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SGICT Builds an Optimization-Based System for Daily Berth Planning

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In container terminal operations, the allocation of berth-side resources to serve calling vessels is called berth planning. For each vessel, berth planning generally involves determining the time interval for berth stay (i.e., berthing and departure times and the handling of start and end times), the berthing position along the quay, and the number of quay cranes that will be dedicated to handle it. The objectives are to maximize the vessel service levels (i.e., minimize the departure lateness) and minimize operating costs during a planning horizon. In this paper, we describe the implementation of an operations research-based solution at Shanghai Guandong International Container Terminal (SGICT), one of the largest container terminals at the Port of Shanghai, to optimize its daily berth planning. We embed our solution into a decision support system (BAPOPT), which provides SGICT's planners with effective and executable berth plans. Using BAPOPT, SGICT expects to improve its vessel-handling productivity by at least 15 percent. With the support of BAPOPT, SGICT has started shifting its operational emphasis from reactive real-time dispatching to proactive resource planning, helping to relieve its operations department from a considerable amount of tedious work and improve the efficiency of its planning department.

Keywords: container terminal optimization; berth allocation; quay crane allocation; decision support system.
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As one of the world's busiest container ports, the Port of Shanghai has handled more than 197 million twenty-foot equivalent units (TEUs) in the past six years, and has ranked first among all leading ports in total throughput since 2010. In 2015, the Port of Shanghai handled an unprecedented 36.5 million TEUs, and this number is expected to increase in 2016.

Shanghai Guandong International Container Terminal (SGICT), one of the largest container terminals at the Port of Shanghai, provides container-handling services for both domestic and international shipping lines, with a business scope that covers import, export, and transshipment containers. It is part of the Yangshan Deep-Water Port located on the Yangshan islands, southeast of Shanghai, and operates 29 quay cranes (QCs), a straight-lined quay wall with a length of 2,600 meters, and a container yard with an area of 120 hectares. Each month, these resources serve more than 150 deep-sea vessels and 100 feeders and barges, producing an average throughput of 0.45 million TEUs.

As a result of the rapid development of China's economy and international trade, the number of containers that SGICT handles is expected to increase steadily during the upcoming years. SGICT's managers found, however, that after several rounds of equipment upgrades, they could no longer improve the terminal's productivity by adding new facilities or equipment. The only way they could seize this business growth opportunity was by implementing technological innovations to support their resource-availability decisions. After a thorough investigation of SGICT's business processes, the managers identified berth planning as the first target of this innovation.

SGICT's berth-planning process has three levels:

(1) Monthly planning: Shipping lines send monthly vessel arrival plans to SGICT, typically by email and electronic data interchange. The planning department then verifies the identities of the vessels and their schedule information, including service, voyage, port of call, estimated import and export throughput, estimated port stay, and physical characteristics, and enters these data into SGICT's information technology (IT) system.

(2) Weekly planning: SGICT receives updated information from the shipping lines about each vessel's estimated time of arrival (ETA) and estimated time of departure (ETD), and assigns a berth number to each vessel; however, it does not include the exact berthing start and end times. Entering the ETA and ETD is a precondition for yard planning to allocate yard space for receiving containers near the berth. When doing weekly planning, managers have little information on the loading and unloading operations of the vessels; they mainly make decisions by analyzing the vessels' historical data.

(3) Daily planning: Daily planning is the most critical step in the berth-planning process, because actual berths with wharf starting and ending positions, berthing start and end times, and numbers of QCs must be assigned to different vessels based on relatively accurate vessel ETAs and ETDs, import and export throughput, and container distributions over vessel bays and yard blocks (YBs). The daily berth plan is used to generate detailed QC loading and discharging schedules and work instructions for yard cranes (YCs) and trailers.

SGICT's managers were interested in daily berth planning, because it is based on more accurate information and occurs immediately before execution. Hence, the main focus of this project was to analyze the process of daily berth planning and propose solutions that would provide efficiency at this planning level. In this project, we (1) modeled the daily berth planning problem using mathematical programming, (2) developed a decomposition heuristic that enables fast generation of executable plans, (3) integrated our solution into a decision support system (DSS), and (4) defined key performance indicators (KPIs) to enable SGICT to evaluate its planning performance.

In the next section, we provide an introduction to berth planning at SGICT, followed by a detailed description of the daily planning problem. We then describe our solution approach and some implementation details of the DSS. Finally, we review the business benefits of the DSS, discuss the extensions we plan to develop in the near future, and suggest directions for future research. Appendix A provides a table of abbreviations that we use in this paper; Appendix B covers the relevant mathematical formulations and algorithmic details.

Daily Berth Planning at SGICT

The daily berth plan serves as the cornerstone of the terminal's daily operations (Figure 1). It provides planners with necessary information to devise crane work plans and vessel stowage plans, which specify the container-handling sequences and map export containers from the yard onto the vessel slots. Based on the QC work schedules, the operations department estimates the throughput in each work shift and determines the participation of YCs and trailers. Orders are then sequentially generated according to the planned QC work queues and container-handling sequences, and executed by the dispatched container-handling equipment (CHE) (i.e., the QCs, YCs, and trailers). Because berths and QCs are scarce resources, a berth plan should drive the execution of operations to achieve efficient resource utilization and satisfactory service.

The planning process at SGICT, which we describe in this section, was previously carried out manually using spreadsheets. The daily berth planning begins at 10 AM and must finish by 2 PM the day prior to execution. Because the previous process lacked KPIs, planners often generated plans based on their own preferences and logic, resulting in inconsistent resource utilization and vessel service. Moreover, creating a berth plan involves respecting a number of practical restrictions, some of which are too complex for the planners to consider; therefore, to develop plans, they relied on their personal experiences. For example, to

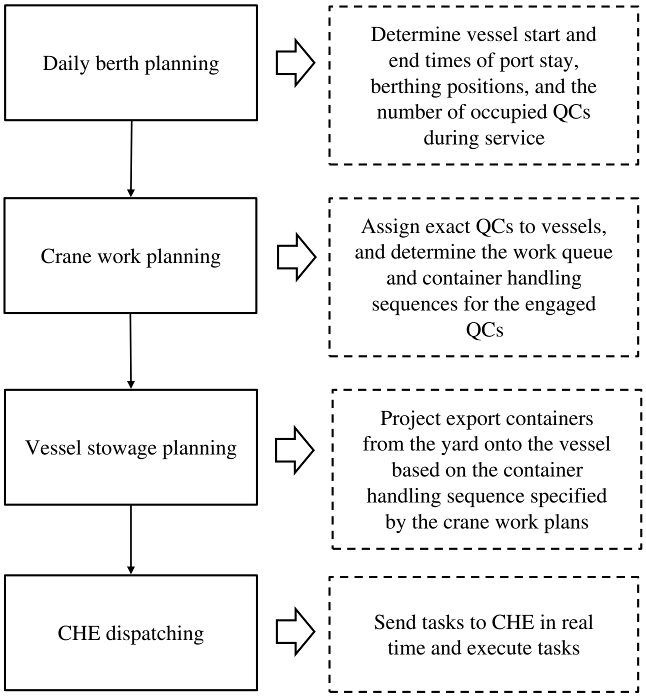

Figure 1: The daily berth planning, which is the focus of this paper, drives the other planning and dispatching decisions at the terminal.

determine the berthing and departure times of vessels, planners should consider the berthing and departure time windows for other vessels; however, for these vessels, they did not have information about the impact of a vessel's occupation of time windows on their berthing and departure times. Consequently, most planners determined the berth-stay intervals for vessels based on their knowledge from past vessel-handling records, and did not sufficiently consider the time-window requirements. As a result, most plans went awry during execution, resulting in tedious workloads for the operations department. It had to simultaneously and reactively deal with planning and execution, thus hindering the exploitation of full terminal productivity. Based on our evaluation, we summarize the limitations of the initial planning process.

