80	0.00%	0.00%	7012
30-90-60-4	11,919,388	7693	8954	1,530,753,775	70	70	0.00%	0.00%	6367
30-90-60-5	11,583,900	7544	8954	1,337,533,904	162	162	0.00%	0.00%	2467
30-90-60-6	12,505,500	9461	8954	1,581,967,827	82	82	0.00%	0.00%	5986
30-90-60-7	12,208,240	8441	8954	1,570,883,859	500	500	0.00%	0.00%	10,341
30-90-60-8	11,647,016	8713	8954	1,494,405,808	91	91	0.00%	0.00%	4110
30-90-60-9	11,926,060	6704	8954	1,331,400,574	104	104	0.00%	0.00%	10,513
30-90-60-10	12,604,200	8485	8954	1,493,232,408	18	18	0.00%	0.00%	9791

8. Conclusions

This paper studies an operational-level daily berth planning problem in a tidal port with the navigation channel flow control. An integrated optimization model on berth allocation and QC assignment is proposed with consideration of the feasible tidal time windows of vessels and the capacity constraint of the navigation channel. Column generation based solution approach is suggested to solve the optimal solution for the proposed model. Numerical experiments are also conducted to validate the efficiency of the proposed solution approach and the effectiveness of the proposed model.

(1) There are very few berth allocation related studies that have considered the factors of tide, navigation channel flow control, and QC assignment decisions simultaneously. This paper makes an explorative study on this new but realistic problem.

(2) An IP model is proposed to consider the above mentioned factors through a comprehensive perspective. The proposed decision model could be potentially useful for some tidal ports with (or without) navigation channels.

(3) A simple but practical solution approach based on column generation is suggested to solve the optimal daily berthing plan for the problem instances with up to 80 vessels, 40 berths, and 120 QCs within one hour, which is acceptable for the real-world applications.

However, this study also has several limitations. Some planning rules used in realistic ports are not considered. For example, if a vessel's arrival time is much later than its originally scheduled time, its priorities will be significantly reduced and it may be punished to wait outside the port even there are available berths. Moreover, recently the concept of 'green port' becomes popular, however, the factor of carbon emission (or fuel consumption), which has been considered by some studies, is not involved in this study. All of these issues can be our research directions in the future.

References

Baldacci R., Mingozzi A., Roberti R., and Wolfler Calvo R. (2013) An exact algorithm for the two-echelon capacitated vehicle routing problem. *Operations Research* 61, 298-314.

Barros, V. H., Costa, T. S., Oliveira, A. and Lorena L. A. N. (2011) Model and heuristic for berth allocation in tidal bulk ports with stock level constraints. *Computers & Industrial Engineering* 60, 606-613.

Barnhart C., Boland N. L., Clarke L. W., Johnson E. L., Nemhauser G.L., Shenoi R.G. (1998) Flight string models for aircraft fleeting and routing. *Transportation Science* 32, 208-220.

Bierwirth, C. and Meisel, F. (2010) A survey of berth allocation and quay crane scheduling problems in container terminals. *European Journal of Operational Research* 202, 615-627.

Bierwirth, C. and Meisel, F. (2015) A follow-up survey of berth allocation and quay crane scheduling problems in container terminals. *European Journal of Operational Research* 244, 675-689.

Chen Z. L. and Powell, W. B. (1999) Solving parallel machine scheduling problems by column generation. *INFORMS Journal on Computing* 11, 78-94.

Chou C. A., Liang Z., Chaovalitwongse W. A., Berger-Wolf T., Dasgupta B., Sheikh S., Putrevu S. L., Ashley M. V. and Caballero I. C. (2015) Column Generation Framework of Nonlinear Similarity Model for Reconstructing Sibling Groups. *INFORMS Journal on Computing* 27, 35-47.

Cordeau, J. F., Gaudioso, M., Laporte, G. and Moccia, L. (2007) The service allocation problem at the Gioia Tauro Maritime Terminal. *European Journal of Operational Research* 176, 1167-1184.

