

Mathematical Programming-Driven Daily Berth Planning in Xiamen Port

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Abstract. In this paper, we introduce the daily berth planning problem for Xiamen Hai-Tian Container Terminal (XHCT) at the Port of Xiamen, China, and propose the development and implementation of a berth planning system. The aim of the berth planning problem is to optimize daily berth plans by considering various decisions, including berth allocation, quay crane assignment, fairway traffic control, and berthing safety requirements. Among these decisions, the berthing safety requirement is a novel but practical problem in berth allocation that concerns the resource allocation related to berthing safety and interrelation with other decisions. A mathematical programming-driven methodological framework is designed with a 0-1 integer linear programming model for problem formulation and a highly efficient decomposition heuristic algorithm for solving the problem. This framework establishes the core for the berth planning system. The adoption of the berth planning system contributes to the increase of container throughput and berth capacity by transforming the planning process of XHCT. Moreover, the mathematical programming-driven daily berth planning informs further intelligent operations development in the Port of Xiamen and other container ports.

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The recent developments in global trade have led to a boom in the container shipping industry, and the development of the southeast coast of China is particularly remarkable. The Port of Xiamen, located in the Xiamen Special Economic Zone of Fujian Province in Southeast China, has developed rapidly since it began offering container services in 1983 (see Figure 1). Xiamen has become a crucial port for cross-strait trade between the Chinese mainland and Taiwan and a key node on the Maritime Silk Road between China and Asia, Europe, and Africa. Various factors led the throughput of the Port of Xiamen to reach 12.05 million 20-foot equivalent units (TEUs) in 2021, and it was ranked the seventh largest port in China and the 13th largest in the world (China Daily 2022).

Although this is a remarkable achievement, increasing pressure has become a central issue for the future development of the Port of Xiamen. The demand for berths and container handling, in addition to the service expectations from shipping companies, shippers,

and the government, has increased, and higher targets for the port's throughput and utilization have been proposed. However, the limited berth capacity and container-handling capability constrain further increases in the port's performance. The Port of Xiamen authorities have strived to assess the potential and have formulated a detailed action plan for the future development of the port, which includes the renovation of existing port equipment, the informatization of workflow and customer service, and intelligent operations development. Aimed at enhancing the planning procedures, including berth, yard, and vessel stowage planning, the intelligent operations development designs and implements intelligent decision-making frameworks and makes full use of berths and port equipment. These measures aim to improve port utilization and operational efficiency and thus help the port adapt to the growing demands as well as service expectations.

In the port's action plan, the intelligent operations development for berth planning at Xiamen Hai-Tian

Figure 1. (Color online) Map of the Port of Xiamen

Source. Google Maps (Accessed in 2022).

Container Terminal (XHCT) is one of the most critical projects. Located on the west shore of Xiamen Island, XHCT is one of the largest and busiest terminals in the Port of Xiamen and accounts for nearly a quarter of the port's total container throughput. The boom in shipping services has led to the steady growth of XHCT's container throughput, which reached 2.63 million TEUs in 2021, an increase of 15% from the previous year. This expansion has placed a tremendous strain on XHCT's berthing and container-handling operations. Operational data suggest that vessels' average waiting time in anchorage before entering the berth is approximately 3.4 hours. During July and August 2021, XHCT experienced incidents that included a typhoon and maintenance work, and vessels' delay time on busy days significantly increased to 18.6 hours on average. Despite the downtime that is due to maintenance work on berths and quay cranes, the terminal's resources had to work continuously. Although the throughput of 2.6 million TEUs represented the best performance in the history of XHCT, this was far from the designed throughput capacity of more than 3.5 million TEUs per year. Thus, less than 75% of the terminal's throughput capacity is utilized on average, indicating that further improvements can be made.

The gap between the actual and design throughputs can be attributed to various factors, including the

limitations brought by weather and water conditions, concerns about berthing safety, variations in the berthing capabilities of different berths, and incidents such as typhoons or military activity. In addition, the traditional berth planning process, which relies on the planners' knowledge and skill, encounters a bottleneck. Manual planning may at times not make full use of berth resources, and the berth plans usually come at the expense of efficiency and resource utilization.

Daily berth planning is typically performed by XHCT and other container terminals once or twice a day. The main decision problems have been identified as berth allocation and quay crane assignment, with fairway traffic control and berthing safety requirements also taken into consideration. Other real-world factors influencing berth planning include tides, fairway traffic control, and port congestion. Among the various decisions and influencing factors, berthing safety requirements make the berth planning of XHCT different. The changeable water and weather conditions in XHCT not only recommend strict safety measures in port operation but also influence berth planning decisions. In addition to safety clearance between vessels, the bollards used to tie mooring lines as temporary anchors should be given consideration in berth plans according to the safety rules. Fenders with different sizes are used to buffer different types of vessels against the quay side, and vessels should

be allocated to the berth with suitable fenders. The berthing safety requirements are practical and urgent issues influencing berth planning; however, to the best of our knowledge, few academic studies or commercial planning software packages have addressed berth allocation problems that incorporate all of these realistic factors. Because of the nature and the urgency of the problem, the Port of Xiamen decided to utilize intelligent operational planning technology to alleviate the bottlenecks in berthing, vessel handling, and berthing safety. Our team has worked toward developing an intelligent berth planning system for XHCT.

Like the general berth planning problems investigated in other studies, the daily berth planning problem at XHCT aims to optimize berth allocation. Mathematical programming models are commonly used for berth allocation problems to describe the objective and complex relationships between various decisions, and optimization algorithms are designed to solve the problem. The particularity of the XHCT daily berth planning problem requires further investigation on both models and algorithms. In the system development, we develop a mathematical programming-driven methodological framework for the XHCT daily berth planning problem based on the general research method of mathematical programming models and optimization algorithms. We formulate a 0-1 integer linear programming model to integrate decision problems with other related factors. We also develop a highly efficient heuristic algorithm to work out the daily berth plan. The model and algorithm are validated by numerical experiments, and we compare the efficiency of the algorithm with that of manual planning. The mathematical programming-driven methodological framework is then used as the core of the system development, and the berth planning system becomes a successful case of turning theoretical operations research to real-world operations management practice.

The remainder of this paper is organized as follows. Related works are classified and analyzed in the next section. The section titled “The Daily Berth Planning Problem” states XHCT’s berth allocation problem by identifying the challenges, specific characteristics, vessels’ berthing procedures, and main decision problems. The section titled “The Berth Planning System” proposes the system framework and mathematical programming-driven methodological framework, in which the models and algorithms are embedded in the system. “Impact and Benefits” lists the practical benefits of the system for the XHCT. “Future Research and Development” is discussed at the end of the paper.

Related Works

Container terminal operation is a systematic planning process that involves various decisions. According to a

survey conducted by Rashidi and Tsang (2013), the berth is the most important resource because it directly affects the capacity of the terminal, and berth allocation decisions influence the turnaround time of vessels and the throughput rate of the port. Berth allocation is generally an operational-level decision aimed at the assignment of quay space and service time to vessels that are to be unloaded and loaded at a terminal (Bierwirth and Meisel 2010). Operational challenges such as the tide-dependent accessibility of ports and crane operation ranges have recently been considered in the berth allocation problem (Bierwirth and Meisel 2015). To assess the current research progress and to obtain useful references for our study, we first review the categories of container terminal operations and then discuss the work related to the daily berth planning of XHCT in terms of berth allocation, quay crane assignment, fairway traffic flow, and berthing safety. We then summarize the reviewed literature and identify any research gaps in the daily berth planning problem.

Terminal operation decision-making problems include mainly the berth allocation, stowage planning, quay crane assignment/scheduling, cargo storage and stocking, transport optimization, and gate operation (Zhou et al. 2021). Berth allocation directly determines the service operations management of container vessels and aims to maximize berth resources with high levels of utilization (Martin-Idrissi et al. 2022). Quay crane assignment and scheduling is a problem closely related to berth allocation. This problem optimizes the quay operation to improve its efficiency and thus the utilization of quayside resources, including quay cranes and berths (Chargui et al. 2023). The containers handled by quay cranes should be transported by efficient container transport. Container transport optimization can be categorized into internal and hinterland transportation. The internal transportation transports containers between the quay side and yards and ensures the continuous and efficient operation of the quay side (Roy et al. 2022). The hinterland transportation transports inbound and outbound containers between the container port and customer points in the hinterland (Pourmohammad-Zia et al. 2023), and the gate operation is also a problem for the management of hinterland transportation (Jin et al. 2023). The yard in a container terminal serves as a temporary storage area for containers, and the yard operations consist mainly of yard crane operation and the associated storage space allocation decisions (Wang et al. 2022, Vallada et al. 2023). Of the various container decision problems, the quay side operations, including berth allocation and quay crane assignment/scheduling, are the most important in container yards because quay side resources are limited (Zhen et al. 2022, Abou Kasm et al. 2023). Current research of container terminal operations highlights the importance of quay side operations. The efficient use of terminal

resources is dependent mainly on berth allocation and quay crane operations (Rodrigues and Agra 2022), which is in line with XHCT's aim to improve terminal efficiency. We identify the research directions and gaps by examining the berth planning details and reviewing the related studies.

The decisions of berth allocation and quay crane assignment are interrelated. The workload of quay cranes can influence the berthing time of vessels, whereas the berth allocation considers and defines the available quay cranes for vessels (Zhen et al. 2021). Recent research attempts to integrate the two problems to explore their relationship and consider realistic factors (Cheimanoff et al. 2022). The factors include the impact of maintenance activities (Zheng et al. 2019), quay crane operating efficiency (He et al. 2021), dynamic crane allocations (Abou Kasm et al. 2020), and feeder arrival (Jia et al. 2020a).

In the decision problem of berth allocation, decisions can be classified as long term, midterm, and short term, depending on the makespan of berth plans. Berth allocation is also related to midterm and long-term planning issues, such as the laycan allocation problem (Bouzekri et al. 2021), the yard allocation problem that considers transshipment and the position of import/export blocks (Liu 2020), berth allocation, which considers line carrier clusters (Zheng et al. 2021), and the robustness of weekly planning (Iris and Lam 2019). Midterm and long-term planning define the preferred berthing positions and berthing time windows of specific routes in advance to improve the service level, which can influence daily berth planning decisions.

The fairway connects berths and outer sea areas through a channel. The fairway sailing condition determines whether a vessel can sail in the fairway. Traffic flow is a major factor related to daily berth planning and also determines whether a vessel can sail in the fairway. The influencing factors can be divided into the control and restriction of fairway traffic flows and the impact of tidal change on vessels. In general, a fairway can operate in either a one-way or two-way mode, depending on the sailing condition, which includes fairway width, water depth, and regulations. If a fairway is too narrow for vessels to sail in parallel, then the fairway must be operated in the one-way mode. Several studies investigate fairway traffic scheduling and control problems and consider restricted channels (Li et al. 2021), anchorage area utilization (Jia et al. 2019), pilot scheduling (Jia et al. 2020b), and the influence of tides (Li and Jia 2019). Channel restriction is closely related to berth allocation in channel-constrained ports (Corry and Bierwirth 2019). Tidal change has a significant influence on the water depth of the fairway. To ensure sailing safety, the under-keel clearance restrictions should be strictly followed to avoid the risk of grounding. Vessels with a deep draft can sail in the fairway only at high tide. This restriction

can be depicted in terms of the feasible berthing and departing time windows of vessels (Zhen et al. 2017). In our paper, we further investigate the influence of fairway traffic control and water depth based on the context of the Dongdu Fairway, which is the only fairway connecting XHCT with the sea.

Berthing safety is the main concern of XHCT. The berthing safety issues and factors include the water depth of the fairway and berth, along with the strict berthing safety regulations regarding bollards and fenders.

Like the concerns about the fairway water depth, changes in the in-berth water depth can also cause the grounding of vessels at low tide, and in-berth under-keel clearance should also be strictly observed. The in-berth water depth limits the berthing time windows of vessels (Qin et al. 2016). If sufficient quay cranes are assigned to a vessel, its container-handling time can be reduced so that the vessel can leave the berth before low tide (Lalla-Ruiz et al. 2016, Malekhamadi et al. 2020).

Waves and wind can push in-berth vessels, leading to the risk of them colliding with the quay. Bollards and fenders are fixed immobile assets that are part of the quay infrastructure and used for in-berth collision prevention (Carbonari et al. 2019). Mooring lines are attached to the bollards as temporary anchors for the vessels, and fenders are used to buffer any collision between the vessels and the quay. Various sizes of fenders can accommodate the berthing requirements of different vessels. Most of the research considering bollards and fenders takes an engineering perspective, whereas few studies consider operations-related problems such as bollard assignment or the influence of fenders from an operations planning perspective. To ensure berthing safety, the bollards and fenders should be further investigated in research into port operations.

Based on our literature review, we propose that research into daily berth planning for XHCT should address the following aspects:

1. To generalize berth allocation to enable practical application, integrated research on multiple related decision problems should be conducted. However, few studies address all of the XHCT's particularities and concerns.

2. Although water depth has been discussed in some studies, berthing safety issues in terms of the resource allocation for bollards and fenders still need further exploration.

Very few real case studies have been conducted to assess the practical implementation of a berth allocation model. Ding et al. (2016) introduced a project for the Port of Shanghai, and similarly to our study, they also investigated the daily berth planning problem. Although their research provides some empirical references, further work is needed in terms of the specific requirements and unique features of the Port of Xiamen.

The Daily Berth Planning Problem

XHCT is the largest container terminal in the Port of Xiamen. After its multiphase construction and extension, XHCT has a 2,486-meter shoreline with 12 berths, 22 quay cranes for the handling of container vessels, and a 620,000-square-meter yard with 48 cranes for handling containers (see Figure 2). The shoreline of XHCT follows a north-south direction. According to the daily operational data for July and August 2021, XHCT handles the berthing needs of approximately 22.4 vessels a day on average, and the length of the vessels varies from less than 70 meters to more than 260 meters. These two months constitute a busy period for the terminal, with many vessels to be handled. Most of the vessels berthing at XHCT are domestic trade vessels or vessels on off-shore routes, including routes to Korea, Japan, and Southeast Asia. Vessels longer than 200 meters make up 20% of all vessels berthing at XHCT and contribute more than 30% of the container-handling volume of the terminal. Small feeder vessels less than 160 meters long account for approximately 40% to 50% of the berthing needs, and the 160- to 200-meter vessels account for approximately 30% to 40% of the berthing needs. Small feeder vessels give rise to more frequent berthing operations. The allocation of berths at XHCT is thus more scattered and complex compared with terminals serving large vessels.

The future development plan of the Port of Xiamen requires XHCT to have higher berth availability, utilization, and service capability. This can be interpreted as serving more vessels and handling more throughput with limited equipment and resources. We assess these challenges by identifying the terminal's infrastructure

and characteristics, and we analyze the operational challenges emerging in recent years.