- The manual process was cumbersome and time consuming.
- The resulting plans might be unreliable or even unexecutable.
- The lack of KPI definitions made evaluating a plan's effectiveness difficult.
- The manual process could not be used to find optimized solutions that promote the efficiency of the terminal operation.

To address these deficiencies, we proposed the following goals for this project.

- Implement a solution that enables fast generation of executable 24-hour berth plans.
- Establish a DSS that incorporate planners' experiences to drive efficiency, while providing decision-making flexibility.
- Define KPIs that provide insights into the performance of the berth planning process.

Problem Description

In this section, we discuss in detail the practical requirements and restrictions involved in the daily berth planning at SGICT.

Periods of Vessel Port Stay

Figure 2 depicts the important periods during a vessel's port stay. Before a vessel arrives, its shipping line informs the terminal of the vessel's ETA (which is the expected time of the vessel's arrival at the anchorage). When the vessel arrives, it is parked at the anchorage and waits for in-wharf permission (Period 1). Once permission is granted, the vessel goes through a navigation channel, which takes about two hours, before it arrives at the berth (Period 2). Before QCs start to handle a vessel, berthing and handling setup operations, including docking, tying ropes, and moving twist locks, must be completed (Period 3). Containers are then loaded or discharged by dedicated QCs during the planned handling interval (Period 4). When the terminal has completed vessel handling, the vessel leaves the berth after departure setup operations (Period 5), travels back to the anchorage (Period 6), and leaves the port.

The most important activity in daily berth planning is to determine the vessels' berth-stay intervals (i.e., Periods 3–5), as Figure 2 illustrates, and the specific berthing locations assigned. QC utilization during this productive period must also be specified.

Vessel Service

Shipping lines usually propose ETDs for vessels as part of the service requirements. For some vessels,

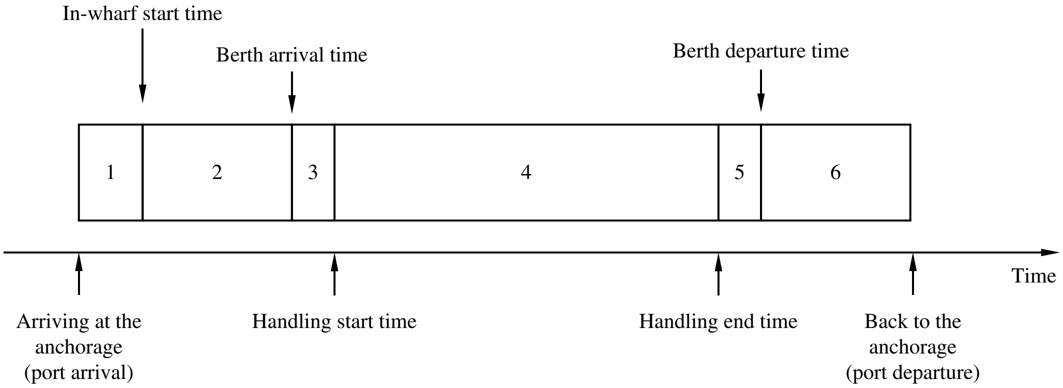

Figure 2: The time interval that a vessel spends at a port is composed of multiple subintervals.

a minimum number of QCs must also be specified; however, satisfying these requirements depends on several factors, including deviations between actual arrival times and the ETAs, and the terms of service, which the terminal provides. Nevertheless, the terminal often prefers to complete vessel handling as quickly as possible to offer favorable service to shipping lines, while also increasing berth productivity. When multiple vessels compete for limited berth space, planners often assign priorities to the vessels and determine the order of service for them. For example, vessels of VIP customers are usually given priority over those of other customers, because VIP customers have additional service guarantees; thus, they are assigned higher service priorities.

Berthing and Departure Time Windows

Although the berth is deep enough to accommodate very large vessels, the navigation channel is relatively shallow because of the huge mass of silt washed from the estuary of the Yangtze River. Larger vessels usually require higher water levels to pass through the channel; therefore, their berthing and departure times depend on the tide.

The determination of vessel berthing and departure times is a time-consuming process for planners, because they must carefully determine whether a vessel's berth-stay interval should fall within a single tide cycle or multiple tide cycles. Figure 3 presents the variation of water levels over time and a vessel's possible berth-stay intervals. In general, a single tide-cycle berth-stay interval guarantees a short vessel turnaround time; however, because it also results in high QC occupation to speed up the handling process, it may hinder the handling efficiency for other vessels. In contrast, a multiple-tide-cycle berth-stay interval requires fewer QCs; however, it is disadvantageous to maintaining high berth productivity, leading to possible delayed departures of subsequent vessels.

To improve the overall vessel-handling capacity, one important task in daily berth planning is to determine the appropriate pace of handling for each vessel; this pace must account for the tide windows.

Channel Flow Control

SGICT's navigation channel is surrounded by many small islands (i.e., the Qiqu Archipelago); therefore, the pilot station, which provides piloting services for the incoming and outgoing vessels, strictly regulates it for safety reasons. Vessels sailing in the channel must be guided by pilot ships to ensure that sailing routes and vessel speed are safe. Because of the limited number of pilot ships, the berth plan is subject to a channel flow-control requirement, which limits the number of vessels that can sail simultaneously in the channel. Moreover, because SGICT shares the channel with a neighboring container terminal, the neighboring terminal's use of the navigation channel must also be a consideration. This limitation is hard to quantify; therefore, planners consider it based on their experiences.

After lengthy discussions with pilots at the pilot station, we were allowed to surrogate the flow control by introducing additional berthing and departure

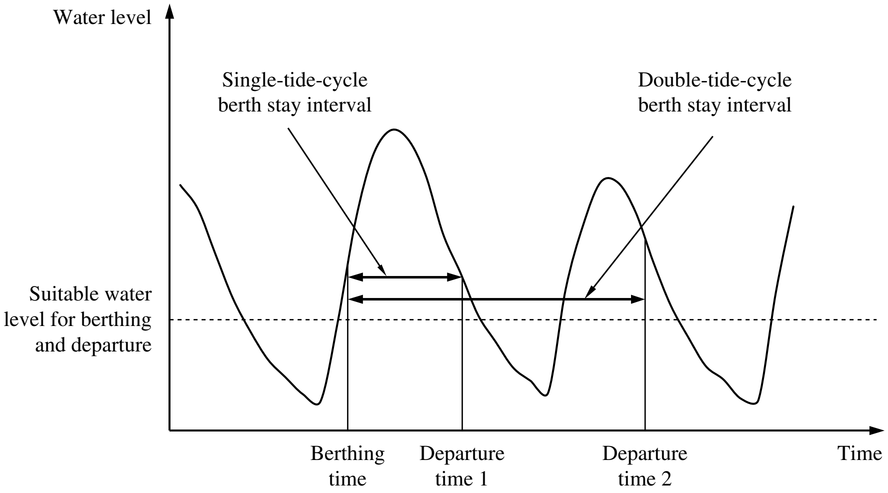

Figure 3: A vessel can only berth and depart when water levels are sufficiently high.

time windows, which they proposed, for the incoming and outgoing vessels. The pilot station determines whether each of these time windows can be used for berthing or departure, and the maximum number of vessels that can use it.

When the terminal devises a plan, it sends the plan to the pilot station to identify any potential noncompliance with safety requirements. If the pilot station detects violations, it suggests plan revisions, or again specifies the berthing and departure time windows to enable the terminal to generate a satisfactory plan.

Vessel Positioning

SGICT's 2,600-meter quay wall is divided into seven berth segments, and each is assigned a berth number. These berth segments are used in weekly planning to define expected berthing ranges for vessels. Some berth segments are equipped with long-reach cranes with a water depth of up to 18 meters. These berths are generally dedicated to deep-sea vessels, which are larger and carry more containers. Small ships, such as barges and shallow-draft feeders, usually share shorter berth segments and use fewer QCs.