Cordeau, J. F., Laporte, G., Legato, P. and Moccia, L. (2005) Models and tabu search heuristics for the berth allocation problem. *Transportation Science* 39, 526-538.

Du. Y., Chen Q., Quan X., Long, L. and Fung R. Y. K. (2011) Berth allocation considering fuel consumption and vessel emissions. *Transportation Research Part E* 47, 1021-1037.

Du, Y., Chen, Q., Lam, J. S. L., Xu, Y. and Cao, J. X. (2015) Modeling the Impacts of Tides and the Virtual Arrival Policy in Berth allocation. *Transportation Science* 49, 939 - 956.

Fransoo, J. C. and Lee, C.-Y. (2013) The critical role of ocean container transport in global supply chain performance. *Production and Operations Management* 22, 253-268.

Giallombardo, G., Moccia, L., Salani, M. and Vacca, I. (2010) Modeling and solving the Tactical Berth Allocation Problem. *Transportation Research Part B* 44, 232-245.

Hu, Q.-M., Hu, Z.-H. and Du, Y. (2014) Berth and quay-crane allocation problem considering fuel consumption and emissions from vessels. *Computers & Industrial Engineering* 70, 1-10.

Imai, A., Chen, H., Nishimura, E. and Papadimitriou, S. (2008) The simultaneous berth and quay crane allocation problem. *Transportation Research Part E* 44, 900-920.

Imai, A., Nagaiwa, K. and Chan, W. (1997) Efficient planning of berthing allocation for container terminals in Asia. *Journal of Advanced Transportation* 31, 75-94.

Imai, A., Nishimura, E., Hattori, M. and Papadimitriou, S. (2007) Berth allocation at intented berths for mega-containerships. *European Journal of Operational Research* 179, 579-593.

Imai, A., Nishimura, E. and Papadimitriou, S. (2001) The dynamic berth allocation problem for a container port. *Transportation Research Part B* 35, 401-417.

Imai, A., Sun, X., Nishimura, E. and Papadimitriou, S. (2005) Berth allocation in a container port: using a continuous location space approach. *Transportation Research Part B* 39, 199-221.

Iris, Ç., Pacino, D., Ropke, S. and Larsen, A. (2015) Integrated Berth Allocation and Quay Crane Assignment Problem: Set partitioning models and computational results, *Transportation Research Part E* 81, 75-97.

Jin, J. G., Lee, D.-H. and Cao, J. X. (2016) Storage yard management in maritime container terminals. *Transportation Science* 50, 1300-1313.

Jin, J. G., Lee, D.-H. and Hu, H. (2015) Tactical berth and yard template design at container transshipment terminals: A column generation based approach. *Transportation Research Part E* 73, 168-184.

Kim, K. H. and Moon, K. C. (2003) Berth scheduling by simulated annealing. *Transportation Research Part B* 37, 541-560.

Lalla-Ruiz, E., Shi, X. and Voß, S. (2016) The waterway ship scheduling problem. *Transportation Research Part D*, in press, doi: 10.1016/j.trd.2016.09.013.

Lee, C.-Y. and Song, D.-P. (2017) Ocean container transport in global supply chains: Overview and research opportunities. *Transportation Research Part B* 95, 442-474.

Legato, P. and Mazza, R. (2001) Berth planning and resources optimization at a container terminal via discrete event simulation. *European Journal of Operational Research* 133, 537-547.

Legato, P., Mazza, R. M. and Gullì, D. (2014) Integrating tactical and operational berth allocation decisions via Simulation–Optimization. *Computers & Industrial Engineering* 78, 84-94.

Liang Z., Chaovalitwongse W. A. and Elsayed E. A. (2014) Sequence Assignment Model for the Flight Conflict Resolution Problem, *Transportation Science* 48, 351-372.

Liu, M., Lee, C.-Y., Zhang, Z. and Chu, C. (2016) Bi-objective optimization for the container terminal integrated planning. *Transportation Research Part B*, 93B, 720-749.