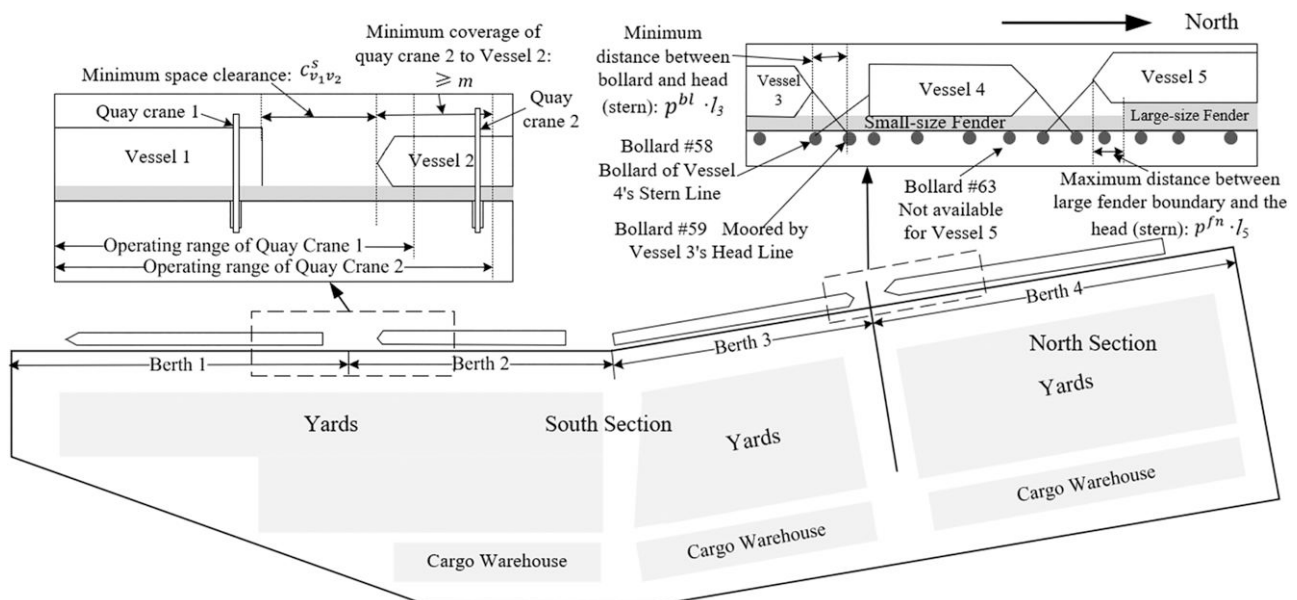
The Challenges of XHCT's Berth Planning

XHCT has specific characteristics in terms of status and berthing conditions because of its multiphase construction and resource integration, which make berth planning more complex. In addition, the requirements from terminal operators, especially the concern of berthing safety, further complicate the problem. The specific characteristics and requirements make the theoretical studies and practices at other terminals hardly applicable at XHCT. The unique berth planning characteristics include the following aspects:

1. The shoreline is divided into two sections, south and north (see Figure 2), which operate independently but plan jointly. The quay cranes' rails end at the section boundary, which limits the moving range of the quay cranes to within one of the two sections. The berthing positions of vessels cannot overlap the boundary between the south and north sections because the separation of the rails prevents quay cranes from moving to the boundary position. Despite the independent operations, the clearance distance between vessels at berths on both sides of the boundary needs to be taken into consideration. A corner divides the south section into two subsections. Some quay cranes can move between the two subsections freely, but the berthing position of vessels cannot overlap this corner.

2. The capacity and functions of berths vary. Although berth allocation is generally a continuous problem, the water depth, shoreline boundary, and throughput of quay cranes lead to different berth capacity limits. The

Figure 2. A Scratch Map of XHCT and the Examples for Berthing Requirement



datum water depth of berths at XHCT ranges from -8.6 meters to -14.2 meters and is influenced by tidal changes. Large vessels can only be assigned to specific deep-water berths, whereas the assignment and operation of small vessels are more flexible. The efficiency of the quay cranes also varies. Berths with twin-lift quay cranes have a higher container-handling capability than those with older and inefficient quay cranes.

3. Fairway traffic control is another factor influencing berth planning. Sailing conditions, including the width and depth of the fairway, can influence vessels' entering and leaving. Dongdu Fairway is the only way for inbound and outbound traffic flow at XHCT. The fairway usually operates in a two-way mode. Because of its width and depth limitations, Dongdu Fairway has to operate in one-way or dedicated mode for the sailing of oversized vessels, depending on their type and length. Tidal changes also directly influence water depth and limit the sailing time windows.

4. The complex sailing and berthing conditions make berthing safety an important and complicated problem that should be given full consideration. The in-berth vessels should be moored to bollards and pressed against fenders. Bollards should be dedicated to large feeders and vessels for mooring safety. Fenders should be considered in berth planning to prevent vessels from leaning against different-sized fenders because of swing. The berthing safety concerns can generally be addressed in hierarchical order intuitively, and the safety concerns can be considered after solving a general berth planning problem. In practice, a general berth planning problem tends to minimize the space clearance between vessels to achieve higher berth utilization. But optimized berth plans without the consideration

of safety requirements may be infeasible because of insufficient available bollards or an inappropriate berthing position that leans against different-sized fenders. Although berth plans can be adjusted to accommodate safety concerns, sometimes the adjustment may become extremely complicated with many vessels reallocated, and a simple adjustment may reduce efficiency. Thus, berthing safety concerns must be integrated into the decision process to ensure that the berth plan is practical and complies with safety requirements.

The berth planning for XHCT is therefore a unique and more complex problem than those addressed in previous studies. To deal with the complexity, all operating procedures and aspects related to the problem must be studied carefully. In the following problem description, we first summarize the berthing procedures and main considerations in berth planning and then conclude with the main decisions on the berth planning problem.

The Vessel Berthing Procedure

Berth planning should be worked out and implemented based on vessels' sailing and berthing operations. Vessels sailing to XHCT should follow the instructions of the port authority and complete the berthing procedures on time. Figure 3 shows a general berthing procedure and key considerations. The regulations, restrictions, and logical relationships in berth planning can be depicted through a summary of the whole berthing procedure. This involves several critical time points, which are explained along with their corresponding abbreviations in Table 1.

Figure 3. Vessel's Berthing Procedure and Relevant Requirements

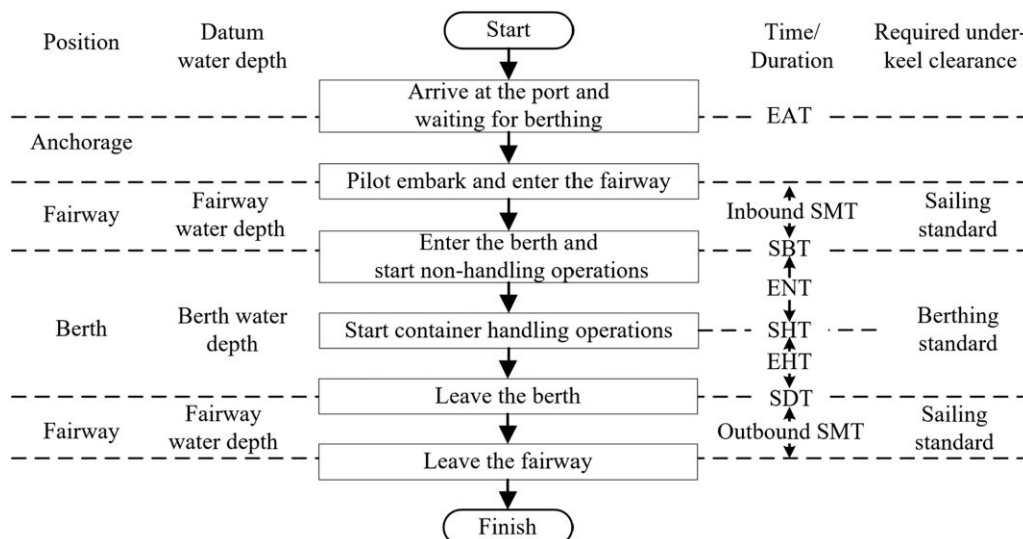


Table 1. Table of Abbreviations of Critical Time Points

Abbreviation	Explanation
EAT	Estimated arrival time
EHT	Estimated container-handling time
ENT	Estimated time for non-handling operations before container handling
SBT	Scheduled berthing time
SDT	Scheduled departure time
SHT	Scheduled start time of handling
SMT	Sailing and maneuvering time

Arriving at the Port. Vessels arriving at XHCT are first guided to the anchorage to wait for berthing. The shipping agents provide the estimated arrival time (EAT) of vessels and update actual EATs according to their real-time positions.

Entering and Leaving the Berth. All vessels entering and leaving the terminal must sail through the Dongdu Fairway. The water depth of the fairway maintains a datum of 11.6 meters and is affected by tidal changes. To ensure safety, the under-keel clearance of vessels sailing in the fairway should be maintained at a minimum standard for sailing. Vessels with deeper drafts may need to wait for high tide to go through the fairway. The estimated total time for sailing between the anchorage and the berth consists of in-fairway sailing time and maneuvering time. During the in-fairway sailing time, the inbound vessel sails in the fairway from the anchorage to the assigned berth, and the outbound vessel sails in the opposite direction. The maneuvering time to enter the berth consists of the maneuver operation, in which a tug tows the vessel between the fairway and its berthing position, a possible 180-degree turn, and other berthing preparations, such as mooring and quay crane moving. For an inbound vessel, when the vessel is finally berthed after sailing and maneuvering, the time point is defined as the scheduled berthing time (SBT). An inbound vessel should enter the fairway in advance to ensure sufficient time for sailing and maneuvering before the SBT. Outbound vessels should leave the berth at the scheduled departure time (SDT) and complete the maneuver operations and in-fairway sailing. The outbound vessels usually have higher maneuvering and sailing priority over the inbound vessels, and both the maneuvering time and in-fairway sailing time are shorter than inbound vessels. When the planning horizon is discretized into timesteps, the estimated timesteps for in-fairway sailing must take a greater number to make sure the duration of timesteps is enough for sailing. If the total estimated in-fairway sailing and maneuvering time is not greater than the duration of timesteps for sailing, then the maneuvering time can be included in the in-fairway sailing time and need not be estimated separately. For the case of XHCT, the

sailing time and maneuvering time used in berth planning are estimated as fixed parameters of timesteps. These estimated timesteps should satisfy the sailing and maneuvering requirements of most vessels.

During the maneuver operation and berthing, vessels are influenced by tidal currents and face the potential risk of losing control. In addition, inbound vessels should be more alert to the risk of colliding with the quay and other vessels while maneuvering toward the berth. To eliminate these risks, it is recommended for a vessel to head against the tide during the maneuver process before mooring and berthing, and a 180-degree turn in maneuver operation is consequently performed by a vessel whose direction follows along with the tide. The outbound vessel's maneuver operation is relatively easier to control and has lower risk than that of an inbound vessel. During the outbound maneuver operation, all outbound vessels can head toward the outbound direction directly, and those vessels that have not made a 180-degree turn before berthing should make this turn as part of the outbound maneuver process. The requirement of vessels' direction for maneuvering and berthing is indicated by the bow's direction in the berth plan of XHCT. The bow of a vessel should point against the tide at its SBT. The bow should point south when entering the berth if the tide is rising and vice versa if the tide is ebbing. The 180-degree turn should be made before berthing if the tide is rising.

The fairway is too narrow for oversized vessels to sail together with other vessels. To ensure sailing safety, temporary closure of the fairway is required to restrict the sailing of other vessels. The temporary closure may restrict the sailing in the opposite direction of an oversized vessel, or the sailing of all the other vessels, depending on the type and length of the oversized vessel. The time for temporary closure depends on the time of oversized vessels passing through the fairway. The vessels affected by the temporary closure must wait until the fairway reopens.

According to the regulations of XHCT, oversized vessels are classified into two classes according to vessel length and width. The general oversized vessels include super Panamax container vessels and ultra-large container vessels. The sailing of the general oversized vessels

requires that the fairway operates in one-way mode, and a temporary closure is imposed on vessels to sail in the opposite direction. The super oversized vessels are usually bigger and longer than the general oversized vessels and require more strict sailing conditions. For the sailing of super oversized vessels, the fairway should be closed to all the other vessels. The temporary closure time of the fairway should be no less than the estimated sailing time for both oversized inbound and outbound vessels. The temporary closure order can be lifted during the maneuvering time if the maneuvering time is considered separately from the in-fairway sailing time. This is because a vessel does not travel along the center line of the fairway during the maneuver operation, and the maneuvering vessel has little influence on other in-fairway vessels.

In-Berth Operations. In-berth operations refer to the activities that should be completed when the vessel is berthing and consist mainly of container handling. Other activities that take place during berthing are classified as non-handling operations. The relevant time points of in-berth operations include the SBT, the scheduled start time of handling (SHT), and the SDT. The time durations corresponding to container handling and non-handling operations are the estimated container-handling time (EHT) and the estimated time for non-handling operations before container handling (ENT), respectively.

The main in-berth operation is loading and unloading containers. The EHT is the estimation of the laytime, that is, the time for container loading and unloading operations. Two main inputs are generally required to estimate EHT: the loading and unloading quantity and the quay cranes allocated to the vessel. The planned loading and unloading quantities are informed by shipping agents in advance. The quay crane assignment is another decision in daily berth planning, which we will describe later.

Non-handling activities may take place when berthing. Some activities can be performed simultaneously with container handling, such as scheduled crew changeovers and resource supplies such as water and fuel. These operations usually have little influence on container handling or EHT. However, some specific operations like customs inspection and quarantines must be performed before the start of container handling because of port authority regulations. These can delay the beginning of the container-handling process. The duration of the delayed time can be summarized as ENT, which can be estimated according to the related operational plans.

To reduce berthing time and improve berth utilization, container handling should start as soon as possible. The SHT can thus be calculated by adding ENT to SBT. After container handling, vessels should leave the berth immediately. The time for vessels leaving the

berth is represented by SDT. The difference between SDT and SHT should be no less than the EHT to ensure sufficient time for operations. Sometimes vessels need to wait for suitable departure conditions, for example, the rising tide or the reopening of the fairway, and the SDT will then be substantially delayed.

The Decision Problems of Berth Planning

Berth planning is a comprehensive decision-making process that involves the decision problems of berthing position, operation time, quay crane assignment, and decisions related to berthing safety. We propose a 0-1 integer programming model in Appendix A to express the decision problem and the internal relationships of the different decisions in detail. The decision problem, objective, and basic principles presented in the mathematical programming model all provide the basis for the decision-making process when developing the system.