When a vessel is associated with a berth number, the yard office allocates sufficient yard space close to the berth for receiving and delivering containers; to determine this allocation, the yard office uses the vessel's Baplie information (i.e., the number of different types of containers to be handled). The yard plan indicates the container distribution in the yard. At the operational level, berth planners use it to determine the exact berthing positions for vessels, such that the overall horizontal distance between a vessel and its associated YBs is minimized. By doing this, both the transportation distance for import containers and housekeeping work for export containers (i.e., repositioning containers from remote YBs into nearby YBs before loading) (Legato et al. 2013) are minimized.

Allocation of Quay Cranes

One of the most important issues in QC allocation is to balance the QC utilization during the planning horizon by reducing the peak number of QCs engaged each hour. This is beneficial for reducing the number of YCs, number of trailers, and manpower to be dispatched for each work shift, because the maximum hourly throughput will be lowered, leading to both improved CHE utilization and operational cost savings.

Planners at SGICT used to assign each vessel a fixed number of QCs and assume that these QCs were dedicated to one vessel until the completion of that vessel's service. This arrangement often resulted in poor QC utilization and underestimation of QC capacity, because it prevented vessels from sharing QCs during vessel handling. However, during execution, sharing QCs among vessels is critical for efficiently using idle QCs and for controlling the pace of the handling process.

To improve QC utilization, we proposed a time-variant QC allocation scheme that allows flexible QC engagement. We adopted the concept of QC-hours (Meisel and Bierwirth 2009) to measure the vessel workload, where a QC-hour represents one hour of QC handling capacity. Adopting this concept allowed us to change the numbers of QCs assigned to a vessel in different hours, provided that the overall assigned QC capacity is sufficient to cover the vessel's workload.

When moving containers, a QC's productivity (i.e., number of moves per hour) depends on both the vessel structure and the type of containers being handled. The QC productivity for each vessel is stored in an array called the "QC productivity profile." This profile is obtained from analyzing historical operational data and is used for deriving vessel workloads.

The QC allocation is subject to QC availability. The number of QCs allocated to a vessel must be no greater than a specified upper limit. In addition, the following criteria must be considered when the QC allocation is made.

(1) The number of QCs allocated to a vessel should be no less than the minimum number of QCs that the vessel requires.

(2) The difference between the numbers of QCs allocated to a vessel during successive hours should be no larger than a predetermined threshold.

(3) The number of QC-hours allocated to a vessel should be no less than the number that the vessel requires.

These criteria are imposed to facilitate the QC operations. Criterion (1) is imposed by the shipping lines (see the *Vessel Service* section). Criterion (2) aims to maintain sufficient QC productivity by restricting the gantry movement of QCs. Criterion (3) seeks to achieve suitable handling efficiency for vessels by allocating adequate QC-hours. These three criteria may be violated if problem infeasibility is encountered. For example, if the total number of available QC-hours is insufficient, then some vessels can be allocated fewer QC-hours than necessary, resulting in a violation of criterion (3). In such a case, the vessel should be handled with a higher efficiency to ensure finishing its service on schedule (e.g., devoting more trailers and YCs to handling the vessel); however, such an efficiency increase is undesirable because it forces the system to run above its effective capacity, and imposes additional pressure on the yard operations to provide adequate support to the QCs.

Objective Priorities

SGICT's managers had three objectives (OBJ) for our system.

- OBJ 1: Improve vessel service levels by minimizing the vessel departure lateness.
- OBJ 2: Balance QC utilization during the planning horizon to leverage the overall CHE utilization.
- OBJ 3: Enable smoother container exchange between the QCs and YCs by minimizing the distances between vessels and their associated YBs.

Because of the fierce competition from other domestic and international ports, improving vessel service was of paramount importance from the managers' perspective. Thus, they considered OBJ 1 to be the most compelling and the highest priority. Improving the utilization of resources was also critical, because it has a major impact on container-handling efficiency and operating costs. Therefore, we prioritized OBJ 2 just below OBJ 1 and above OBJ 3.

In multiobjective optimization, defining objective priorities is generally achieved by assigning weight coefficients to a linearly weighted objective function. In our problem, we have three objectives. If we penalize the deviation of the solution from criteria (1)–(3) using linear weights, we will have six objectives in total. However, the choice of weights is cumbersome (especially when the objectives are of different orders of magnitude), because it requires excessive tuning efforts for different problem instances, which renders this approach unappealing in practice. To simplify the treatment of multiple objectives and to achieve an effective problem-solving approach, we proposed a decomposition heuristic that sequentially addresses several subproblems. In each subproblem, we optimize one of the three objectives, while taking into account criteria (1)–(3). Next, we present our solution approach.

Solution Approach

During the past decade, container terminal operations management has received broad attention in the operations research/management science (OR/MS) community. A number of review papers in this field have been published recently; examples include Carlo et al. (2013), Gorman et al. (2014), and Gharehgozli et al. (2015). The problem we study is generally referred to as the integrated berth allocation and QC allocation problem. Stahlbock and Voß (2008) and Bierwirth and Meisel (2010, 2015) provide extensive reviews of studies of related problems. Researchers have studied berth allocation problems at both the tactical level (Giallombardo et al. 2010) and the operational level (Kim and Moon 2003) with discrete (Imai et al. 2003), continuous (Imai et al. 2005), and hybrid (Hoffarth and Voß 1994) berth layouts. With respect to QC allocation, both time-variant (Park and Kim 2003, Meisel and Bierwirth 2009) and time-invariant (Imai et al. 2008) assignment schemes have been investigated. The majority of research efforts focus on improving vessel service in terms of time-related measurements, such as vessel waiting time (Moorthy and Teo 2006), vessel handling time (Cordeau et al. 2005), tardiness in departure (Chen et al. 2012), and service completion time (Emde et al. 2014). Although previous works have investigated various business scenarios, only a few articles have considered the impact of tidal effect on berth operation and navigation channel control. The studies by Xu et al. (2012) and Du et al. (2015) are the most relevant to our work. Xu et al. (2012) studied a berth allocation problem with water-depth consideration by dividing the planning horizon into a high-water period and a low-water period. Their model considers the tidal condition at the berth and not at the navigation channel. Du et al. (2015) model the tidal effect at the navigation channel in a berth allocation problem, and adopt a "virtual arrival policy" to minimize both vessel emissions at port and fuel consumption. They assume that the time required to handle each vessel is given a priori. This differs from the problem setting of our study, where the vessel handling time depends on the QC allocation. The control of resource utilization during vessel handling has also received relatively little attention in the berth and QC allocation literature, despite its impact on cost savings. To the best of our knowledge, no published work has provided satisfactory solutions that meet SGICT's requirements. The existing methodologies require excessive computational efforts to address an integrated problem, or they fail to capture SGICT's berth planning business, which has multiple objectives and decision criteria.

In view of the problem complexity and the multiobjective nature of the problem, we developed a decomposition heuristic and addressed the problem in three phases. Appendix B provides the associated mathematical models and implementation details of the heuristic. In Phase 1, we discretize the quay into berth segments, and assign each vessel to one berth segment by solving a discrete berth allocation model. For each vessel, we restrict the candidate berth segments to the one assigned in the weekly plan and its adjacent berth segments. In this model, we extend the planning horizon by 24 hours to look ahead through the following day. The most important issue at this stage is to find the best berth-stay intervals for the incoming vessels such that the time-window requirements are satisfied and the overall weighted lateness is minimized. For this purpose, we use a binary variable to indicate whether the berth-stay interval of a vessel falls within a single tide cycle or double tide cycles to berth and depart within feasible time windows; to achieve acceptable berth productivity, the duration of the berth stay for a vessel cannot normally exceed two tide cycles. In addition, depending on the length of the berth-stay interval, we assign each vessel an average number of QCs, which we derive from analyzing historical operational data.