Meisel, F. and Bierwirth, C. (2009) Heuristics for the integration of crane productivity in berth allocation problem. *Transportation Research Part E* 45, 196-209.

Meisel, F. and Bierwirth, C. (2013) A framework for integrated berth allocation and crane operations planning in seaport container terminals. *Transportation Science* 47, 131-147.

Meng, Q., Wang, S., Andersson, H. and Thun, K. (2014) Containership routing and scheduling in liner shipping: overview and future research directions. *Transportation Science* 48, 265-280.

Meng, Q., Wang, S. and Lee, C.-Y. (2015) A tailored branch-and-price approach for a joint tramp ship routing and bunkering problem. *Transportation Research Part B* 72, 1-19.

Monaco, M. F. and Sammarra, M. (2007) The berth allocation problem: A strong formulation solved by a Lagrangean approach. *Transportation Science* 41, 265-280.

Moorthy, R. and Teo, C. P. (2006) Berth management in container terminal: the template design problem. *OR Spectrum* 28, 495-518.

Nishimura, E., Imai, A. and Papadimitriou, S. (2001) Berth allocation planning in the public berth system by genetic algorithms. *European Journal of Operational Research* 131, 282-292.

Park, K. T. and Kim, K. H. (2002) Berth scheduling for container terminals by using a sub-gradient optimization technique. *Journal of the Operational Research Society* 53, 1054-1062.

Park, Y. M. and Kim, K. H. (2003) A scheduling method for berth and quay cranes. *OR Spectrum* 25, 1-23.

Phillips, T. (1999) Harmonic analysis and prediction of tides. Accessed December 5, 2015, http://www.math.sunysb.edu/~tony/tides/harmonic.html.

Port of Hamburg (2016). Accessed July 16, 2016, http://www.hafen-hamburg.de.

Qin, T., Du, Y. and Sha, M. (2016) Evaluating the solution performance of IP and CP for berth allocation with time-varying water depth. *Transportation Research Part E* 87, 167-185.

SHMSA (2016) Accessed July 16, 2016, http://www.shmsa.gov.cn.

Stahlbock, R. and Voß, S. (2008) Operations research at container terminals: A literature update. *OR Spectrum* 30, 1-52.

Steenken, D., Voß, S. and Stahlbock, R. (2004) Container terminal operation and operations research - A classification and literature review. *OR Spectrum* 26, 3-49.

Taylor, P. (2007) Fitting the tide. Accessed July 16, 2016, www.mast.queensu.ca/~peter/grade12/ MHF4U-2/23.pdf.

Türkoğulları, Y. B., Taşkın, Z. C., Aras, N. and Altınel, İ. K. (2014). Optimal berth allocation and time-invariant quay crane assignment in container terminals. *European Journal of Operational Research*, 235 , 88-101 .

Türkoğulları, Y. B., Taşkın, Z. C., Aras, N. and Altınel, İ. K. (2016) Optimal Berth Allocation, Time-variant Quay Crane Assignment and Scheduling with Crane Setups in Container Terminals. *European Journal of Operational Research* 254, 985-1001.

Vacca, I., Salani, M. and Bierlaire, M. (2013) An exact algorithm for the integrated planning of berth allocation and quay crane assignment. *Transportation Science* 47, 148-161.

van den Akker J. M., Hoogeveen J. A. and van de Velde S. L. (1999) Parallel machine Scheduling by column generation. *Operations Research* 47, 862-872.

Vis, I. F. A. and de Koster, R. (2003) Transshipment of containers at a container terminal: An overview. *European Journal of Operational Research* 147, 1-16.

Xu, D., Li, C. L. and Leung, J. Y. T. (2012) Berth allocation with time-dependent physical limitations on vessels. *European Journal of Operational Research* 216, 47-56.

Zhen, L., Chew, E. P. and Lee, L. H. (2011) An integrated model for berth template and yard template planning in transshipment hubs. *Transportation Science* 45, 483-504.