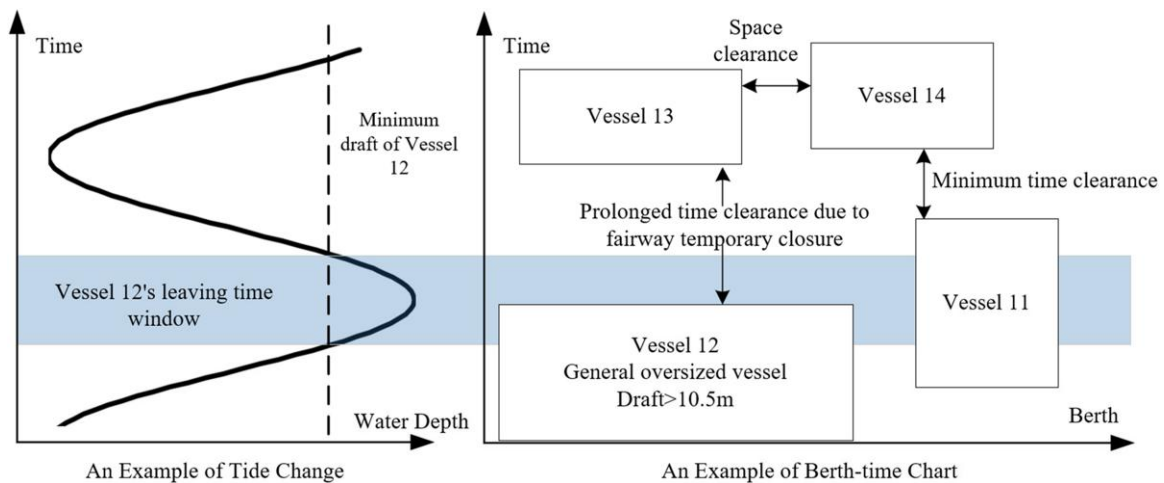
Planning Horizon. XHCT and other container terminals in the Port of Xiamen select 24 hours as the planning horizon for daily berth planning and other operational activities. Because the uncertainty is not characterized in the proposed system, setting a relatively short planning period can help to reduce the uncertainty of the EAT, the loading and unloading quantities, and the efficiency of terminal operations. To simplify the decision-making procedures, the planning horizon is discretized into timesteps in half an hour.

Berthing Position of Vessels. The berthing position is a major decision in the berth allocation problem. A vessel's berthing position can be expressed by the position of bow and stern on the shoreline. In the berth planning of XHCT, the southernmost and northernmost positions are used to indicate vessels' berthing positions. The main factors to consider in a generalized berth allocation problem include water depth and space clearance.

Water Depth. All in-berth vessels should keep a minimum under-keel clearance when berthing. A vessel can be allocated to a berth only when the water depth of the berthing position is greater than the sum of the vessel's draft and its minimum under-keel clearance during its in-berth time. The required under-keel clearance during berthing is usually shallower than that during sailing.

Space Clearance. To prevent the collision of in-berth vessels and ensure sufficient space for vessels entering and leaving the berth, a clearance distance should be kept between two adjacent vessels (see Figures 2 and 4). A minimum space clearance distance is required for all vessels. Additional space clearance should be reserved for large vessels, which can be calculated using a specific proportion of the vessel's length. Thus, the space

Figure 4. (Color online) An Example of Berth-Time Chart and the Influence of Tide



clearance distance between two adjacent vessels should be the maximum of three quantities: the minimum space clearance distance, a specific proportion of the length of the southern vessel, and a specific proportion of the length of the northern vessel.

Berthing Time of Vessels. For the vessels' berthing procedures, the SBT and SDT are the critical time decisions in berth planning. The EAT, EHT, and ENT are the necessary time durations for these decisions. The SBT and SDT decisions should consider the tide and any fairway temporary closure.

Time Clearance. Time clearance is required between a vessel and other vessels that berth at the same position. The purpose of time clearance is to allow time for vessels' maneuvering operations to enter and leave the berth. The difference between the SBT of a vessel and the SDT of other vessels berthed at the same position should be greater than the minimum time clearance requirement, which depends on the maneuvering time.

Fairway Temporary Closure. Fairway temporary closure restricts vessels' sailing and thus influences the SBT and STD. The SBT and SDT will be delayed until the fairway is reopened. Figure 4 gives an example of time clearance. In this figure, the planning horizon is discretized into timesteps of half an hour. The sailing times for both inbound and outbound vessels are to be estimated as two timesteps. The inbound maneuvering time takes one timestep, whereas the outbound time need not be separately estimated. Vessels 14 and 11 keep a minimum time clearance of three timesteps, that is, $SBT_{14} = SDT_{11} + 3$. Vessel 13's SBT is delayed by the temporary closure, which is imposed by the leaving of Vessel 12. Vessel 12's SDT is SDT_{12} . Vessel 12 sails in the fairway for an hour and leaves the fairway at $SDT_{12} + 2$.

At the time that Vessel 12 leaves the fairway, Vessel 13 can enter the fairway. Thus, $SBT_{13} = SDT_{12} + 2 + 2 + 1 = SDT_{12} + 5$, and Vessels 13 and 12 have a prolonged time clearance of 2.5 hours.

Quay Crane Assignment. Quay cranes are the main equipment used for handling containers and are deployed along the quay side. In general, the quay crane assignment assigns quay cranes to vessels for container handling. Quay crane assignment is related to the spatial and temporal allocation of berths. In terms of spatial factors, quay crane assignment is dependent on the berthing position of vessels because the operating range of quay cranes is limited by rails and electrical cables. The quay cranes are deployed along the shoreline in a fixed sequence. They cannot pass each other when moving, so the moving range is also restricted by the position of adjacent quay cranes. In terms of temporal factors, quay crane assignment can influence the berthing time of vessels. By assigning more quay cranes, a vessel's container-handling process can be finished faster, and the in-berth time is thus significantly reduced. In addition to the assignment among vessels, quay crane assignment determines details of the quay crane operations, including the actual working bays and container-handling sequence. These decisions track quay crane movement precisely and instruct the detail quay crane operations. The stowage plan should be known in advance to provide the container-loading positions and determine container-handling sequences.

In the daily planning problem for XHCT, the quay crane assignment problem is divided into two parts, and a two-step decision mode is formulated. The quay crane assignment, which assigns quay cranes to different vessels at different timesteps, is integrated as a part of the berth planning and worked out first. The detailed quay crane operation and scheduling decisions are

then worked out after knowing the berth plan and stowage plan. The purpose of the two-step mode is to balance the requirements of reasonable berth planning and a frequently changing stowage plan. The berth plan should be implemented as soon as it is issued and should avoid repeated changes because the berth plan determines other operational plans of relevant organizations, such as the port authority and shipping companies. An unexpected change of berth plan after issuing would incur extra costs and disrupt other operational plans. However, the stowage plan may be changed many times until berthing because the list of export containers to be loaded onto a vessel may change because of late delivery, custom detention, or other unexpected events. Changes in stowage plans affect the handling volumes and the berthing times of vessels, which can consequently change the optimal berth plan along with the quay crane assignment. Although embedding quay crane operation decisions into berth planning may better improve berth utilization, the consequent berth changes may make this impractical for the terminal and other relevant organizations. Therefore, the two-step decision mode of berth planning and quay crane operation has been applied consistently. In addition, XHCT requires the berthing safety to be the most important and urgent consideration of the berth planning system. If the detailed quay crane operation decisions were included in the system, the whole berth planning problem would become more complicated, which could reduce decision-making efficiency and prolong the system development process.

Some empirically based requirements describing detailed quay crane operation characteristics are applied in the daily berth planning of XHCT. The operating range requirement determines whether a quay crane can be assigned to a vessel with respect to the quay crane operating range and the vessel's berthing position. The operating range of the quay crane should cover the vessel to at least the minimum length required so that a quay crane can handle several bays of containers for the vessel (see Figure 2). The targeted hourly efficiency level is also a main reference factor for quay crane assignment. Long-term and midterm berth planning define the preferred berthing positions and time windows of specific routes in advance and set minimum targeted hourly efficiency to ensure highly efficient operations of these routes. The targeted hourly efficiency is the implementation of long-term and midterm planning requirements into daily berth planning and requires enough quay cranes and other resources to be assigned to specific vessels. The targeted hourly efficiency in daily berth planning should not only satisfy the target and berthing time windows defined in long-term and midterm planning but also fit into the specific situations on the planning days.

Decisions Related to Berthing Safety. The decisions related to berthing safety requirements include the decision of bollard assignment and the impact of fenders. Bollards and fenders are fixed, immobile assets that are part of the quay infrastructure. Both factors can influence the decision mechanism of berth allocation.

All in-berth vessels must be moored to the bollards at the quay side to prevent any unexpected movement caused by tide or wind changes. Two critical bollards, namely the northernmost bollard and the southernmost bollard, are determined in berth plans. The northernmost and southernmost bollards are used to moor the bow line and stern line, and bollards between these two are used for the mooring of other lines, like breast lines and spring lines. The upper-right section of Figure 2 shows an example of bollard assignment. The main concern of bollard assignment is how to efficiently assign mooring bollards to different vessels to meet the safety requirements. According to the port safety regulations, the bollards should be allocated according to the following rules:

1. The northernmost and southernmost bollards should be located within the space clearance between two adjacent vessels or located at the exact position of the bow or stern of the adjacent vessel. A bollard assignment plan that leads to the mooring line overlapping the adjacent vessel must be prohibited to prevent any friction between mooring lines and other vessels.
2. To ensure mooring safety, the angles between mooring lines and the shoreline should be controlled within the appropriate range. Such requirements can be interpreted as the minimum necessary distance between the selected bollards and the bow or stern of the vessel. The minimum necessary distance can be calculated as a specific proportion of the vessel's length, according to the experience of XHCT's daily operation.
3. To ensure the tightness of the mooring, a bollard should be dedicated to a vessel's head line or stern line. Sometimes the available bollards may be insufficient, and two adjacent vessels are allowed to share a bollard if both of the two vessels are smaller than a specific standard.

Most previous studies of berth allocation do not consider the impact of bollard assignment on berth planning. The berthing positions of vessels must be adjusted to suit the bollard assignment requirement. It seems to be easy to implement a fine berthing position adjustment by a few meters to meet the requirement. However, if many vessels are waiting for berthing, the space clearance approaches the minimum limit with insufficient available bollards between vessels. Adjusting only one or two vessels' berthing positions may cause wide-ranging implications of insufficient space clearance or available bollards for other vessels and lead to the overall change of berth plan. Thus, bollard

assignment is necessary to implement in berth planning despite its complexity.

To adapt to the berthing needs of different vessels, fenders with different sizes and functions are used in different berths. The quay of XHCT equips two types of fenders, namely large fenders and small fenders. Large fenders are usually deployed at deep-water berths to accommodate the berthing requirement of large vessels. Small fenders can be used only for the buffering of small vessels, so only berths of shallow water depths can use this type of fender. The berth planning should consider the performance and applicability of fenders and assign vessels to berths with suitable fenders. The berthing position of a vessel can overlap different types of fenders in a continuous berth allocation problem, which can lead to safety issues about berth allocation. The relevant rules of fenders are illustrated in Figure 2. If a vessel's berthing position is allocated mainly to the berths with small fenders (Vessel 6), then the bow and the stern of the vessel cannot be allocated to positions with large fenders. If a vessel is allocated mainly to berths with large fenders (Vessel 7), then it is allowed to be allocated to a berthing position in which a short part of the vessel's hull is berthed at positions with small fenders. The length of the part of the vessel's hull berthed at positions with small fenders should then not exceed a specific proportion of the vessel's length.

The Berth Planning System

XHCT used to make berth plans manually and encountered problems such as inefficiency and low berth utilization. The development of the berth planning system is a part of intelligent operations development to break through bottlenecks and better cooperate with other processes and systems. To develop the berth planning system, we first analyze the process of manual berth planning and data exchange between systems to find the general functions and features that berth planning should realize. The mathematical programming-driven methodological framework constitutes the fundamental component of the berth planning system, and the major effort we put in for this method is in its development and implementation.

The Manual Berth Planning Process

The manual planning process at XHCT involves various considerations, settings, and procedures for berth allocation, which is used as the basis for further system development. According to the daily work procedure of XHCT, the daily berth plan works out the schedule for vessel berthing from the upcoming 12 p.m. on one day until 12 p.m. the next day. The daily berth planning process starts at 8 a.m. every day to ensure that the latest data are acquired and must be completed

and submitted for review and discussion by 10 a.m. to ensure that the plan can be implemented before 12 p.m., the beginning of the upcoming planning horizon. These tight time limits make planning a challenging task that relies on the knowledge, intelligence, and hard work of three experienced planners. If a planner is absent, the berth planning for the other two on-duty planners is more difficult on that day. The general manual berth planning procedures can be divided into three parts: data collection, preliminary planning, and detailed planning.

Data Collection. Data collection is the preparation work that should be done before the preliminary berth planning process, which starts at 8 a.m. every day. There are three types of data that need to be collected, namely the status of vessels, maintenance and temporary incidents, and vessels' arriving notices.

Vessel status includes the status of already berthed vessels and the status of vessels waiting to berth. The status of already berthed vessels collects mainly the SDTs, berthing positions, and bollard assignments. The status can be collected and updated by monitoring the real-time loading/unloading progress. The berthing positions of in-berth vessels are difficult to shift to another position in practice, so the operations of already berthed vessels should continue into the upcoming planning period at the berths occupied previously. Therefore, the berth plan of arriving vessels should accommodate the berth occupancy of already berthed vessels.

Maintenance and temporary incidents may block the use of berths, equipment, and fairways. Such incidents can be foreseen before berth planning and should therefore be taken into account to minimize the influence on port operations.

Vessels' arriving notices are informed by shipping agents. The agents send emails to the planners to provide the arriving vessels' information for berth planning, including voyages, EAT, draft, and loading/unloading volumes. In manual planning, the planners have to repeatedly confirm the information to shipping agents and transform it into standardized data for reference.

The Berth Planning Procedure. After acquiring the necessary data and information, the berth planning process begins. In traditional manual planning, the plan is developed by the planners according to their experience and calculations. In addition to the operational decisions such as berthing position and time decisions, there are many complex strategic and tactical problems to deal with, such as the berthing priority of vessels, the relationship between daily berth planning and midterm planning, and the influence of other incidents. Manual berth planning is thus divided into the

two steps of preliminary planning and detailed planning to reduce complexity.

The preliminary planning aims at solving the main strategic and tactical problems. The planners determine which vessels are berthing in the planning period according to the berthing priority. Then, they draw on their experience to determine the approximate position according to the estimation of the berthing capabilities and the berthing time according to loading/unloading volume. These decisions are expressed in terms of the assignment of quay cranes and targeted hourly efficiency, which serve as the link between different levels of problems. Once the quay crane assignment is worked out, the approximate berthing position can be determined by the operating range of the quay cranes. The targeted hourly efficiency of vessels is correlated with the number and efficiency of assigned quay cranes, and the laytime of vessels can then be derived.

After the preliminary planning, the planners work on the detailed planning, which is the most time-consuming work of the process. Decisions regarding berthing position, operation time, and bollard assignment should be worked out in this stage according to the aforementioned requirements. In manual planning, the berthing time is typically delayed to avoid the influence of tide and temporary closure. The planners create rules to allocate key bollards to vessels. However, sometimes the delays and rules cannot efficiently deal with the changeable berthing requirements. To improve the berth utilization in the detailed planning, the preliminary plans need to be changed repeatedly to try more plans and find the best one. In general, if more than 25 vessels are waiting to berth, most of the time and effort in the planning process is spent on changing and reworking the preliminary plans.