Following the determination of the berth-stay intervals and the average QC capacity allocated to each vessel, we attempt to revise the QC engagement in Phase 2; our goal is to balance the QC utilization within the extended planning horizon. We reallocate the QCs by executing a tailor-made subroutine that successively reduces the number of QCs at peak hours, while respecting the vessel workloads, the maximum number of available QCs, and the maximum limit on the number of QCs allocated to vessels. After reallocating the QCs, we invoke a postprocessing step to check whether the number of QCs used in each hour exceeds the number of available QCs. If conflict is detected, the subroutine fixes the solution by relaxing the QC allocation criteria, as we describe in the *QC Allocation* section. If the QC capacities of some vessels become insufficient to cover their workloads, the subroutine suggests a higher QC handling efficiency for these vessels to ensure completing the service on schedule.

Finally, in Phase 3, we determine the vessels' exact berthing positions along the quay by solving a linear programming (LP) model, taking into account the vessels' suitable berthing ranges, the safety clearance between vessels, the container distributions in the yard, and the berth segment assigned to each vessel in Phase 1. The LP model minimizes the horizontal transportation distance of the containers. To guarantee solution feasibility, we use an "overlap matrix" to indicate whether the berth-stay intervals of two vessels overlap with each other; see Appendix B for details. Because each vessel was already assigned a berth number in Phase 1, we reduce the problem complexity by imposing a requirement that vessel i must be assigned to a lower bow position than vessel j if these two vessels' berth-stay intervals overlap each other and that vessel i has a smaller berth number than vessel j.

The benefits of solving the problem as a decomposition problem are threefold. First, the complexity of the problem is greatly reduced. This technique offers shorter computational time for solving each subproblem and enables fast generation of feasible solutions, which is important to SGICT. Second, decomposition enables OBJ 1–3 to be treated separately. Therefore, objective priorities can be handled by modeling the corresponding subproblems and defining a sequence in which these subproblems are solved. Finally, compared to an integrated-solution approach, decomposition provides more flexibility for extensions and adaptations. Instead of modifying the entire problem to address changes in demand, the heuristic requires only that the corresponding subproblem be modified, thus greatly facilitating the maintenance of the optimization engine. Despite some common weaknesses associated with decomposition approaches, such as weakened solution quality caused by the lack of connectivity among the subproblems, or infeasibility resulting from improper decomposition of the original problem, applying decomposition appears to be an attractive approach for solving many problems.

System Implementation

SGICT employs a terminal operating system (TOS), an IT system dedicated to the terminal's operations. The TOS connects directly to the operational database (ODB) and provides information to allow multiple departments to execute the corresponding business processes.

To support the berth planning process, we integrated our solution into the TOS and developed a DSS, the berth allocation problem optimizer (BAPOPT), which includes our decomposition heuristic embedded in its kernel. Figure 4 shows the integration framework of the BAPOPT and the data flows between its component modules. All the input data of our optimizer originate from two databases—the ODB and the historical database (HDB). The ODB stores general terminal configurations (e.g., berth, QC, and yard configurations), tide tables, algorithm parameters (e.g., planning horizon, priority settings). It also stores the operational data (e.g., weekly plan, vessel information, container distribution in the yard, QC availability), which are filtered and organized in the TOS modules before being entered into the optimizer.

Previous operational data are removed from the ODB and archived in the HDB periodically (e.g., every three weeks). These historical data are analyzed via a dedicated statistics toolkit, which applies time-series analysis to estimate the QC allocation profiles (i.e., the number of QCs used for various berth-stay intervals) and the QC productivity profiles for vessels.

Before the heuristic is invoked, all the input data are handled by a preprocessor that performs data verification, time-window calculations, and workload transformation. The preprocessor standardizes the necessary data for our algorithm and ensures the successful execution of the optimizer. After execution, the optimizer outputs the daily berth plan solution, user-specified reports, and KPIs to the related TOS modules.

BAPOPT uses the software framework on which the TOS is based. Hence, without any data adapters, the berth module can access and visualize the berth plans that BAPOPT generates, thus allowing planners to easily and conveniently modify and evaluate their plans. In addition, the integration framework greatly facilitates uncertainty handling. If a daily berth plan cannot be executed successfully because of unexpected events, such as QC breakdowns, loading and (or) unloading uncertainties, or inaccurate ETAs or ETDs, planners can replan by simply rerunning the

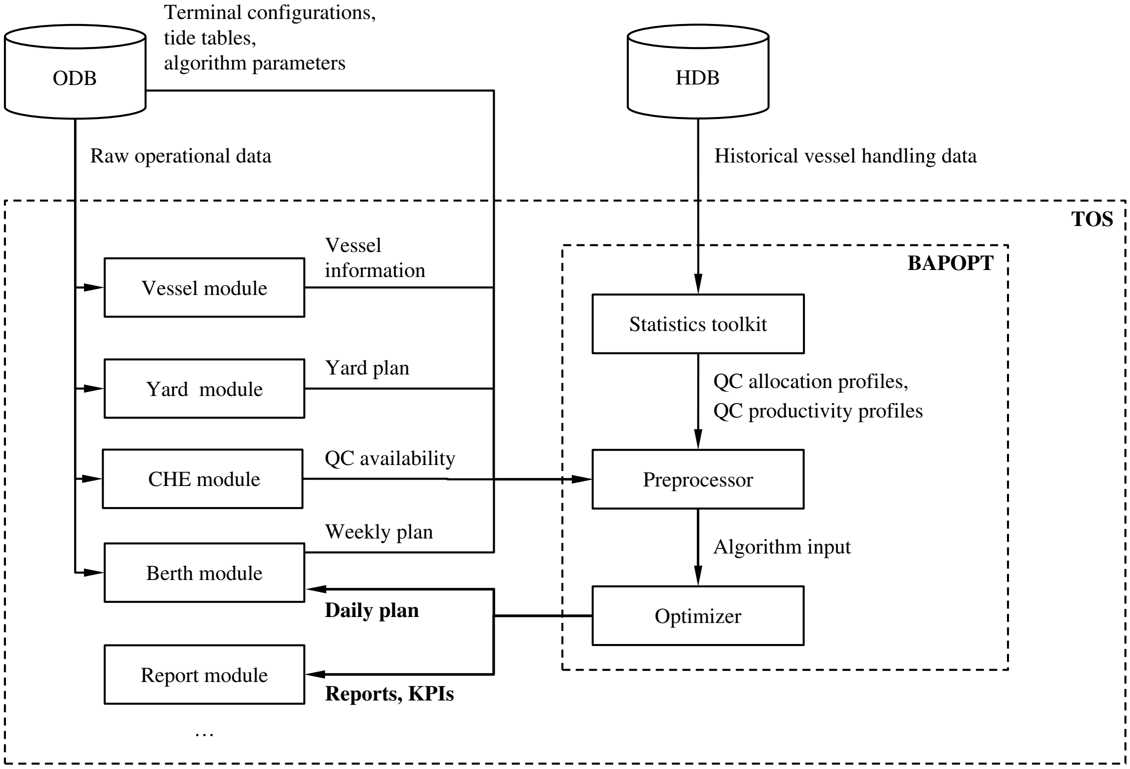

Figure 4: We integrated our berth allocation problem optimizer (BAPOPT) into the terminal operating system (TOS) that SGICT uses to manage its port operations.

optimizer. In this case, BAPOPT is able to access the latest information from the TOS modules and quickly generate a new berth plan using the updated input data.

Results

To evaluate the computational performance of our system, we extracted typical instances of busy days from the HDB and summarized the corresponding performance characteristics. We performed our tests on an i5-2450M processor with 8 GB RAM. As Table 1 shows, the majority of the computations occur in the first phase (the average computational time per instance is about 10 seconds) of the heuristic, where the optimizer attempts to solve the discrete berth allocation model with time-window constraints. In the second and third phases, however, the solution times are much shorter (less than two seconds) because efficient solution strategies are applied. The fast generation of solutions is critical to SGICT because it enables planners to replan whenever necessary (e.g., when a vessel's arrival plan is cancelled unexpectedly), and to perform what-if analysis based on different scenario configurations to support better decisions.