By repeating this process many times, the planners work out a complete berth plan to submit for revision. The managers check whether the plan meets the operation and safety requirements and provide feedback for correction. The revised plan is then discussed and

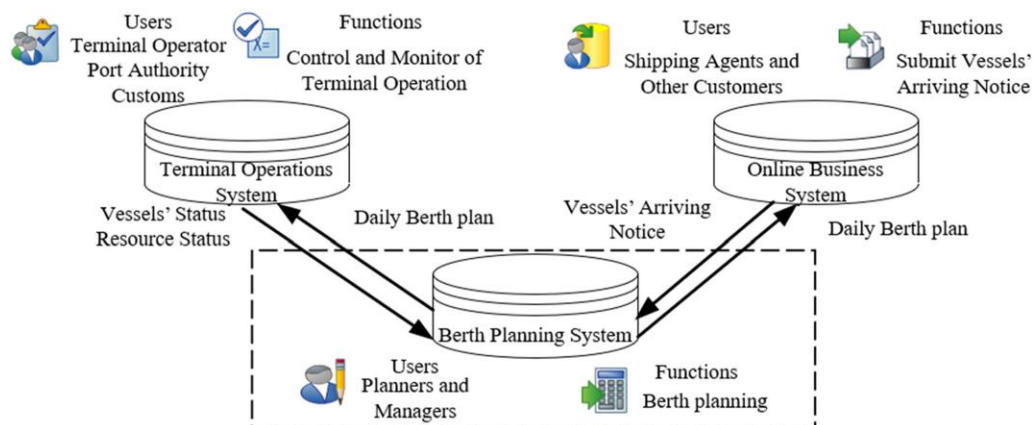
issued in the daily work meeting starting at 10 a.m. every day. After issuing the plan, the planners monitor the implementation of the berth plan and change it if necessary. The monitoring process usually requires less work than the planning, leaving some planners idle. Manual planning is indeed time-consuming and labor-intensive work. It is difficult for planners to try more potential plans and revise them in the limited time frame. The manual planning approach also requires a high level of human resource allocation. It usually takes one to two years of training and practice for a planner to gain the basic qualifications.

Data Exchange Between Systems

XHCT and other terminals of the Port of Xiamen have developed their own information and management systems to support the port's operation. The terminal operations system (TOS) controls and monitors the operations of XHCT and other terminals. The online business system provides customer services to shippers, shipping agents, shipping companies, and other logistics companies. These two systems are directly linked to the berth planning system with data and information exchange. We set up a data docking mode for the two systems for data transmission and real-time data collection and exchange. Figure 5 illustrates the internal information exchange between these two systems.

The TOS provides essential data on vessel status and the operational progress to the berth planning system, and the daily berth plan is one of the most important inputs for the TOS. The online business system collects the vessel arrival notices submitted by shipping agents and releases the terminal's operating status, including berth plans, to customers. The information exchange not only provides necessary input data to the berth planning system but also exchanges berth plans as the output to maintain the normal operation of other systems.

Figure 5. (Color online) The Information Exchange Between Systems



Some of the data and specific settings need to be defined by the planners. Therefore, we add an interface to input special requirements before berth plans are made. Planners can define the priority or sequence of vessels waiting to berth so that vessels with a higher priority can enter the berths earlier. Planners can also specify the berth allocation decisions of vessels and add incidents that could result in berth downtime. These special requirements are then further considered in the berth planning process.

The main challenge for data exchange is the interconnections among the existing systems. Informatization is executed in multiple stages, and the interface designs of the different systems vary. The integration of protocols of these systems is challenging and involves many system developers. Data accuracy is also an important consideration in data exchange. The speed of data exchange between systems also influences the accuracy of data and the operations of the terminal. The usability of the interface is another important consideration because this interface enables interactions between planners and the system.

The Decision-Making Process and the Combinational Interface

The decision problem of berth planning is highly complicated because many factors must be considered. The problem and related factors are outlined in Figure 6

in the form of a data structure. We integrate the entire decision process and formulate an integrated berth planning problem with the objective of minimizing the total delay time of SBT to improve berth utilization. The integrated problem optimizes the plan for berth allocation, quay crane assignment, traffic flow, and berthing safety requirements. Based on the berth allocation problem, we develop a mathematical programming-driven methodological framework for the decision-making process and further system development. In the framework, we develop a 0-1 integer linear programming model to characterize the proposed problem, as shown in Appendix A. The 0-1 integer linear programming model is used as the basis for problem-solving and algorithm design, and the basic setting of the algorithm is shown in the subsection “Algorithm Design” and in Appendix B. By developing such a solution methodological framework, the core of the system’s decision-making process is formulated.

After the completion of the process of berth planning, the planners and managers revise the output plan. The system is designed with a combinational interface to show the result and assist in manual revision. The combinational interface proposes berth plans using data tables (see Figure 7) and graphical dynamic berth plan charts (see Figure 8). The graphical dynamic berth plan charts are based on the charts used for the berth plan and allow visual revision. To change the berth plan, the planners can input a specific value into the

Figure 6. (Color online) Data Structure of the System

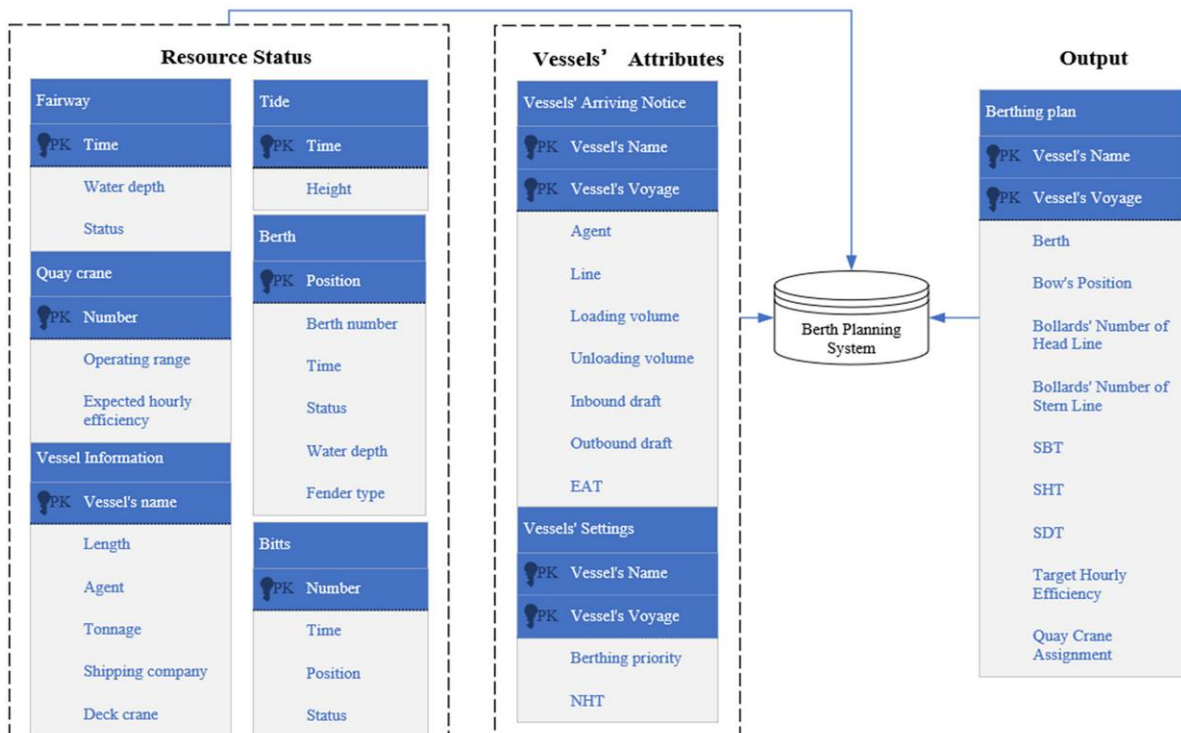


Figure 7. (Color online) Data Table of the System

Lock	Berth No.	Vessel	Voyage	Position (south)	Bollard (south)	Bollard (north)	Length	Hourly efficiency	Unload	Load	EAT	SBT	SHT	SDT
☒	1	16#	LILA BHUM	852S	2328	103	114	135.90	20	71	42	2022-04-05 19:00	2022-04-07 09:30	2022-04-08 09:00
☒	2	15#	HANSA MEERSBURG	0JV8ZW1...	2114	90	104	179.64	50	584	466	2022-04-06 18:00	2022-04-07 08:30	2022-04-08 12:00
☒	3	13#	CAIYUNHE	1803N	1647	64	75	182.87	33	336	555	2022-04-07 01:00	2022-04-07 19:00	2022-04-09 05:00
☒	4	10#	OOCL GENOA	056W	1125	45	59	335.00	60	55	495	2022-04-07 02:00	2022-04-08 08:30	2022-04-08 20:00
☒	5	14#	MAERSK DAVAO	212N	1870	74	89	185.99	20	308	41	2022-04-07 10:00	2022-04-08 13:00	2022-04-09 08:00
☒	6	8#	WAN HAI 103	W391	600	24	32	144.10	30	393	193	2022-04-07 11:00	2022-04-07 23:30	2022-04-08 22:00
☒	7	16#	HALIBUT	213S	2317	103	114	147.82	30	282	141	2022-04-07 14:00	2022-04-08 11:30	2022-04-09 05:00
☒	8	9#	YM MATURITY	080W	781	31	46	299.20	60	367	423	2022-04-07 16:30	2022-04-08 08:30	2022-04-09 05:00
☒	9	12#	HAI BANG DA 338	220407C	456	18	22	59.98	20	95	85	2022-04-07 17:00	2022-04-08 01:00	2022-04-08 11:30
☒	10	15#	STC HAINAN	2209N	2094	88	102	171.99	30	304	256	2022-04-07 17:00	2022-04-08 14:30	2022-04-09 13:00
☒	11	7#	JI HAI ZHI XING	475N	288	11	19	140.00	20	328	0	2022-04-07 21:00	2022-04-08 06:30	2022-04-09 12:00
☒	12	6#	LIAN HE FANG ZHOU	C053	154	5	12	108.80	20	0	147	2022-04-07 22:00	2022-04-08 08:00	2022-04-08 16:00
☒	13	14#	TUO YUAN	C056	1875	75	85	124.00	20	106	30	2022-04-07 23:00	2022-04-07 23:30	2022-04-08 10:30
☐	14	10#	SITC GUANGXI	2206S	1109	45	53	171.99	40	0	210	2022-04-08 01:00	2022-04-08 23:30	2022-04-09 07:00
☐	15	11#	EVER COPE	N009E	1313	52	59	171.90	40	21	293	2022-04-08 09:00	2022-04-08 22:30	2022-04-09 07:00

data table or drag or input a specific value into the dynamic chart. The system checks the revised result automatically and provides error messages using dialogue boxes. After the revision, the system creates the berth plan chart and data spreadsheet for daily work and for the issue of berth plans.

The main challenges in the decision-making process are summarized as follows.

The Solution Complexity of Berth Planning. Berth planning is a complex integrated optimization problem with many real-world factors that must be considered. Few studies have considered complex berthing safety requirements along with the basic decision problem of berth allocation. Finding a highly efficient solution method to solve this problem is the greatest challenge in this process.

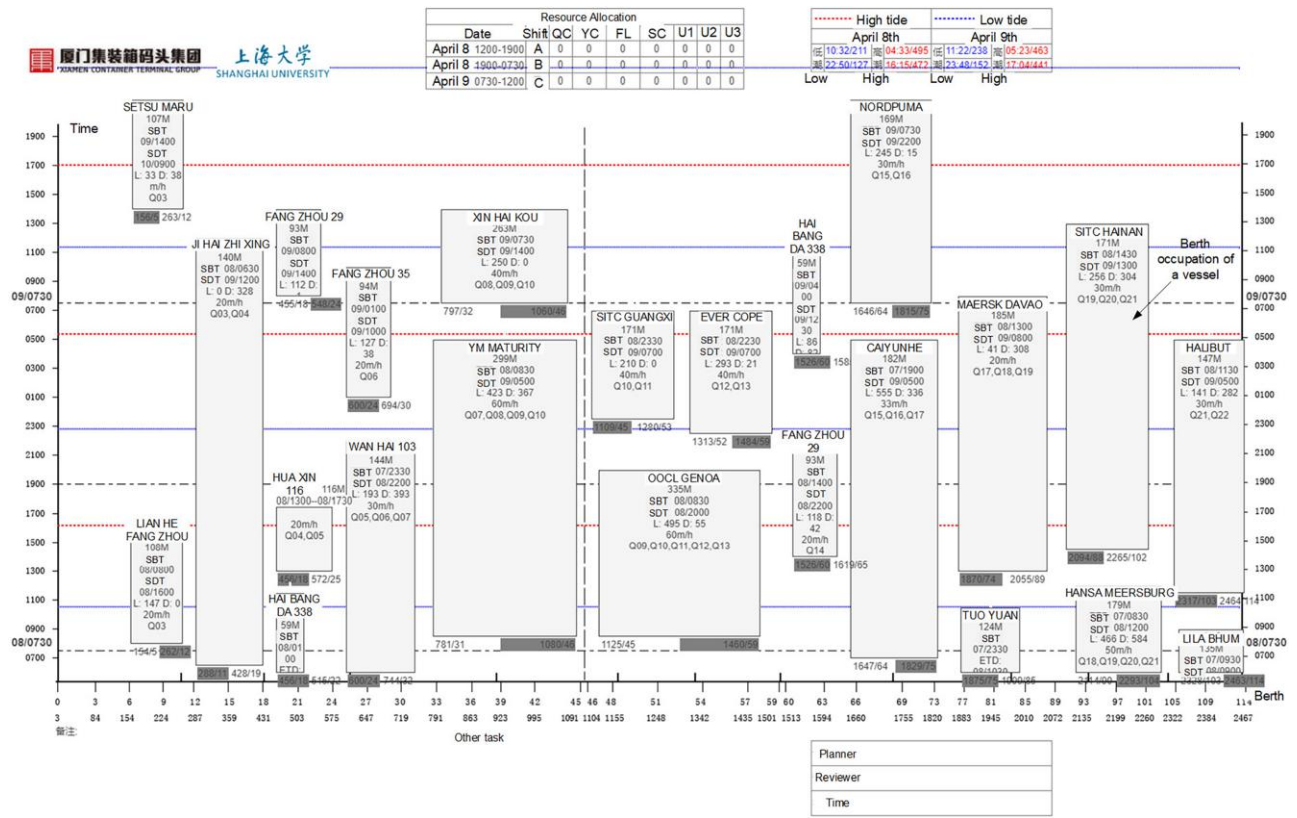
The Development of the Combinational Interface. The combinational interface adopts the tables and charts that have been adopted in manual berth planning; in addition, more embedded functions support tables and charts to form novel human-computer interaction interfaces in berth planning. This interface connects with the database for berth planning so that the system can function seamlessly. The graphical dynamic berth planning chart is the main innovation of the system that helps planners and managers revise and change berth plans more easily. To the best of our knowledge, no such system has been developed yet.

Algorithm Design

In view of the problem complexity raised by the multi-factor decision problem and safety requirements, we develop a two-phase decomposition heuristic algorithm that combines the common characteristics of the berth planning problem, the specifics of XHCT, and the experience and intelligence involved in manual berth planning. The first phase of the decomposition heuristic solves a preliminary berth planning problem based on the activity-based classification method. The second phase is to work out a detailed berth plan. The development of the algorithm follows the basic principles implied by the mathematical programming model of the berth planning problem. The detailed procedure of the algorithm is given in Appendix B.