In response to SGICT's lack of knowledge about planning performance, we developed the following KPIs:

- KPI 1: QC throughput rate—measured by number of TEUs per QC-hour.
- KPI 2: QC utilization rate—measured by QC-hours for vessel handling divided by the total number of available QC-hours.
- KPI 3: Berth utilization rate—measured by meter hours for vessel handling divided by total number of available meter hours.
- KPI 4: Service level by vessel—measured by total number of hours of lateness.

Date	No. of deep-sea vessels	No. of feeders and barges	Total throughput (TEUs)	Preprocessing time (seconds)	Solution time in Phase 1 (seconds)	Solution time in Phase 2 (seconds)	Solution time in Phase 3 (seconds)
06 Feb 2015	8	5	21,426	2.1	8.2	1.2	0.5
10 Feb 2015	8	4	29,230	2.5	10.7	1.0	0.5
12 Feb 2015	6	6	21,141	1.8	9.1	0.8	0.4
13 Feb 2015	7	5	25,144	2.0	10.8	1.5	0.5
18 Feb 2015	7	6	25,627	2.0	9.2	1.6	0.5
22 Feb 2015	8	6	29,377	1.5	11.5	1.5	0.3
25 Feb 2015	7	7	26,302	2.1	10.1	1.1	0.4
28 Feb 2015	6	8	24,672	2.4	8.9	0.8	0.6
29 Feb 2015	7	6	25,320	1.8	9.6	1.1	0.4

Table 1: Our berth allocation optimization algorithm solves real-world problems in a few seconds.

KPI 1 reflects the overall QC productivity. A higher KPI 1 value indicates higher vessel-handling efficiency by the terminal. KPIs 2 and 3 reflect the performance of the terminal resource utilization. If the terminal's overall workload (i.e., the total number of containers to be handled) has not increased, then increasing the value of KPI 1 will lead to decreased values of both KPIs 2 and 3. However, if the terminal is able to handle more vessels (or containers) as a result of better berth plans, then the values of KPIs 2 and 3 will increase as the value of KPI 1 increases. Therefore, simultaneously improving KPIs 1–3 is desirable from the terminal's perspective. Lower KPI 4 values usually indicate better vessel service by the terminal.

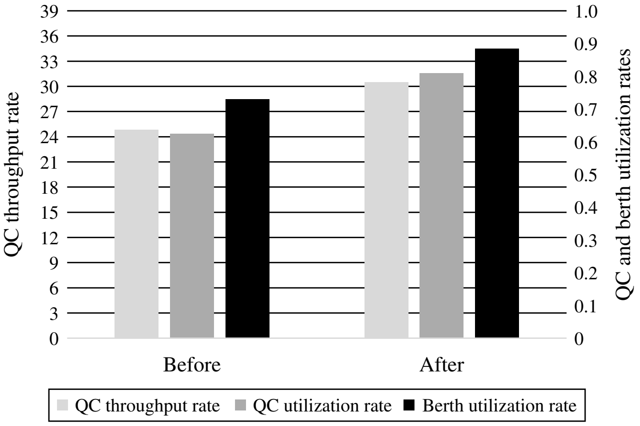

Figure 5: The berth allocation optimizer improved the quay crane and berth utilization rates and the quay crane throughput rate.

Figure 5 depicts SGICT's 2014 average planning performance (i.e., before adopting BAPOPT) and that of the first quarter of 2015 (i.e., after adopting BAPOPT). As the figure shows, SGICT achieved substantial improvements in KPIs 1–3 with the support of BAPOPT. The main reason for such improvements is that BAPOPT is able to optimize the berthing and departure time windows and QC allocation patterns for the vessels, leading to an appropriate vessel-handling pace and resource utilization, and eventually allowing more vessels to be served than in plans that were generated manually. Because of the improvement in KPIs 1–3, SGICT managers were confident they would achieve an overall terminal productivity improvement of at least 15 percent by the end of 2015.

Before using the BAPOPT, planners tended to reserve as many QCs as possible for large vessels to achieve short turnaround times; however, they paid little attention to the sufficiency of QC capacities for feeders and barges. In our view, overemphasizing the sufficiency of resources for large vessels guarantees satisfactory service for important customers, but is likely to cause unbalanced resource utilization. To verify this assertion, we applied our heuristic to comprehensive instances and compared our solutions with manually generated ones. The simulation results showed that in our solution, KPI 4 was at the same level as the manual solution for deep-sea vessels; in addition, service for feeders and barges improved. Moreover, our solution handled two more vessels per day on average than the manual solution. This productivity enhancement corresponded to a monthly throughput increase of about 80,000 TEUs.

Because of its effective underlying heuristic, BAPOPT considerably improved the work efficiency of the planning department; it reduced the time spent on daily berth planning from four hours to less than one hour. With sufficient vessel and yard information, planners can now build detailed 48-hour plans by simply extending the planning horizon, or running the heuristic using a rolling horizon. In addition, the availability of a reliable solution has relieved the control room from having to make frequent plan revisions during execution. The new method is superior to the previous empirical method in the following aspects.

- It enables fast generation of solutions, thus simplifying the execution of berth planning.
- It accounts for various practical restrictions and generates executable plans.
- It improves terminal productivity and resource utilization.

SGICT's managers realize that the decomposition heuristic satisfies their requirements for pursuing different goals, and BAPOPT is valuable because it lays a solid foundation for applying technological innovation to the decision-making process for terminal resource utilization. Because of these business benefits, SGICT has started shifting its operational emphasis from reactive real-time dispatching to proactive resource planning, which we believe represents significant progress in container terminal management.

Extensions and Future Research

We successfully deployed and used BAPOPT; however, based on user feedback, several issues remain to be addressed. (1) Because the heuristic is unable to determine if a vessel should be served, it cannot generate feasible solutions when an excessive number of vessels is entered into the optimizer. Thus, it relies on planner preferences and tuning efforts to perform vessel selection under hectic conditions (i.e., too many vessels are waiting at the anchorage). (2) The time-variant QC allocation scheme allocates the number of QCs to each vessel during each hour; however, it does not explicitly specify which QCs should be allocated to a vessel. As a result, allocating and scheduling exact QCs is too complex to perform manually.

Our development focus for the near future includes addressing these problems. First, we intend to introduce additional binary variables into our model to enable automated vessel selection. However, this decision is subject to several factors, such as the requirements to balance service for VIP customers, coordination of the vessel handling time with the arrival times of export containers, and the trade-off between increasing berth throughput and controlling the distribution of task densities in the yard. To make our model more applicable to SGICT, we need to do more research to quantify its requirements. Second, effective QC scheduling approaches would be useful for evaluating the merits of different QC allocation solutions. Therefore, we are looking at incorporating a QC scheduling module into our solution framework, as Meisel and Bierwirth (2013) studied. The main challenge in doing so is to efficiently address QC scheduling, while respecting the resource restrictions within a multivessel environment.

In addition to these issues, another possible deficiency in our decomposition solution approach is its weak solution quality, which results from the lack of connectivity among the subproblems, as we mention in the *Solution Approach* section. Our heuristic decomposes the problem into three phases, and executes the three phases only once. One way to improve the effectiveness of our solution is to develop an iterative heuristic that returns to Phase 1 after executing Phases 2 and 3, and continues to search for improvements until it reaches a specified stopping criterion. This approach, however, will increase the computation time.