In the first phase of the decomposition algorithm, the berths are discretized into several segments according to the definition of the operational practices. The shoreline is partitioned into several berths according to water depth, quay crane working range, boundary, and other factors related to the berth operation. The berths are numbered sequentially and are used to express the approximate position of vessels. The activity-based classification method classifies berths into large, medium, and small types according to berthing capability factors such as water depth and quay crane efficiency. Based on the classification, we can calculate the berthing needs of different types of vessels and flexibly define the type of each berth by using several predefined berth templates. These templates provide instructions for classifying and

Figure 8. (Color online) Graphic Dynamic Berth Plan Chart of the System



defining berths' functions, utilizing berthing capabilities, and allocating vessels to different berths. In the operation of XHCT, different types of vessels need to berth every day. The classification criteria of vessels depend mainly on the length. Corresponding to the berth classification standards, vessels can also be divided into three types: large, medium, and small. The classification of berths and vessels enables the design of the heuristic algorithm and reduces the complexity of the problem based on operational practice. To improve the solution quality and maximize berth utilization, various detailed features describing the capability of berths need to be clarified, including the maximum vessel length, maximum draft, and different berth allocation methods. The preliminary berth allocation is worked out by assigning vessels to different berths according to the corresponding relationship of vessel and berth types. The output result of the first phase is the preliminary vessel allocation to discretized berths, which is used in the second phase.

The second phase of the decomposition algorithm works out the detailed berth plan based on the preliminary berth plan. The main decision in this step is the berthing sequence of all berths, and then the detailed berth allocation decisions can be made, including the berthing position, SBT, SDT, and bollard assignment.

The order of berth allocation is based on the priority order of each berth in the berth template. The berths with higher priorities are allocated first. For the vessels preliminarily allocated to each berth, their berthing sequence is allocated according to the priority. The SBT, SDT, berthing position, quay crane assignment, and bollard assignment are calculated with the consideration of fairway traffic flow control and the berthing safety requirements.

Development and Implementation of the Mathematical Programming-Driven Method

The berth planning system embedded with the 0-1 integer programming model and the two-phase decomposition heuristic algorithm was developed and went through the trial and adjustment procedure. According to the requirements of XHCT, the results obtained by the berth planning system should be better than those worked out manually because the total waiting time and the number of vessels unable to berth should be significantly reduced. The computation time of the system should be no more than 10 seconds to ensure computational efficiency. These requirements challenged our model and algorithm development, for which transforming the theory into practice takes much effort.

In the test and improvement stage, we apply a theoretical research-based approach to validate the effectiveness and efficiency of the model and algorithm. We conduct comparative experiments using CPLEX and the proposed algorithm based on the setting of XHCT. The results obtained by CPLEX are used as the benchmark for the evaluation and improvement of the proposed decomposition algorithm. This is a common method in optimization research for testing the algorithm's performance. The difference in the objective values obtained by the two methods is measured by *GAP*, in which the objective value obtained by CPLEX is used as the benchmark. The details of the experiment are given in the "Algorithm Performance Experiments" of Appendix C. Through continuous testing and improvement, the decomposition algorithm maintains relatively high efficiency, which indicates that the algorithm can be used for developing the system.

After the algorithm was tested and improved, the trial version of the system was developed and deployed at the terminal. During the trial, the berth plans worked out by the system were compared with the results of manual planning to evaluate the practicability of the system. The comparison used the weighted total waiting time as the main indicator for operational efficiency and berth utilization. The number of vessels unable to berth was used as another indicator. The weights were determined by port operators, in which higher weights were given to large vessels with higher handling volume. In addition, some subjective factors like the operators' judgments, requirements of the government and maritime authorities, and emergency needs could also affect the weights. The trials in real operation helped us find the bugs in the system, and the final version of the system was developed and released after further improvements. Real instances of representative days were selected according to three representative types: days with maintenance works and some resources unavailable, normal days, and busy days with more vessels waiting to berth. The results of selected instances are listed in the comparisons between the berth planning system and manual planning in Appendix C to illustrate the improvements of the system. Compared with the results of manual berth planning, the proposed berth planning system is efficient in different scenarios and can help XHCT reduce weighted waiting times by 15.54%. The system can thus significantly reduce vessel waiting times and improve berth utilization.

Berth planning over periods of more than one day is applied in some container terminals, which can enhance the berth planning efficiency by preventing unreasonable solutions at the end of the planning period. A multi-day plan is beyond the capabilities of manual planning. The high computational efficiency of a berth planning system makes it possible to effectively extend the planning periods, and we designed experiments to test the

capability and possibility of extending planning periods. We extended the periods to two days, three days, and four days, and each planning period group had nine randomly generated instances. The number of vessels arriving each day and the loading and unloading volume of each vessel during the planned period were roughly consistent with the one-day planning period situation. The results for the experiments with extended planning periods show the capability of the algorithm in handling different planning periods under different situations, which can be found in Appendix C. Note that uncertainty factors are not characterized in the embedded model and algorithm, which may make the plans of the next few days impractical and need further changes. In the proposed system, the 24-hour planning period setting is adopted according to the planning process of XHCT. Adding the consideration of uncertainty could be more meaningful and practical for extending the planning period for future planning process reengineering.

Implementation Challenges

During the development and trial, our team members worked to improve the system and encountered difficulties in transforming theory into practice. The challenges and the experience of how to overcome difficulties are summarized in the following points.

Various decisions and requirements should be incorporated, which adds complexity to the problem. The difficulty of bollard assignment can be summarized as how the space clearance can be reduced while keeping sufficient bollards between vessels. The tide and channel restrictions influence the decisions of vessels entering, leaving, and handling. The fenders limit the use and function of the berths. Based on mathematical programming theory, the requirements of all of the aforementioned decision problems are reflected and explained in the model in a generalized form, which provides a reference for the algorithm development.

The development and improvement of the algorithm takes much effort. Computation time is one concern for XHCT. We decompose the berth planning problem and design a two-phase decomposition algorithm. The two-phase setting of the algorithm simplifies the decision process of the problem and reduces the computational complexity. The decomposition algorithm introduces a level of customized design into preliminary berth allocation. The customized design should involve an in-depth analysis of activity-based classifications of berth functions and vessel types, and the effectiveness of classifications depends on the mining of historical data. Through continuous adjustments, reasonable classifications are added into the algorithm, and the algorithm achieves satisfactory results in experiments and tests.

The design of the system interfaces and data structures not only requires support of the decision-making

process but also incorporates the various demands and requirements. XHCT has put forward valuable suggestions for the design of the system interfaces and data structures, which drive us to develop more practical functions. The decision-making interfaces follow the usual practice of traditional manual planning and create a visual interface with more embedded functions.

These experiences are all integrated and implemented in the aforementioned system along with the embedded mathematical programming-driven methodological framework. After adjustments and tests, the system can realize XHCT's requirements. The berth plan worked out by the system has proven to be practical, accurate, and efficient through numerical experiments and tests, so the system has finally been accepted and put into use.

Impact and Benefits

The proposed system was put into operation for XHCT's berth planning in late 2021. It creates extra value for XHCT by improving terminal operations and reengineering the berth planning process. By integrating the safety concerns into general berth planning decisions, the system fills the gap between research and practice by considering berthing safety and creates a practical approach for XHCT to improve berth utilization. The benefits of the system implementation can be reflected in the data of port operations, whereas the benefits of reshaping the berth planning process are also significant.

Benefits in Terminal Operational Data

The year 2022 was a year of rapid development for the Port of Xiamen and for XHCT. The Port of Xiamen planned to open more new routes to Regional Comprehensive Economic Partnership countries and to improve the service frequency of cross-strait routes and shuttle shipping services. These actions significantly increased berthing needs and challenged the berth planning process. With the help of the berth planning system, these increased needs were confidently handled by XHCT's operators. An analysis of the operational data for 2022 can illustrate the contribution of the system.

XHCT completed a container throughput of 2.74 million TEUs in 2022, with a year-on-year increase of approximately 4.18%. The increase was due mainly to the opening of new routes and, more importantly, was inseparable from improvements on the use of the berth planning system. XHCT's increase in container throughput is the most prominent among all terminals at the Port of Xiamen, for which the average increase in throughput was 3.22% during the same period. All terminals at the port faced similar effects of market change, so the main point that made XHCT outperform the average level was that XHCT was the only

terminal using the berth planning system. Compared with the designed throughput, the average utilization of XHCT in 2022 was approximately 79%, which is significantly higher than the average resource utilization rate of less than 75% in 2021. In January, July, and August 2022, the terminal's average monthly utilization rate exceeded 85%.

Shipping service improvements are major contributing factors in the increase of throughput. XHCT opened 15 new routes and increased the service frequency of cross-strait routes and shuttle shipping services during 2022. These service improvements led to an increase in the number of berthing needs by nearly 20%, with the average daily berthing needs in July and August 2022 increasing to more than 26 vessels. This increase requires more available berths for different vessels. With the help of the berth planning system, the potential of the berths can be expanded. More berthing needs can be allocated with reasonable berth plans, which stands in stark contrast to the manual planning's extreme and resource strain in the same period of 2021. The efficient use of berth resources meant that the weighted total waiting time for all vessels remained at a relatively stable level compared with the same period in 2021, and the average waiting time for all vessels was reduced by 15% to approximately 2.9 hours. The waiting time for more than 75% of vessels was less than six hours. These measures mean that more vessels' berthing needs can be handled in time.

Benefits of Reshaping the Berth Planning Process

In addition to the operational benefits, the berth planning system has reshaped the planning process. Manual berth planning has been replaced by the efficient berth planning system. The results of the reshaping on the berth planning process are reflected mainly in human resources and intelligent operations development.

Human Resource Restructuring

Manual berth planning requires at least three experienced planners working together. After the completion of the daily berth plan, one planner monitors the implementation, whereas the other two are idle. The implementation of the proposed system reduces the time spent on planning from at least two hours to approximately 15 minutes, and human resources can then be allocated more efficiently. With the proposed system, only one part-time planner is required for the berth planning process for checking and monitoring, which can dramatically reduce labor costs by 600,000 Chinese Yuan (about 83700 US dollars, which can be calculated by 200,000 Chinese Yuan/planner per year $\times$ 3 planners = 600,000 Chinese Yuan). The savings of qualified planners can be utilized in other positions.

Intangible Improvements in Port Intelligent Operations Development

The proposed berth planning system will further promote the intelligent operations development process already underway at the Port of Xiamen. The Port has established a framework of management systems to cover aspects such as terminal planning, operations, and customer service. The berth planning system attempts to achieve intelligent operations development in XHCT, where the decision-making process is changed to a more efficient method. Moreover, the informatization of port operations has also been realized. The berth plan and other relevant data can be exchanged among the berth planning system, TOS, and other decision-making systems, thus improving the efficiency of daily operations. The information exchange between the berth planning system and the business system creates new service modes to shippers and shipping companies.

Future Research and Development

The success of the proposed daily berth planning system will be a step forward for the Port of Xiamen and for the authors' team. The system has been approved by XHCT, and its usability and efficiency have been confirmed by practice. The Port of Xiamen has planned to extend intelligent berth planning to other terminals soon. In late 2021, the Port of Xiamen began the aggregate planning of the Songyu and Haicang Port Areas. The construction of the automated terminal in the Liuwudian Port Area is also steadily progressing. The scope and functions of these port areas are different from those of XHCT. The Songyu and Haicang Port Areas are the main ports for berthing deep-sea mega vessels bound for Europe and America. In addition, numerous inbound and outbound feeders transfer containers between the two port areas and other container terminals. The aggregate planning merges the operations and resource allocation of adjacent terminals in the two port areas to improve resource utilization. The aggregate planning increases the scale of decision making, which requires more efficient and intelligent berth planning methods. Based on the experience of the XHCT berth planning system, several future challenges in the berth planning of the two port areas need to be solved as follows.

Robust Daily Berth Planning

Uncertainties in port operations, such as vessel arrival time, quay crane operating efficiency, container load and unload quantity, and container transshipments, influence berth planning. The proposed berth planning system takes the daily berth planning as a static problem, achieves higher computational efficiency, and overcomes the issues of berthing safety. Uncertainties

have not been taken into account in the proposed system, so some settings in human planning are employed to reduce the influence of uncertainties like the 24-hour planning period and empirical-based requirements. In the future, the Port of Xiamen expects that the berth planning system will be embedded with operational uncertainties to provide a more flexible and robust berth plan. The dynamics in operations, especially the quay crane scheduling, are suggested to be considered to incorporate realistic operational factors. The effectiveness of robust daily berth planning makes it possible to extend the planning period to several days, which can improve the overall performance of berth scheduling and avoid any unreasonable decisions at the end of planning period.

Collaborative Scheduling and Berth Allocation for the Shuttle Shipping Service

The shuttle shipping service is a key aspect of the Port of Xiamen's future development. Transshipment between vessels is not considered in the proposed berth planning system, and the connection between different routes and vessels is considered only in midterm planning. A detailed collaborative scheduling for shuttle shipping services could not only improve the performance of XHCT but also support the further development of the shipping network for the Port of Xiamen. The schedule and berthing time windows of the shuttle shipping service should be connected and coordinated with those of key routes. The berthing position of feeders should be allocated efficiently to minimize transshipment distance and reduce interference with the berthing of ocean vessels.

Intelligent Decision Making for Midterm and Long-Term Berth Planning

The Port of Xiamen needs to make decisions on midterm and long-term operations management issues, such as extensions of the shipping network for the Maritime Silk Road, berth planning improvement for specific routes, and the strategic planning on functional division and coordination of terminals. Daily berth planning should be conducted in conjunction with midterm and long-term berth planning.

The implementation of the proposed berth planning system in other container terminals of the Port of Xiamen is estimated to contribute more than 10 million Chinese Yuan (about 1.4 million US dollars) per year in economic benefits. We believe that the development of the berth planning system will be challenging but beneficial for the Port of Xiamen and for the authors' team.

Appendix A. Mathematical Model

We formulate a mixed-integer linear programming model to describe the problem in a precise way.