Another weakness of our decomposition approach is that it uses the weekly berth plan to generate the berth allocation solution in Phase 1, but does not consider the yard-area distribution associated with the vessels. Thus, it relies on the assumption that the yard areas allocated to a vessel are concentrated and are close to the berth segment assigned to the vessel in the weekly plan. This assumption, however, may not hold in practice because yard allocation can change dynamically and yard planners may not be able to reserve the most preferred (or nearest) yard areas for a vessel. In this case, our heuristic might not generate a good solution in Phase 3. In view of this, additional research on integrating berth, QC, and yard allocation is an interesting future direction for academic research.

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Appendix A. Table of Abbreviations

Abbreviation	Meaning
BAPOPT	Berth Allocation Problem Optimizer
CHE	Container-handling equipment
DSS	Decision support system
ETA	Estimated time of arrival
ETD	Estimated time of departure
HDB	Historical database
IT	Information technology
KPI	Key performance indicator
LP	Linear programming
OBJ	Objective
ODB	Operational database
QC	Quay crane
SGICT	Shanghai Guandong International Container Terminal
TEU	Twenty-foot equivalent unit
TOS	Terminal operating system
YB	Yard block
YC	Yard crane

Appendix B. The Decomposition Heuristic

As we describe in the *Solution Approach* section, we decompose the original problem into three subproblems, which we solve sequentially.

Phase 1: In this phase, we solve a discrete berth allocation problem (problem **M1**) as a mixed-integer linear program (MILP). In this discrete berth allocation problem, the planning horizon, which is normally 48 hours, covers a set of nonoverlapping time windows during which vessels can berth and a set of nonoverlapping time windows during which vessels can depart. These two sets of time windows, denoted as Ω^1 and Ω^2, are imposed by the pilot station for the purpose of traffic control for the navigation channel, as we describe above in the *Channel Flow Control* section. For each vessel i, there is also a set Ω_i of nonoverlapping time windows during which vessel i can berth or depart with a satisfactory water level as the water level rises and falls according to the tide cycles. Vessel i may either berth and depart within the same time window in Ω_i (called single-tide-cycle handling) or berth and depart in two consecutive time windows in Ω_i (called double-tide-cycle handling). The start time of each time window in Ω_i is no less than the ETA of vessel i. If vessel i has no water-level requirement, then Ω_i is the interval between the ETA and the end of the planning horizon. The MILP model can be described as follows (note: this is a condensed version of the MILP we implemented at SGICT; it is mathematically equivalent to the implemented version):

Sets:

V: Set of incoming vessels.
B_i: Set of suitable berth segments for vessel $i \in V$.
Ω^1: Set of time windows during which vessels can berth.
Ω^2: Set of time windows during which vessels can depart.
Ω_i: Set of time windows during which vessel i can berth or depart with a satisfactory water level.
$\Gamma_i = \{(\omega, \omega') \mid \omega$ and ω' are consecutive time windows in $\Omega_i\}$.

Input:

w_i: Service priority of vessel i (note: a larger value indicates a higher priority).
W_i: Workload of vessel i (in QC-hours).
S_b: Earliest time that berth b becomes available.
$\alpha_{i\omega}$, $\beta_{i\omega}$: Start and end times of time window $\omega \in \Omega_i$ for vessel i.
α_u^1, β_u^1: Start and end times of time window $u \in \Omega^1$.
α_v^2, β_v^2: Start and end times of time window $v \in \Omega^2$.
N_u^1: Maximum number of vessels that may simultaneously use time window $u \in \Omega^1$.
N_v^2: Maximum number of vessels that may simultaneously use time window $v \in \Omega^2$.
Q_i^1: Estimated number of QCs required by vessel i if single-tide-cycle handling is used.
Q_i^2: Estimated number of QCs required by vessel i if double-tide-cycle handling is used.
τ^1: Berthing setup time.
τ^2: Departure setup time.
τ^3: Travel time for a vessel to get through the navigation channel.
M: A large number.

Decision Variables:

y_{ib}: $=1$ if vessel i is served at berth $b \in B_i$; 0 otherwise.
h_i: Berthing time of vessel i.
l_i: Departure time of vessel i.
$\varepsilon_{i\omega}^1$: $=1$ if vessel i berths during time window $\omega \in \Omega_i$; 0 otherwise.
$\varepsilon_{i\omega}^2$: $=1$ if vessel i departs during time window $\omega \in \Omega_i$; 0 otherwise.
λ_{iu}^1: $=1$ if vessel i berths during time window $u \in \Omega^1$; 0 otherwise.

λ^2_{iv}: $=1$ if vessel i departs during time window $v \in \Omega^2$; 0 otherwise.
σ_i: $=1$ if vessel i uses single-tide-cycle handling; 0 if it uses double-tide-cycle handling.
δ_{ij}: $=1$ if vessels i and j are assigned to the same berth, and i is served earlier than j; 0 otherwise.

Formulation:

$$\textbf{M1}: \quad \text{minimize} \sum_{i\in V} w_i l_i \tag{B1}$$

subject to

$$\sum_{b\in B_i} y_{ib} = 1, \quad i \in V \tag{B2}$$

$$h_i \geq S_b y_{ib}, \quad b \in B_i;\, i \in V \tag{B3}$$

$$\alpha_{i\omega}\varepsilon^1_{i\omega} + \tau^3 \leq h_i \leq M(1-\varepsilon^1_{i\omega}) + \beta_{i\omega}, \quad \omega \in \Omega_i;\, i \in V \tag{B4}$$

$$\alpha_{i\omega}\varepsilon^2_{i\omega} \leq l_i \leq M(1-\varepsilon^2_{i\omega}) + \beta_{i\omega} - \tau^3, \quad \omega \in \Omega_i;\, i \in V \tag{B5}$$

$$\sum_{\omega\in\Omega_i} \varepsilon^1_{i\omega} = 1, \quad i \in V \tag{B6}$$

$$\sum_{\omega\in\Omega_i} \varepsilon^2_{i\omega} = 1, \quad i \in V \tag{B7}$$

$$\alpha^1_u \lambda^1_{iu} \leq h_i \leq M(1-\lambda^1_{iu}) + \beta^1_u, \quad u \in \Omega^1;\, i \in V \tag{B8}$$

$$\alpha^2_v \lambda^2_{iv} \leq l_i \leq M(1-\lambda^2_{iv}) + \beta^2_v, \quad v \in \Omega^2;\, i \in V \tag{B9}$$

$$\sum_{u\in\Omega^1} \lambda^1_{iu} = 1, \quad i \in V \tag{B10}$$

$$\sum_{v\in\Omega^2} \lambda^2_{iv} = 1, \quad i \in V \tag{B11}$$

$$\sum_{i\in V} \lambda^1_{iu} \leq N^1_u, \quad u \in \Omega^1 \tag{B12}$$

$$\sum_{i\in V} \lambda^2_{iv} \leq N^2_v, \quad v \in \Omega^2 \tag{B13}$$

$$l_i - h_j \leq M(1-\delta_{ij}), \quad i, j \in V;\, i \neq j \tag{B14}$$

$$1 - \delta_{ij} - \delta_{ji} \leq M(2 - y_{ib} - y_{jb}), \; b \in B_i \cap B_j;\, i, j \in V;\, i \neq j \tag{B15}$$

$$\varepsilon^2_{i\omega} - \varepsilon^1_{i\omega} \leq 1 - \sigma_i, \quad \omega \in \Omega_i;\, i \in V \tag{B16}$$

$$\varepsilon^2_{i\omega'} - \varepsilon^1_{i\omega} \leq M\sigma_i, \quad (\omega, \omega') \in \Gamma_i;\, i \in V \tag{B17}$$

$$l_i - h_i \geq \frac{W_i \sigma_i}{Q^1_i} + \frac{W_i(1-\sigma_i)}{Q^2_i} + \tau^1 + \tau^2, \quad i \in V \tag{B18}$$

$$l_i, h_i \geq 0, \quad i \in V \tag{B19}$$

$$\begin{aligned} &y_{ib}, \varepsilon^1_{i\omega}, \varepsilon^2_{i\omega}, \lambda^1_u, \lambda^2_v, \sigma_i, \delta_{ij} \in \{0,1\}, \\ &\qquad b \in B_i;\, \omega \in \Omega_i;\, u \in \Omega^1;\, v \in \Omega^2;\, i, j \in V;\, i \neq j \end{aligned} \tag{B20}$$