Notations

Indices and Sets

$\mathcal{B}$	set of berth segments, which are generated by discretizing the shoreline in short and equal length and indexed by b . $\mathcal{B} = \{0, 1, 2, \dots, \mathcal{B} - 1\}$. The segment index $b = 0$ refers to the segment at one end of the shoreline, and all segments are numbered in a certain direction. $\mathcal{B}' = \mathcal{B} - \{0\}$. For the case of XHCT, the berth segments are discretized in meters, and all berth segments are numbered from south to north. The segment index $b = 0$ of XHCT refers to the southernmost berth segment. $\mathcal{B}^{[x,y]} = \{b \min\{\mathcal{B}\} + x \leq b \leq \max\{\mathcal{B}\} - y\}$.
$\hat{\mathcal{B}}$	set of berth segments with bollards.
$\tilde{\mathcal{B}}_q$	set of berth sections that quay crane q 's operating range covers.
$\mathcal{H}$	set of timesteps in the planning horizon, which is indexed by h . $\mathcal{H} = \{0, 1, 2, \dots, \bar{h} - 1, \hat{h}, \dots, h^{end}\}$, where $\bar{h}$ represents the maximum timestep of the planning period. The timesteps should be a fixed duration of time according to the terminal's requirement. Additional timesteps are included in this set for the planning of vessels whose SDT is later than the end of the planning period. h^{end} represents the maximum timestep. $\mathcal{H}' = \mathcal{H} - \{0\}$. $\mathcal{H}^{[x,y]} = \{h x \leq h \leq h^{end} - y\}$. For the case of XHCT, $\bar{h} = 47$, $h^{end} = 191$, and the duration of a timestep in the planning horizon is half an hour.
$\underline{\mathcal{H}}$	set of timesteps before the planning horizon. The operations during the timesteps involved in this set will influence the berth planning in the planning period. $\bar{\mathcal{H}} = \mathcal{H} \cup \underline{\mathcal{H}}$. $\bar{\mathcal{H}}' = \bar{\mathcal{H}} - \{0\}$. For the case of XHCT, $\underline{\mathcal{H}} = \{-4, -3, -2, -1\}$. $\bar{\mathcal{H}}^{[x,y]} = \{h \min\{\underline{\mathcal{H}}\} + x \leq h \leq h^{end} - y\}$.
$\hat{\mathcal{K}}$	set of timesteps influenced by the fairway temporary closure of the same direction.
$\check{\mathcal{K}}$	set of timesteps influenced by the fairway temporary closure of the opposite direction.
$\mathcal{Q}$	set of quay cranes, which are indexed by q . $\mathcal{Q} = \{0, 1, 2, \dots, \mathcal{Q} - 1\}$. The quay crane index $q = 0$ refers to the southernmost quay crane. The index increases as we move from south to north along the quay.
$\mathcal{V}$	set of all vessels, which are indexed by v .
$\mathcal{V}'$	set of vessels waiting to enter the berth in the planning horizon.
$\mathcal{V}''$	set of in-berth vessels at the beginning of the planning horizon.
$\hat{\mathcal{V}}$	set of vessels that require fairway temporary closure of the same direction when sailing in the fairway. Vessels in this set can be in-berth vessels at the beginning of the planning horizon or vessels waiting to enter the planning horizon.
$\check{\mathcal{V}}$	vessels that require fairway temporary closure of the opposite direction when sailing in the fairway. Vessels in this set can be in-berth vessels at the beginning of the planning horizon or vessels waiting to be berthed in the planning horizon.

Parameters

a_{vb}	set to 1 if the already berthed vessel v 's southernmost position is located in the north of berth segment b , 0 otherwise.
a'_{vb}	set to 1 if the already berthed vessel v 's northernmost position is located in the north of berth segment b , 0 otherwise.
b_{vh}	set to 1 if the SBT of already berthed vessel v is not earlier than timestep h , 0 otherwise.
b'_{vh}	set to 1 if the SDT of already berthed vessel v is not earlier than timestep h , 0 otherwise.
b''_{vh}	set to 1 if the container handling of already-berthed vessel v is not earlier than timestep h , 0 otherwise.
c^{sl}	minimum fairway sailing time for an inbound vessel traveling from the anchorage to the berth.
c^{sp}	minimum space clearance requirement between two vessels berthing at the same time.
$c_{v_1 v_2}^s$	minimum space clearance requirement between vessels v_1 and v_2 if the two vessels berth at the same time. $c_{v_1 v_2}^s = \max\{c^{sp}, p^{sp} \cdot l_{v_1}, p^{sp} \cdot l_{v_2}\}$.
c^{ti}	minimum time clearance between two vessels allocated to the same berth segment.
d_{vbh}^{berth}	set to 1 if the berth segment b satisfies the berthing requirement of vessel v at timestep h , 0 otherwise. The berthing requirement includes water depth, size of fenders, and other related factors.
d_h^{dire}	set to 1 if a vessel enters the berth at timestep h , and the vessel should maneuver a 180-degree turn before entering the berth, 0 otherwise.
d_{vh}^{enter}	set to 1 if vessel v enters the berth at timestep h , and the fairway depth satisfies the vessel's water depth requirement during the vessel's whole inbound fairway sailing process, 0 otherwise.
d_{vh}^{leave}	set to 1 if vessel v leaves the berth at timestep h , and the fairway depth satisfies the vessel's water depth requirement during the vessel's whole outbound fairway sailing process, 0 otherwise.
ENT_v	vessel v 's ENT.
EAT_v	vessel v 's EAT.
ef_q	working efficiency of quay crane q per timestep.
f_b	set to 1 if berth segment b is equipped with a large-size fender, 0 otherwise.
g_v	target working efficiency of vessel v per timestep.
l_v	vessel v 's length.
m	minimum covering range requirement of a quay crane assigned to a vessel.
n_b	set to 1 if berth segment b is available for vessel berthing during the planning horizon, 0 otherwise.
p^{bl}	minimum proportion of the vessels' length to be kept as the distance between vessels' bow (stern) and the selected bollard.
p^{fn}	minimum proportion of the vessels' length to berth alongside large fenders.
p^{sp}	minimum proportion of the vessels' length to be kept as the space clearance.
r_{vb}	set to 1 if the already-berthed vessel v 's southernmost bollard is located in the north of berth segment b , 0 otherwise.

r'_{vb}	set to 1 if the already-berthed vessel v 's northernmost bollard is located in the north of berth segment b , 0 otherwise.
$s_{v_1v_2}$	set to 1 if vessel v_1 and v_2 can share a bollard, 0 otherwise.
vol_v	vessel v 's total load and unload volume.
w_v	weight of vessel v 's berthing delay, which is used to express the priority of vessels. Vessels with higher priority will have higher weights.
z_{qvh}	set to 1 if quay crane q was assigned to the already-berthed vessel v 's during timestep h , 0 otherwise

Decision Variables

α_{vb}	binary, set to 1 if vessel v 's southernmost position is located in the north of segment b , 0 otherwise.
α'_{vb}	binary, set to 1 if vessel v 's northernmost position is located in the south of segment b , 0 otherwise.
β_{vh}	binary, set to 1 if vessel v 's SBT is later than timestep h , 0 otherwise.
β'_{vh}	binary, set to 1 if vessel v 's SDT is later than timestep h , 0 otherwise.
β''_{vh}	binary, set to 1 if vessel v 's container-handling operations starts later than timestep h , 0 otherwise.
γ_{vb}	binary, set to 1 if vessel v 's southernmost bollard is located in the north of segment b , 0 otherwise.
γ'_{vb}	binary, set to 1 if vessel v 's northernmost bollard is located in the north of segment b , 0 otherwise.
ζ_{qvh}	binary, set to 1 if quay crane q is assigned to handle vessel v 's container at timestep h , 0 otherwise.
$\eta_{v_1v_2}$	binary, set to 1 if vessel v_1 berths in the south of v_2 , and the two vessels work at the same time, 0 otherwise.
θ_{vb}	binary, set to 1 if vessel v berths at segment b , and segment b is covered by large fenders, 0 otherwise.
θ'_v	binary, set to 1 if vessel v berths in the area with large fenders, 0 otherwise
$\kappa_{v_1v_2}$	binary, set to 1 if vessel v_1 berths after v_2 left, and the two vessels berth at the same segment, 0 otherwise.
μ_v	binary, set to 1 if vessel v should maneuver a 180-degree turn before entering the berth, 0 otherwise.

Mathematical Model Objective Function

$$\text{minimize } \sum_{v \in \mathcal{V}'} w_v \left(\sum_{h \in \mathcal{H}} \beta_{vh} - EAT_v - c^{sl} \right) \quad (\text{A.1})$$

Constraints

Basic Berth Allocation

$$\begin{aligned} \alpha_{vb} &\leq \alpha_{v,b-1} & \forall v \in \mathcal{V}', b \in \mathcal{B}' & \quad (\text{A.2a}) \\ \alpha'_{vb} &\leq \alpha'_{v,b-1} & \forall v \in \mathcal{V}', b \in \mathcal{B}' & \quad (\text{A.2b}) \\ \beta_{vh} &\leq \beta_{v,h-1} & \forall v \in \mathcal{V}', h \in \overline{\mathcal{H}}' & \quad (\text{A.3a}) \\ \beta'_{vh} &\leq \beta'_{v,h-1} & \forall v \in \mathcal{V}', h \in \overline{\mathcal{H}}' & \quad (\text{A.3b}) \\ \beta''_{vh} &\leq \beta''_{v,h-1} & \forall v \in \mathcal{V}', h \in \overline{\mathcal{H}}' & \quad (\text{A.3c}) \\ \sum_{b \in \mathcal{B}} (\alpha'_{vb} - \alpha_{vb}) &= l_v & \forall v \in \mathcal{V}' & \quad (\text{A.4}) \\ \sum_{h \in \mathcal{H}} (\beta''_{vh} - \beta_{vh}) &\geq ENT_v & \forall v \in \mathcal{V}' & \quad (\text{A.5}) \end{aligned}$$

$$\sum_{h \in \mathcal{H}} \beta_{vh} \geq c^{sl} + EAT_v \quad \forall v \in \mathcal{V}' \quad (\text{A.6})$$

$$\alpha'_{vb} - \alpha_{vb} \leq n_b \quad \forall v \in \mathcal{V}', b \in \mathcal{B} \quad (\text{A.7})$$

$$\mu_v = \sum_{h \in \mathcal{H}'} d_h^{dire} (\beta_{v,h-1} - \beta_{vh}) \quad \forall v \in \mathcal{V}' \quad (\text{A.8})$$

Time and Space Clearance

$$\beta'_{v_1h} - \beta_{v_1h} + \beta'_{v_2h} - \beta_{v_2h} - 1 \leq \eta_{v_1v_2} + \eta_{v_2v_1} \leq 1 \quad \forall v_1, v_2 \in \mathcal{V}, v_1 \neq v_2, h \in \overline{\mathcal{H}} \quad (\text{A.9})$$

$$\alpha_{v_2,b+c_{v_1v_2}^s} \geq \alpha'_{v_1b} - (1 - \eta_{v_1v_2}) \quad \forall v_1, v_2 \in \mathcal{V}, v_1 \neq v_2, b \in \mathcal{B}^{[0, c_{v_1v_2}^s]} \quad (\text{A.10})$$

$$\alpha'_{v_1b} - \alpha_{v_1b} + \alpha'_{v_2b} - \alpha_{v_2b} - 1 \leq (\kappa_{v_1v_2} + \kappa_{v_2v_1}) \leq 1 \quad \forall v_1, v_2 \in \mathcal{V}, v_1 \neq v_2, b \in \mathcal{B} \quad (\text{A.11})$$

$$\beta_{v_2,h+c_{v_1v_2}^{ti}} \geq \beta'_{v_1h} - (1 - \kappa_{v_1v_2}) \quad \forall v_1, v_2 \in \mathcal{V}, v_1 \neq v_2, h \in \mathcal{H}^{[0, c_{v_1v_2}^{ti}]} \quad (\text{A.12})$$

Fenders

$$\theta_{vb} = f_b (\alpha'_{vb} - \alpha_{vb}) \quad \forall v \in \mathcal{V}', b \in \mathcal{B} \quad (\text{A.13})$$

$$\theta_{vb} \leq \theta'_v \leq \sum_{b' \in \mathcal{B}} \theta_{vb'} \quad \forall v \in \mathcal{V}', b \in \mathcal{B} \quad (\text{A.14})$$

$$p^m \cdot l_v \cdot \theta'_v \leq \sum_{b \in \mathcal{B}} \theta_{vb} \leq l_v \cdot \theta'_v \quad \forall v \in \mathcal{V}' \quad (\text{A.15})$$

Quay Crane Assignment

$$m\zeta_{qvh} \leq \sum_{b \in \mathcal{B}_q} (\alpha'_{vb} - \alpha_{vb}) \quad \forall q \in \mathcal{Q}, v \in \mathcal{V}', h \in \mathcal{H} \quad (\text{A.16})$$

$$\zeta_{qvh} \leq \beta'_{vh} - \beta''_{vh} \quad \forall q \in \mathcal{Q}, v \in \mathcal{V}', h \in \mathcal{H} \quad (\text{A.17})$$

$$\sum_{q \in \mathcal{Q}} \zeta_{qvh} ef_q \geq g_v (\beta'_{vh} - \beta''_{vh}) \quad \forall v \in \mathcal{V}', h \in \mathcal{H} \quad (\text{A.18})$$

$$\sum_{q \in \mathcal{Q}} \sum_{h \in \mathcal{H}} \zeta_{qvh} ef_q \geq vol_v \quad \forall v \in \mathcal{V}' \quad (\text{A.19})$$

$$\sum_{v \in \mathcal{V}'} \zeta_{qvh} \leq 1 \quad \forall q \in \mathcal{Q}, h \in \mathcal{H} \quad (\text{A.20})$$

$$\zeta_{q_1v_1h} \leq 2 - \zeta_{q_2v_2h} - \eta_{v_1v_2} \quad \forall v_1, v_2 \in \mathcal{V}, q_1, q_2 \in \mathcal{Q}, q_1 > q_2, h \in \mathcal{H} \quad (\text{A.21})$$

Bollards Assignment

$$\gamma_{vb} \leq \gamma_{v,b-1} \quad \forall v \in \mathcal{V}', b \in \dot{\mathcal{B}} \quad (\text{A.22a})$$

$$\gamma'_{vb} \leq \gamma'_{v,b-1} \quad \forall v \in \mathcal{V}', b \in \dot{\mathcal{B}} \quad (\text{A.22b})$$

$$\gamma_{vb} = \gamma_{v,b-1} \quad \forall v \in \mathcal{V}', b \in \mathcal{B}' - \dot{\mathcal{B}} \quad (\text{A.23a})$$

$$\gamma'_{vb} = \gamma'_{v,b-1} \quad \forall v \in \mathcal{V}', b \in \mathcal{B}' - \dot{\mathcal{B}} \quad (\text{A.23b})$$

$$\sum_{b \in \mathcal{B}} (\alpha_{vb} - \gamma_{vb}) \geq p^{bl} \cdot l_v \quad \forall v \in \mathcal{V} \quad (\text{A.24a})$$

$$\sum_{b \in \mathcal{B}} (\gamma'_{vb} - \alpha'_{vb}) \geq p^{bl} \cdot l_v \quad \forall v \in \mathcal{V} \quad (\text{A.24b})$$

$$\gamma_{v_2b} \geq \alpha'_{v_1b} + \eta_{v_1v_2} - 1 \quad \forall v_1, v_2 \in \mathcal{V}, v_1 \neq v_2, b \in \mathcal{B} \quad (\text{A.25a})$$

$$\gamma'_{v_1b} \leq \alpha_{v_2b} - \eta_{v_1v_2} + 1 \quad \forall v_1, v_2 \in \mathcal{V}, v_1 \neq v_2, b \in \mathcal{B} \quad (\text{A.25b})$$

$$\gamma'_{v_1, b-1} - \gamma'_{v_1b} + \gamma_{v_2, b-1} - \gamma_{v_2b} \leq 2 + s_{v_1v_2} - \eta_{v_1v_2} \quad \forall v_1, v_2 \in \mathcal{V}, v_1 \neq v_2, b \in \hat{\mathcal{B}} \quad (\text{A.26})$$

Fairway Traffic Control

$$1 - (\beta'_{v_1, h-1} - \beta'_{v_1h}) \geq \beta_{v_2, h-1+k} - \beta_{v_2, h+k} \quad \forall v_1 \in \check{\mathcal{V}}, v_2 \in \mathcal{V}', v_1 \neq v_2, k \in \check{\mathcal{K}}, h \in \overline{\mathcal{H}}^{[1, k]} \quad (\text{A.27a})$$

$$1 - (\beta_{v_1, h-1} - \beta_{v_1h}) \geq \beta'_{v_2, h-1-k} - \beta'_{v_2, h-k} \quad \forall v_1 \in \check{\mathcal{V}}, v_2 \in \mathcal{V}', v_1 \neq v_2, k \in \check{\mathcal{K}}, h \in \overline{\mathcal{H}}^{[1+k, 0]} \quad (\text{A.27b})$$

$$1 - (\beta'_{v_1, h-1} - \beta'_{v_1h}) \geq \beta'_{v_2, h-1+k} - \beta'_{v_2, h+k} \quad \forall v_1 \in \hat{\mathcal{V}}, v_2 \in \mathcal{V}', v_1 \neq v_2, k \in \hat{\mathcal{K}}, h \in \overline{\mathcal{H}}^{[1, k]} \quad (\text{A.28a})$$

$$1 - (\beta_{v_1, h-1} - \beta_{v_1h}) \geq \beta_{v_2, h-1+k} - \beta_{v_2, h+k} \quad \forall v_1 \in \hat{\mathcal{V}}, v_2 \in \mathcal{V}', v_1 \neq v_2, k \in \hat{\mathcal{K}}, h \in \overline{\mathcal{H}}^{[1+k, 0]} \quad (\text{A.28b})$$

Water Depth and Tide

$$\beta_{v, h-1} - \beta_{vh} \leq d_{vh}^{\text{enter}} \quad \forall v \in \mathcal{V}', h \in \mathcal{H}' \quad (\text{A.29a})$$

$$\beta'_{v, h-1} - \beta'_{vh} \leq d_{vh}^{\text{leave}} \quad \forall v \in \mathcal{V}', h \in \mathcal{H} \quad (\text{A.29b})$$

$$\alpha'_{vb} - \alpha_{vb} + \beta'_{vh} - \beta_{vh} \leq d_{vbh}^{\text{berth}} + 1 \quad \forall b \in \mathcal{B}, v \in \mathcal{V}', h \in \mathcal{H} \quad (\text{A.30})$$

Berth Occupancy for Already Berthed Vessels

$$\alpha_{vb} = a_{vb} \quad \forall v \in \mathcal{V}'', b \in \mathcal{B} \quad (\text{A.31a})$$

$$\alpha'_{vb} = a'_{vb} \quad \forall v \in \mathcal{V}'', b \in \mathcal{B} \quad (\text{A.31b})$$

$$\beta_{vh} = b_{vh} \quad \forall v \in \mathcal{V}'', h \in \overline{\mathcal{H}} \quad (\text{A.32a})$$

$$\beta'_{vh} = b'_{vh} \quad \forall v \in \mathcal{V}'', h \in \overline{\mathcal{H}} \quad (\text{A.32b})$$

$$\beta''_{vh} = b''_{vh} \quad \forall v \in \mathcal{V}'', h \in \overline{\mathcal{H}} \quad (\text{A.32c})$$

$$\gamma_{vb} = r_{vb} \quad \forall v \in \mathcal{V}'', b \in \mathcal{B} \quad (\text{A.33a})$$

$$\gamma'_{vb} = r'_{vb} \quad \forall v \in \mathcal{V}'', b \in \mathcal{B} \quad (\text{A.33b})$$

$$\zeta_{qvht} = z_{qvht} \quad \forall q \in \mathcal{Q}, v \in \mathcal{V}'', h \in \mathcal{H} \quad (\text{A.34})$$

Definition of Decision Variables

$$\alpha_{vb}, \alpha'_{vb} \in \{0, 1\} \quad \forall v \in \mathcal{V}, b \in \mathcal{B} \quad (\text{A.35})$$

$$\beta_{vh}, \beta'_{vh}, \beta''_{vh} \in \{0, 1\} \quad \forall v \in \mathcal{V}', h \in \mathcal{H}, \text{ or } v \in \mathcal{V}'', h \in \overline{\mathcal{H}} \quad (\text{A.36})$$

$$\gamma_{vb}, \gamma'_{vb} \in \{0, 1\} \quad \forall v \in \mathcal{V}, b \in \mathcal{B} \quad (\text{A.37})$$

$$\zeta_{qvht} \in \{0, 1\} \quad \forall q \in \mathcal{Q}, v \in \mathcal{V}, h \in \mathcal{H} \quad (\text{A.38})$$

$$\eta_{v_1v_2}, \kappa_{v_1v_2} \in \{0, 1\} \quad \forall v_1, v_2 \in \mathcal{V} \quad (\text{A.39})$$

$$\theta_{vb} \in \{0, 1\} \quad \forall v \in \mathcal{V}', b \in \mathcal{B} \quad (\text{A.40})$$

$$\theta'_v \in \{0, 1\} \quad \forall v \in \mathcal{V} \quad (\text{A.41})$$

Objective (A.1) minimizes the total weighted berthing delay of all vessels. Constraints group (A.2) ensures that variables

$\alpha_{v,b}, \alpha'_{v,b}$ are nonincreasing in b , and constraints group (3) ensures $\beta_{v,h}, \beta'_{v,h}, \beta''_{v,h}$ are nonincreasing in h . Constraint (A.4) defines that vessel v occupies berthing space with the vessel's length l_v . Constraint (A.5) defines that the difference between SHT and SBT of vessel v should be no less than the ENT of the vessel. This constraint ensures that there is enough time for non-handling activities that must be done before container handling. Constraint (A.6) defines that the difference of SBT and EAT should satisfy the minimum sailing time of inbound vessels. Constraint (A.7) prevents vessels berthing at the segment that cannot be occupied, that is, the corner segments, boundary of different sections, and berth segment under maintenance. Constraint (A.8) defines if a vessel needs to maneuver a 180-degree turn before entering the berth. Constraint (A.9) clarifies that the relationship of berthing space occupancy should exist between vessels berthing at the same time. Constraint (A.10) ensures the space clearance between vessels berthing at the same time. Constraint (A.11) clarifies the relationship of time that should exist between vessels occupying the same berth segment. Constraint (A.12) guarantees that the time clearance between vessels occupies the same berth segment. Constraints (A.13)–(A.15) describe the berth allocation rules affected by the different sizes of fenders. Constraints (A.13) and (A.14) determine whether vessel v berths at berth segments with large fenders. Constraint (A.15) states that if a vessel berth at the segments with large fenders, then the length between the boundary of the fenders and the bow (stern) in the berth with small fenders should meet the minimum proportion requirement of the vessels' length to berth alongside the large fenders. Constraints (A.16)–(A.21) describe the quay crane allocation problem. Constraint (A.16) makes sure that a quay crane can be assigned to a vessel only when the operating range of quay cranes should meet the requirement of minimum covering length of a vessel. Constraint (A.17) states that a quay crane can be assigned to a vessel during the vessel's in-berth time. Constraint (A.18) makes sure that the hourly efficiency of quay cranes assigned to a vessel meets the requirement of the targeted hourly efficiency. Constraint (A.19) makes sure that the quay cranes can handle all loading/unloading containers during the assigned time. Constraint (A.20) makes sure that a quay crane can be assigned to only one vessel in a timestep. Constraint (A.21) ensures that quay cranes should be assigned in accordance with the position relationships of quay cranes and in-berth vessels. This constraint also makes sure that the quay cranes cannot pass each other and have a fixed sequence along the quay. Constraints (A.22)–(A.26) state the rules of bollards assignment. Constraint groups (A.22) and (A.23) guarantee the nonincreasing feature of variables $\gamma_{v,b}$ and $\gamma'_{v,b}$. In addition, the bollards should be selected among segments with bollards. Constraint group (A.24) defines the minimum space between vessels and bollards; that is, the distance between vessels' bow (stern) and selected bollard should be greater than the minimum length requirement that can be calculated by a proportion of vessel's length. Constraint group (A.25) makes sure the position of the selected bollard is not occupied by other vessels during the in-berth time. Constraint (A.26) ensures that a bollard should be assigned to only one vessel if the two vessels do not satisfy the requirement of sharing the same bollard. Constraint groups (A.27) and (A.28) apply the rules of fairway temporary closure. The temporary closure

for vessels sailing in the opposite direction of oversize vessels is implied by constraint group (A.27), and the temporary closure for vessels sailing in the same direction when oversize vessels occupy the fairway is implied by constraint group (A.28). Constraints (A.29) and (A.30) state the water depth requirement. Constraint group (A.29) applies the fairway depth requirement for entering and leaving the berth. Constraint (A.30) ensures that the berth segment b satisfies the berthing requirement of vessel v during the berthing process. Constraints (A.31)–(A.34) state the berth occupancy for already berthed vessels. Constraints (A.35)–(A.41) define the decision variables.

Appendix B. The Two-Step Decomposition Algorithm

In view of the classification of vessels, we can conclude and classify the following berth types:

a. Berths for large vessels should be reserved for the berthing of large vessels and vessels with higher water depth requirement. The berthing of these vessels usually follows strict requirements, for example, higher targeted quay crane efficiency or deeper water depth requirement. To satisfy the berthing needs, more quay cranes are assigned to vessels. Berths for large vessels can also be occupied by two smaller vessels at the same time.

b. General berths are berths with normal berth capabilities, that is, berths with average water depth and quay crane allocation. These berths are suitable for the berthing of most vessels, except for large vessels with strict berthing requirements. The assignment of quay cranes should be determined according to the loading/unloading quantity and overall resource allocation of the terminal.

c. Berths for small vessels are the berths with more berthing restrictions, including shallow water depth, shorter shoreline length, and lower quay crane working efficiency. These berths are suitable only for smaller vessels with lower loading/unloading volume and shallower draft. The handling of small vessels usually requires only one to two quay cranes because the loading/unloading volume of these vessels is usually less, and the water depth requirement is usually not the limiting factor. For the berthing of some larger vessels, two or more continuous berths may be occupied at the same time. Some small vessels often share a berth with another vessel. For these situations, some berths can be attached with attributes to provide references of more diversified berth plans. To summarize

the classifications, we can conclude some combinations of berth classifications and functions in berth templates based on the status of the terminal. The berth templates can provide necessary input and instructions of the two-phase algorithm. The detailed settings of berth templates are listed in Table B.1.

Phase 1: Preliminary Berth Allocation

Input: vessels' attributes, vessels' berthing priority vPr_v , berth type and vessel type set $\mathcal{T}$, set of discretized berths $\mathcal{BD}$, set of type t berths $\mathcal{BT}_t$, estimated earliest available time of berths $bET_{\mathcal{BD}}$, average quay crane expected efficiency $\bar{e}$, expected minimum efficiency for different vessels eff_e , total load/unload volume of a vessel vol_v , and expected non-handling time ENT_v .

Output: vessels' preliminary berth allocation pre_v .

1. Set the set of vessels' types $\mathcal{VT}_t = \emptyset$, $t \in \mathcal{T}$, estimated working time of different types of vessels $VTM_t = 0$, vessel v 's preliminary berth allocation of $pre_v = -1$
2. For $v \in V$ do
3. If $l_v \geq lc_L$, then
4. $\mathcal{VT}_L = \mathcal{VT}_L \cup \{v\}$, $EHT_v = \frac{vol_v}{eff_L}$, $VTM_L = VTM_L + EHT_v + ENT_v + c^{ti}$
5. Else if $dr_v^{in} \geq dc_L$ or $dr_v^{out} \geq dc_L$ then
6. $\mathcal{VT}_L = \mathcal{VT}_L \cup \{v\}$, $EHT_v = \frac{vol_v}{eff_L}$, $VTM_L = VTM_L + EHT_v + ENT_v + c^{ti}$
7. Else if $l_v \leq lc_S$ then
8. $\mathcal{VT}_S = \mathcal{VT}_S \cup \{v\}$, $EHT_v = \frac{vol_v}{eff_S}$, $VTM_S = VTM_S + EHT_v + ENT_v + c^{ti}$
9. Else $\mathcal{VT}_M = \mathcal{VT}_M \cup \{v\}$, $EHT_v = \frac{vol_v}{eff_M}$, $VTM_M = VTM_M + vol_v$ //vessels classification
10. End If
11. End For
12. Select the appropriate berthing template according to VTM_t and $\max\{l_v\}$, and
13. Sort the vessels according to pr_v to get the sorted vessels sequence in different types VT_t
14. For t from L to S , do
15. For i from 1 to $|\mathcal{VT}_t|$, do
16. Set $pendV = s\mathcal{VT}_t.indexof(i)$
17. Sort $\mathcal{BT}_t$ according to earliest available time b^{earl} to get the sorted sequence in different types $s\mathcal{BT}_t$
18. Set $bAlte = 0$, $bDiff = \max\{bLen_b\}$
19. For j from 1 to $|\mathcal{BT}_t|$, do

Table B.1. Detailed Settings in Berth Templates

Notation	Meaning
$\mathcal{BD}$	Set of discretized berths, indexed by k
$\mathcal{T}$	Set of berth and vessel types, indexed by t . $\mathcal{T} = \{L, M, S\}$
$sDeci$	Sorted sequence of berths according to the decision sequence
$\mathcal{VT}_t$	Set of type t vessels
$\mathcal{BT}_t$	Set of type t berths
$bLen_k$	Maximum available length of discretized berth k
$bDep_k$	Maximum allowed draft of discretized berth k
$bEff_k$	Minimum efficiency of discretized berth k
$rPosi_{k,v}$	Set of alternative berth position of vessel v if this vessel is allocated to discretized berth k The alternative berth positions define all possible south positions of the vessel and are listed in sequence of priority.

```

20. Set  $pendB = SBT_t.indexo(j)$ 
21. If  $0 \leq bLen_{pendB} - l_{pendV} \leq bDiff$ , do
22.    $bAlte = pendB, bDiff = bLen_{pendB}$ 
23. End If
24. End For
25.  $pre_{pendV} = bAlte,$ 
    $bET_{bAlte} = bET_{bAlte} + EHT_{pendV} + ENT_{pendV} + c^{ti}$ 
26. End For
27. End For
28. For  $k$  in  $\mathcal{BD}$  do
29. Sort the vessels according to  $pr_v$  to get the sorted
   vessel sequence allocated to discretized berth  $k$   $sVes_k$ 
30. End For

```

Phase 2: Vessel Berth Allocation Decisions

Input: vessels' preliminary berth allocation pre_v , sorted sequence of vessels allocated to discretized berth k $sVes_k$, estimated earliest available time of berths discretized in meters bET_b , parameters listed in Appendix A.