The objective of **M1** is to minimize the total weighted departure lateness $\sum_{i\in V} w_i(l_i - D_i)$ of vessels, where D_i is the ETD of vessel i. In objective function (B1), the constant term "$\sum_{i\in V} w_i D_i$" has been omitted. Constraint (B2) states that each vessel must be assigned a berth segment. Constraint (B3) ensures that each berth cannot be occupied before it becomes available. Constraints (B4)–(B7) ensure that all vessels can berth and depart with satisfactory water levels. Constraints (B8)–(B11) ensure that the berthing and departure times of all vessels fall within the feasible time windows provided by the pilot station. Constraints (B12) and (B13) limit each time window in Ω^1 and Ω^2, respectively, to be used by a maximum number of vessels. Constraints (B14) and (B15) ensure that either $l_i \leq h_j$ or $l_j \leq h_i$ when vessels i and j are assigned to the same berth segment. Constraints (B16) and (B17) determine whether a vessel requires single-tide-cycle handling or double-tide-cycle handling. Constraint (B18) ensures that the allocated QC capacity is sufficient for covering the workload of each vessel. In this constraint, W_i/Q^1_i is the amount of time vessel i occupies the berth if single-tide-cycle handling is used, and W_i/Q^2_i is the amount of time it occupies the berth if double-tide-cycle handling is used. Constraints (B19) and (B20) specify the nonnegativity and binary requirements of the decision variables.

After solving **M1**, we obtain the berth segment and the berth-stay time interval for each vessel. Each vessel i is also assigned either Q^1_i or Q^2_i QCs, where Q^1_i and Q^2_i are obtained from analyzing the historical operation data.

Phase 2: In this phase, we revise the QC allocation to balance QC utilization. Specific requirements must be satisfied. (1) The number of QCs allocated at any hour t must not exceed the number of QCs available in that hour, $\bar{Q}_t$. (2) The number of QCs allocated to any vessel i must be less than the maximum limit $Q^{\max}_i$. A minimum number of QCs $Q^{\min}_i$ is also imposed for vessel i; however, whether this requirement can be satisfied depends on the availability of QCs. This phase is conducted by executing a heuristic subroutine (procedure **P**). The following are inputs to this subroutine:

$T = \{1, 2, \ldots, H\}$: Set of hours in the planning horizon.
m_t: Number of vessels served at the t-th hour.
$(v^t_1, v^t_2, \ldots, v^t_{m_t})$: Array of vessels that are served at the t-th hour, in ascending order of service priority.
W_i: Workload of vessel i (in QC-hours).
π_i: Historical average handling efficiency of vessel i (QC moves per hour).

The major variables used in this subroutine are as follows:

q_{it}: Number of QCs allocated to vessel i at the t-th hour.
$W'_i = \sum_{t\in T} q_{it}$: QC capacity assigned to vessel i.
$Q^{\text{sum}}_t = \sum_{i\in V} q_{it}$: QC utilization at the t-th hour.
T^1: Set of hours with the highest QC utilization; that is, $T^1 = \{t_1 \in T \mid Q^{\text{sum}}_{t_1} = \max_{t\in T}\{Q^{\text{sum}}_t\}\}$.
T^2_i: Set of hours during which vessel i is served and the QC utilization is not the highest; that is, $T^2_i = \{t_2 \in T \mid t_2 \in [h_i + \tau^1, l_i - \tau^2]$ and $Q^{\text{sum}}_{t_2} < \max_{t\in T}\{Q^{\text{sum}}_t\}\}$.
T^3: Set of hours during which the number of allocated QCs exceeds the number of available QCs; that is, $T^3 = \{t_3 \in T \mid Q^{\text{sum}}_{t_3} > \bar{Q}_{t_3}\}$.
π'_i: Resulting handling efficiency of vessel i.

From the solution of **M1**, we obtain the vessel array $(v_1^t, v_2^t, \ldots, v_{m_t}^t)$ for each $t \in T$. We also obtain $q_{it} = \sigma_i Q_i^1 + (1-\sigma_i) Q_i^2$ for all $t \in [h_i + \tau^1, l_i - \tau^2]$ and $i \in V$ as the initial QC allocation of procedure **P**. Procedure **P** is given as follows, where we assume that the values of W_i' and Q_t^{sum} are updated automatically when the value of q_{it} changes:

Procedure **P**:

Step 1: (Reduce peak QC utilization—Remove surplus QC capacities)

1.1: Determine T^1.

1.2: Randomly select t_1 from T^1. Set $s := 1$.

1.3: Set $i := v_s^{t_1}$. Let $\varphi \geq 0$ be the maximum possible amount that q_{it_1} can be reduced. Set $q_{it_1} := q_{it_1} - \varphi$.

Step 2: (Reduce peak QC utilization—Reallocate QC capacities)

2.1: Determine T_i^2.

2.2: Randomly select t_2 from T_i^2. Let φ be the maximum possible amount that can be transferred from q_{it_1} to q_{it_2}. If $\varphi > 0$, then set $q_{it_1} := q_{it_1} - \varphi$, $q_{it_2} := q_{it_2} + \varphi$, and go to Step 1.

2.3: Set $T_i^2 := T_i^2 \backslash \{t_2\}$. If $T_i^2 \neq \varnothing$, then go to step 2.2.

2.4: If $s < m_{t_1}$, then set $s := s + 1$ and go to step 1.3.

2.5: Set $T^1 := T^1 \backslash \{t_1\}$. If $T^1 \neq \varnothing$, then go to step 1.2.

Step 3: (Postprocessing)

3.1: If $Q_t^{\text{sum}} \leq \bar{Q}_t$ for all $t \in T$, then set $\pi_i' := (W_i / W_i') \pi_i$ for all $i \in V$, terminate the procedure, and output π_i' and q_{it} for all $i \in V$ and $t \in T$; otherwise, determine T^3.

3.2: Randomly select t_3 from T^3. Set $s := 1$ and $\varphi := \lceil (Q_{t_3}^{\text{sum}} - \bar{Q}_{t_3}) / m_{t_3} \rceil$.

3.3: Set $i := v_s^{t_3}$, $q_{it_3} := \max\{0, q_{it_3} - \varphi\}$. If $Q_{t_3}^{\text{sum}} \leq \bar{Q}_{t_3}$, then go to step 3.5.

3.4: If $s < m_{t_3}$, then set $s := s + 1$ and go to step 3.3.

3.5: Set $T^3 := T^3 \backslash \{t_3\}$. If $T^3 \neq \varnothing$, then go to step 3.2; otherwise, go to step 3.1.

This procedure attempts to iteratively reduce the QC engagement at peak hours (Steps 1 and 2). It also revises the handling efficiency for the vessels to guarantee feasibility of the QC allocation solution (Step 3). In Steps 1 and 2, to avoid having a large variation in the number of QCs assigned to a vessel, a condition is imposed such that the difference between the numbers of QCs assigned to a vessel at successive hours must not exceed a given threshold ρ. In step 1.3, the value of φ is selected such that it does not exceed $W_i' - W_i$, and that the new q_{it_1} value is no smaller than $Q_i^{\min}$, $q_{i,t_1-1} - \rho$ (if $t_1 - 1 \in [h_i + \tau^1, l_i - \tau^2]$), and $q_{i,t_1+1} - \rho$ (if $t_1 + 1 \in [h_i + \tau^1, l_i - \tau^2]$). In step 2.2, the value of φ is selected such that the new q_{it_1} value is no smaller than $Q_i^{\min}$, $q_{i,t_1-1} - \rho$ (if $t_1 - 1 \in [h_i + \tau^1, l_i - \tau^2]$), and $q_{i,t_1+1} - \rho$ (if $t_1 + 1 \in [h_i + \tau^1, l_i - \tau^2]$), that the new q_{it_2} value is no larger than $Q_i^{\max}$, $q_{i,t_2-1} + \rho$ (if $t_2 - 1 \in [h_i + \tau^1, l_i - \tau^2]$), $q_{i,t_2+1} + \rho$ (if $t_2 + 1 \in [h_i + \tau^1, l_i - \tau^2]$), and that the updated $Q_{t_2}^{\text{sum}}$ value is no larger than $\bar{Q}_{t_2}$ and $Q_{t_1}^{\text{sum}} - 1$.