Output: detailed berth allocation, including $sPosi_v$ for the south position, $nPosi_v$ for the north position, SBT_v for SBT, SDT_v for SDT, $sBoll_v$ for the south bollard, $nBoll_v$ for the north bollard, and $\zeta_{q,v,h}$ for the assignment of quay cranes to vessels.

```

1. Set the occupancy status of berth  $b$  in time  $h$   $occu_{b,h}$  to zero, set the status of fairway temporary closure  $fIn_h = 0, fOut_h = 0$ 
2. For  $k$  in  $sDeci$ , do
3. For  $v$  in  $sVes_k$ , do
4. For  $b$  in  $rPosi_{k,v}$ , do
5. For  $h$  from 1 to  $|H|$ , do
6. If  $berthAvai(v,b,h) = true$ , do
7. Set the possible SDT  $pSDT = h + EHT + ENT$ 
8. While  $fOut_{pSDT_v} = 0$ 
9.  $pSDT = pSDT + 1$ 
10. End While
11. If  $\exists b' \leq b' \leq b + l_v, d_{v,b,pSDT}^{berth} = 0$ 
12. Continue
13. End If
14. If  $v \in V_2$  or  $v \in V_4$ ,
   Set  $fIn$  and  $fOut$  according to fairway temporary closure rule
15. End If
16. Set  $sPosi_v = b, nPosi_v = b + l_v, SBT_v = h$ , and  $SDT_v = pSDT$ 
17. For  $b'$  from  $b$  to  $b + vLen_v, h'$  from  $h$  to  $pSDT$ , do
18.  $occu_{b',h'} = 1$ 
19. End For
20. For  $\{b', h'\} \in cleRng_v$ , do
21.  $occu_{b',h'} = 2$ 
22. End For
23. Go to Line 2
24. End If
25. End For
26. End For
27. End For
28. End For
29. End For

```

```

30. For  $v$  in  $V$  do
31. For  $b$  from  $nPosi_v + p^{sp} \cdot l_v$  to  $|B|$ , do
32. If  $bollPosi_b = 1$ , do
33.  $nBoll_v = bollNum_b$ 
34. End If
35. If  $\exists h$  from  $SBT_v$  to  $SDT_v, occu_{b,h'} = 1$ 
36. Break
37. End If
38. End For
39. For  $b$  from  $sPosi_v - p^{sp} \cdot l_v$  to 1, do
40. If  $bollPosi_b = 1$ , do
41.  $sBoll_v = bollNum_b$ 
42. End If
43. If  $\exists h$  from  $SBT_v$  to  $SDT_v, occu_{b,h'} = 1$ 
44. Break
45. End If
46. End For
47. End For
48. For  $h$  from 1 to  $h$ .
49. List all in-berth vessels  $inVessel_h$ .
50. For  $v \in inVessel_h$ .
51. Select appropriate quay cranes to assign to vessel  $v$  as the set of  $qcAssn_v$  according to  $vEffi_v$ , relative position of vessels in  $inVessel_h$ , and the availability of quay cranes.
52. For  $q \in qcAssn_v$ . do
53.  $\zeta_{q,v,h} = 1$ 
54. End for
55. End For
56. End For

```

Notes

1. $berthAvai(v,b,h)$ checks the possibility that the vessel berths with the south position b and SBT h by the following criteria:

- $\forall h \leq h' \leq h + EHT + ENT, b \leq b' \leq b + vLen_v, occu_{b',h'} = 0$, and $d_{v,b,h}^{berth} = 1$
- $\forall h \leq h' \leq h + EHT + ENT, b - space(v, v^l) \leq b' \leq b$, or $b + vLen_v \leq b' \leq b + vLen_v + space(v, v^r), occu_{b',h'} = 0$ or 2
- $d_{v,h}^{entry} = 1, fClos_h = 0$

2. $cleRng_v$ is the set occupied by clearance space or time of vessel v and includes the following positions at these times:

- b' from b to $b + l_v, h'$ from $pSDT$ to $pSDT + 3$
- b' from $b - \max\{c^{sp}, p^{sp} \cdot l_v\}$ to b, h' from h to $pSDT$
- b' from b to $b + \max\{c^{sp}, p^{sp} \cdot l_v\}, h'$ from h to $pSDT$

3. The minimum space clearance of $space(v_1, v_2)$ is determined by the following rule:

- The space should be greater than the minimum space clearance requirement $\max\{c^{sp}, p^{sp} \cdot l_{v_1}, p^{sp} \cdot l_{v_2}\}$
- The space clearance between two vessels should ensure that there are enough bollards between the two vessels.

Appendix C. Numerical Experimental Results

Appendix C lists the numerical experimental results of the proposed algorithm embedded in the berth planning system. During the test and improvement process, we conduct extensive tests to verify and improve the proposed algorithm. The results of comparative experiments performed by CPLEX and the proposed algorithm are listed first. Then, the comparison between the results of the berth planning system and manual planning

are conducted to evaluate the performance of the berth planning system under different real instances. Furthermore, a set of large-scale experiments with extended planning horizons were conducted to test the efficiency.

Algorithm Performance Experiments

Table C.1 shows the results of small-scale instances. From the table, we can see that the decomposition algorithm can always obtain results with better or the same objective values. In terms of computation time, the algorithm spends a much shorter time than CPLEX for all of the instances with more vessels. The CPLEX can find the optimal solution for only four or six vessels within 3,600 seconds. When the number of vessels increases to eight, for some instances, CPLEX can obtain only feasible solutions that are not better than the solutions obtained by the decomposition algorithm. From the results of large-scale instances shown in Table C.2, CPLEX cannot obtain results in 3,600 seconds and is not competent to solve real-scale problems. The results show that the algorithm can realize the efficient planning of a large number of vessels and meet XHCT's computation time requirement.

Comparisons Between the Berth Planning System and Manual Planning

In the previous comparative experiments, CPLEX cannot obtain a solution within a reasonable time, which makes it hard to evaluate the algorithm performance of large-scale instances. Meanwhile, the test and improvement of the proposed system require more experiments in practical application. Experiments based on real operational data were conducted, and the manual planning was selected as the benchmark to evaluate the performance of the algorithm.

Several representative days with different scenarios are selected and listed in Table C.3 to present the improvement of the system. Instances in Group 1 represent the days with maintenance works when some berth resources are unavailable. Instances in Group 2 represent normal days with most of the berthing resources available. Instances in Group 3 represent busy days when more berthing needs to be handled. Compared with the results of manual berth planning, the proposed berth planning system is efficient in different scenarios and can help XHCT reduce weighted waiting times by 15.54%. The number of vessels unable to berth has also been reduced. These results indicate that the system can significantly reduce vessel waiting times and improve berth utilization.

Table C.1. Algorithm Performance for Small-Scale Instances

Instances		CPLEX		Algorithm		GAP
No. of vessels	ID	Z_c	t_c	Z_a	t_a	
4	1	0	12	0	3	0.00%
	2	4.5	18	4.5	3	0.00%
	3	0	20	0	2	0.00%
	4	0	15	0	4	0.00%
	5	3	17	3	3	0.00%
	6	5.5	18	5.5	3	0.00%
	7	6.5	17	6.5	2	0.00%
	8	0	19	0	5	0.00%
	9	0	10	0	3	0.00%
6	1	0	466	0	3	0.00%
	2	12	620	12	3	0.00%
	3	6.5	756	6.5	5	0.00%
	4	10	447	10	4	0.00%
	5	13	698	13	3	0.00%
	6	4.5	949	5	6	−11.11%
	7	16	203	16	4	0.00%
	8	0	847	0	3	0.00%
	9	5.5	106	6	5	−9.09%
8	1	3.5	1,628	3.5	3	0.00%
	2	18	>3,600	16	4	11.11%
	3	15.5	>3,600	15	4	3.23%
	4	13	>3,600	13	3	0.00%
	5	16.5	2,512	16.5	5	0.00%
	6	12	3,104	12.5	6	−4.17%
	7	14	>3,600	11	5	21.43%
	8	19.5	>3,600	19	4	2.56%
	9	8	1,209	8	5	0.00%

Notes. (1) Z_c represents the objective value of optimal solution obtained by CPLEX in 3,600 seconds. If CPLEX cannot obtain the optimal solution within 3,600 seconds, then Z_c represents the objective value of feasible solution obtained by CPLEX at 3,600 seconds. Z_a represents the solution obtained by the decomposition algorithm. (2) t_c and t_a represent the computation time of CPLEX and the algorithm in seconds. (3) $GAP = (Z_c - Z_a)/Z_c$.

Table C.2. Algorithm Performance for Large-Scale Instances Under the Planning Environment of XHCT

Instances: no. of vessels	ID	Z_a	N_a	t_a
20	1	40	0	6
	2	65.5	0	5
	3	25	0	6
	4	58	0	5
	5	72	0	8
	6	16	0	7
	7	34	0	5
	8	22	0	6
	9	33.5	0	7
30	1	27	0	7
	2	61	0	9
	3	40	0	7
	4	48	0	7
	5	52.5	0	9
	6	107.5	0	8
	7	128.5	1	9
	8	134	1	8
	9	162.5	0	7
35	1	52	0	7
	2	78	0	9
	3	140	0	7
	4	138.5	0	7
	5	152.5	0	9
	6	207.5	3	8
	7	158.25	1	9
	8	164	1	8
	9	192.5	2	7

Notes. (1) Z_a represents the solution obtained by the decomposition algorithm. (2) N_a represents the no. of vessels unable to berth during the planning period. (3) t_a represents the computation time of decomposition algorithm in seconds.

Experiments with Extended Planning Periods

The experiments with extended planning periods were conducted to test the computational performance of the proposed decomposition algorithm with planning periods extended and number of vessels increased accordingly. The planning periods

were extended to two days, three days, and four days, and each planning period group has nine randomly generated instances. The experiment results in Table C.4 indicate that the computational efficiency of the decomposition algorithm is competent for extended planning periods.

Table C.3. Berth Plan Comparison Between the Berth Planning System and Manual Planning of XHCT

Group	Instances	No. of vessels	Berth planning system		Manual planning		GAP^z
			Z_a	N_a	Z_m	N_m	
1	1	14	73	0	75.5	0	3.31%
	2	15	62	0	68.5	0	9.49%
	3	16	89	0	95	0	6.32%
	4	12	43.5	0	57	0	23.68%
	5	17	39.5	0	46.5	1	15.05%
	6	13	48	0	52	0	7.69%
	7	18	61.5	1	67	2	8.21%
	8	19	51	0	54.5	2	6.42%
	9	12	29	0	34	0	14.71%
2	1	22	96	0	112.5	1	14.67%
	2	23	105	0	118.5	0	11.39%
	3	20	78	0	102.5	1	23.90%
	4	25	106.7	1	125	1	14.64%
	5	19	75	0	101.5	0	26.11%
	6	20	91.5	1	112	2	18.30%

Table C.3. (Continued)

Group	Instances	No. of vessels	Berth planning system		Manual planning		GAP^z
			Z_a	N_a	Z_m	N_m	
3	7	22	95	0	120	0	20.83%
	8	24	82	0	108.5	1	24.42%
	9	21	85.5	0	103	0	16.99%
	1	31	107	0	129.5	2	17.37%
	2	30	162.5	0	216	5	24.77%
	3	30	128.5	0	154	3	16.56%
	4	34	156.5	2	198	2	20.96%
	5	31	124	0	168.5	1	26.41%
	6	36	168	4	184.5	6	8.94%
	7	32	105	1	119	1	11.76%
	8	30	134	0	149.5	0	10.37%
	9	31	121.5	0	145	2	16.21%

Notes. (1) Z_a represents the solution obtained by the decomposition algorithm. Z_m represents the solution obtained by manual planning. (2) N_a represents the no. of vessels unable to berth during the planning period obtained by the algorithm. N_m represents the no. of vessels unable to berth during the planning period obtained by manual planning. (3) GAP^z represents the waiting time reduction rate between the algorithm and manual planning. $GAP^z = (Z_m - Z_a)/Z_m$.

Table C.4. Algorithm Performance for Large-Scale Instances with Extended Planning Periods

Instances				
Planning horizon	No. of vessels	Z_a	N_a	t_a
96	42	65	0	15
	48	77.25	0	19
	42	74	0	18
	45	48.5	0	12
	60	87.25	0	23
	65	90.5	1	22
	61	95.75	0	21
	67	123	2	29
	68	101	1	31
	144	98.5	0	40
144	69	136	0	42
	70	93.5	0	38
	71	117.25	0	46
	82	195	5	61
	71	149.25	0	55
	75	167.5	1	57
	79	209.75	3	62
	74	159	0	61
	192	202	0	85
	85	198.25	0	89
192	78	249.5	0	76
	72	260.25	0	81
	125	297.5	2	105
	130	312.5	6	116
	119	286	0	110
	117	290.25	0	119
	123	337.5	4	113

Notes. (1) Z_a represents the solution obtained by the decomposition algorithm. (2) N_a represents the no. of vessels unable to berth during the planning period. (3) t_a represents the computation time of decomposition algorithm in seconds.

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Verification Letter

Pei Ye, Head of Information System Department, Hai-Tian Branch, Xiamen Container Terminal Group, No. 8, Xiangyu Rd., Huli District, Xiamen, Fujian, China 361006, writes:

“I hereby certify as the Head of Information System Department, Hai-Tian Branch, Xiamen Container Terminal Group, that the berth planning system, developed by the team headed by Prof. Lu Zhen of Shanghai University, has been used successfully at the Xiamen Hai-Tian Container Terminal (XHCT) in daily berth planning since 2021.

“The berth planning system has significantly helped improve XHCT’s operation since its introduction. During the year 2022, XHCT’s container throughput reached 2.74 million TEUs, a year-on-year increase of approximately 4.18%. The year-on-year growth rate was the highest among all terminals in the Port of Xiamen and exceeded the average growth rate of 3.22%. With the addition of 15 new routes opened in 2022 and the increased frequency of other routes, the average

weekly berthing requirements has significantly increased by about 20%. These berthing requirements are satisfied by the system, with a waiting time of more than 75% vessels' berthing requirements less than six hours. Besides the contribution reflected by the terminal operational data, the berth planning process of XHCT has been reshaped with higher efficiency and quality.

"The system is a successful enterprise-university cooperation practice for the intelligentization of the Port of Xiamen. In the future, we are willing to promote the system to other terminals at the Port of Xiamen and continue the cooperation with Shanghai University to realize more values."

Lu Zhen is a professor and dean at the School of Management, Shanghai University, Shanghai, China. His research interests include port operations and maritime transportation optimization and decision support systems. He is a Distinguished Fellow of the International Engineering and Technology Institute and Fellow of the Operational Research Society (United Kingdom). He was awarded the following: State Council Special Allowance Expert, National Funds for Distinguished Young Scientists, and Changjiang Young Scholar in China.

Haolin Li is a postdoctoral researcher at the School of Management, Shanghai University, Shanghai, China. His research interests include port operations management and logistics and supply chain management. His research findings have been published in journals,

including *Annals of Operations Research*, *Transportation Research Part E*, and *Computers & Industrial Engineering*.

Liyang Xiao is an assistant professor at the School of Management, Shanghai University, Shanghai, China. His research interests include logistics and supply chain management, medical operations optimization, and port and shipping logistics. He has extensive experience in the field of logistics and medical operations management. His research findings have been published in journals, including *Computers & Operations Research*, *Expert Systems with Applications*, *International Journal of Production Research*, and *Transportation Research Part E*.

Dayu Lin is currently the vice general manager of the Xiamen Container Terminal Group (XCTG), Xiamen, Fujian, China. He was the general manager of Hai-Tian Branch of XCTG during the development of the berth planning system. In recent years, he has participated in several important system development projects of XCTG and supports the development of the berth planning system of the Xiamen Hai-Tian Container Terminal.

Shuaian Wang is a professor at the Faculty of Business, Hong Kong Polytechnic University, Hong Kong, China. His research interests include big data in shipping, green shipping, shipping operations management, and port planning and operations. He is co-editor-in-chief of *Transportation Research Part E*, editor-in-chief of *Cleaner Logistics Supply Chain*, and editor-in-chief of *Communications in Transportation Research*. He won the INFORMS Computing Society Harvey J. Greenberg Research Award in 2023.