In Step 3, the procedure resolves conflicts by preventing the number of allocated QCs from exceeding the number of available QCs, but relaxing the QC allocation criteria (as we describe in the *QC Allocation* section). In steps 3.2 and 3.3, when a period $t_3 \in T^3$ with $Q_{t_3}^{\text{sum}} > \bar{Q}_{t_3}$ is identified, the QC allocation q_{it_3} is reduced. Step 3 terminates once the condition "$Q_t^{\text{sum}} \leq \bar{Q}_t$ for all $t \in T$" is met. After executing procedure **P**, the allocated QC capacities may become less than the QC requirements of some vessels (i.e., $W_i' < W_i$ for some $i \in V$). Those vessels are thus expected to be handled with higher QC efficiency to finish the service on schedule. The indicator π_i' is used to inform planners about the handling efficiency required for vessel i to achieve the given solution.

In Steps 1–3, we always begin by revising the QC allocation for vessels with lower service priorities. This strategy aims to maintain the QC productivity for the higher-priority vessels by making their QC engagement at different hours as stable as possible. Procedure **P** is executed 100 times and the resulting solution in the minimum peak QC utilization is kept as the final solution. If more than one solution obtains the same maximum QC utilization, planners will determine which solution to accept based on their preferences on QC allocation patterns and the corresponding handling efficiency of vessels.

Phase 3: In this phase, we find exact berthing positions for the incoming vessels. We define an overlap matrix $\{O_{ij} \mid i, j \in V \cup V'\}$, where

$$O_{ij} = \begin{cases} 0, & \text{if } l_i \leq h_j \text{ or } h_i \geq l_j; \\ 1, & \text{otherwise}; \end{cases} \tag{B21}$$

where V' is the set of vessels that are being served at the beginning of the planning horizon. Vessels i and j cannot overlap along the quay if $O_{ij} = 1$. All the incoming vessels are positioned by solving the following LP model:

Sets:

V: Set of incoming vessels.
V': Set of vessels that are being served at the beginning of the planning horizon.
K_i: Set of YBs that receive or provide containers for vessel i.

Input:

$\{O_{ij} \mid i, j \in V \cup V'\}$: Overlap matrix.
C_{ik}: Number of containers to be handled in YB k for vessel i.
U_k: Position of YB k on the quay axis.
P_i: Bow position of vessel i, for $i \in V'$.
P_i^1, P_i^2: Start and end positions of the suitable berthing range for vessel i (i.e., the consecutive berth segments in B_i).
L_i: Length of vessel i.
μ: Safety clearance between two vessels that are served simultaneously at berth.
X_{ij}: =1 if vessel i is associated with a smaller berth number compared to vessel j; 0 otherwise.
M: A large number.

Decision Variables:

p_i: Bow position of vessel i along the quay, for $i \in V \cup V'$.
d_{ik}: Horizontal container transportation distance between vessel i and YB k.

$$\textbf{M2:} \quad \text{minimize} \sum_{i\in V}\sum_{k\in K_i} C_{ik} d_{ik} \tag{B22}$$

subject to

$$p_i \ge P_i^1, \quad i \in V \tag{B23}$$

$$p_i + L_i \le P_i^2, \quad i \in V \tag{B24}$$

$$p_i = P_i, \quad i \in V' \tag{B25}$$

$$p_i + L_i + \mu - p_j \le M(1 - X_{ij}), \quad i, j \in V \cup V'; i \ne j; O_{ij} = 1 \tag{B26}$$

$$d_{ik} \ge \left(p_i + \frac{L_i}{2}\right) - U_k, \quad k \in K_i; i \in V \tag{B27}$$

$$d_{ik} \ge U_k - \left(p_i + \frac{L_i}{2}\right), \quad k \in K_i; i \in V \tag{B28}$$

$$p_i, d_{ik} \ge 0, \quad k \in K_i; i \in V \tag{B29}$$

Objective function (B22) minimizes the total horizontal container transportation distance covered by the trailers. Constraints (B23) and (B24) ensure that all vessels are positioned within their suitable berthing ranges. Equation (B25) fixes the berthing positions for vessels that are already at berth. Constraint (B26) imposes a safety clearance between vessels. Constraints (B27) and (B28) imply that $d_{ik} \ge |(p_i + L_i/2) - U_k|$, where $|(p_i + L_i/2) - U_k|$ is the horizontal distance between vessel i and YB k. Constraint (B29) specifies the nonnegativity requirements of the decision variables.

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Verification Letter

Zhou Yu, Vice General Manager, Shanghai Guandong International Container Terminal Co., Ltd. (SGICT), No. 1 Tonghui Road, Luchao Town, Nanhui District, Shanghai, China 201308, writes:

"I hereby confirm that the decision support system, BAPOPT, developed by Dr. Yi Ding and his team, has been successfully deployed and used at SGICT. The results presented in the manuscript 'SGICT Builds an Optimization-Based System for Daily Berth Planning' have been approved by our company's senior management.

"Berth planning has never been an easy task at SGICT. The frequently updated vessel information, complicated hydrological and geographical conditions, and various operational requirements have made the berth planning process quite difficult to carry out. In the past, the planning process was done manually and required several hours. With the support of operations research methodology, our new system is able to generate more reasonable and reliable berth plans automatically within several minutes. As a result, the efficiency of the berth planning process has increased substantially. The system also enables our planners to analyze the impacts of various factors on the vessel service, which helps them gain deeper insights into the berth planning business. It also serves as a simulation tool that helps our planners understand the terminal operation under different scenarios. For example, it can inform us how the daily workload distribution of the container yard will be affected if one more vessel or one fewer vessel is admitted to the terminal.

"Our next step is to develop more sophisticated decision support tools to support the quay crane scheduling and vessel stowage processes, which involve even more detailed and complicated operational considerations. This will definitely be a more challenging and time-consuming project. However, with the success of BAPOPT, we are confident about the development of these new planning tools."

Yi Ding is a lecturer at the Logistics Research Center of Shanghai Maritime University, where he obtained his doctoral degree in logistics engineering. As a project manager of Shanghai International Port (Group) Co., Ltd., he has ten years of experience in developing container terminal operating systems and some decision support systems for port operations. He currently provides consulting services for port companies. His research focuses on optimization of container terminal operations and information systems. He has authored a book and several journal articles in these fields.

Shuai Jia is a PhD student at the Department of Logistics and Maritime Studies of The Hong Kong Polytechnic University. He obtained a master's degree and a bachelor's degree in logistics engineering from Shanghai Maritime University and Shandong Jiaotong University, respectively. Prior to commencing his PhD study, he worked for Shanghai International Port (Group) Co., Ltd. for three years as a software engineer and business analyst. His research interests include port operations management, maritime logistics, supply chain management, and combinatorial optimization.

Tianyi Gu is a PhD student at the Department of Computer Science of the University of New Hampshire. He obtained a master's degree and a bachelor's degree in logistics engineering from Shanghai Maritime University. Prior to commencing his PhD study, he worked for Shanghai International Port (Group) Co., Ltd. for three years as a software engineer and business analyst. His research interests include artificial intelligence, heuristic search, robotics, multi-agent systems, and machine learning.

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