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# SGICT Builds an Optimization-Based System for Daily Berth Planning

In container terminal operations, the allocation of berth-side resources to serve calling vessels is called berth planning. Generally, berth planning involves determining for each vessel the time interval for berth stay (i.e., berthing/departure times and handling start/end times), the berthing position along the quay, and the number of quay cranes (QCs) that will be dedicated to handle it, with the objectives to maximize the vessel service levels (i.e., minimizing 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 of the Port of Shanghai, to optimize berth planning in daily practice. We embed our solution into a decision support system, BAPOPT, which provides planners at SGICT with effective and executable berth plans. Using BAPOPT, SGICT expects to improve vessel handling productivity by at least 15%. With the support of BAPOPT, SGICT has started shifting its operational emphasis from reactive real-time dispatching to proactive resource planning, helping to relieve the operations department from much tedious work and to improve the work efficiency of the 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 162 million twenty-foot equivalent units (TEUs) in the past five years, ranking the first among all leading ports in total throughput since 2010. In 2014, the Port of Shanghai handled an unprecedented 35.2 million TEUs, and this number is expected to increase further in 2015.

Shanghai Guandong International Container Terminal (SGICT), one of the largest container terminals of the Port of Shanghai, provides container handling service for both domestic and international shipping lines, with a business scope covering import, export, and transshipment containers. It is part of the Yangshan Deep-water Port located on Yangshan islands, southeast of Shanghai. It 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 are utilized to serve over 150 deep-sea vessels and 100 feeders and barges, producing an average throughput of 0.45 million TEUs.

Owing to the rapid development of China's economy and international trade, the number of containers to be handled at SGICT is expected to increase steadily over the following years. However, SGICT's managers found that, after several rounds of equipment upgrades, they can hardly improve the terminal productivity by further introducing new facilities. The only way to seize the business growth opportunity is to implement technological innovation to support decision-making concerning the utilization of available resources. After a thorough investigation on the business processes of SGICT, the managers have identified berth planning as the starting point of this innovation.

The berth planning process of SGICT consists of the following three levels (see Figure 1):

(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, before feeding them into the information technology (IT) system.

(2) Weekly planning: SGICT receives updated information on vessels' estimated time of arrival (ETA) and estimated time of departure (ETD) from the shipping lines

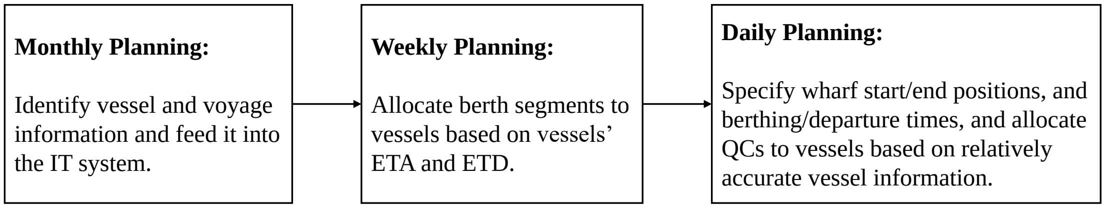

**Figure 1** **The berth planning process at SGICT comprises three levels.**

and assigns a berth number to each vessel without the exact berthing start and end times. It is a precondition for yard planning in order to allocate yard space to receive containers near the berth. During weekly planning, very little information is known on the loading/unloading operations of the vessels, and decisions are made mainly by analyzing the historical data of the vessels.

(3) Daily planning: Daily planning is the most critical step in the berth planning process, as 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 are most interested in daily berth planning, because it is based on more accurate information and is carried out just before execution. Hence, the main focus of this project is to analyze the daily berth planning process and propose solutions that drives efficiency at this planning level. In this project, we (1) modeled the daily berth planning problem by 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 evaluation of the planning performances.

In the following, we provide an introduction of the berth planning operation 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 point out directions for future research. Appendix A provides a table of abbreviations that are used in this paper, and 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 (see Figure 2). It provides planners with necessary information to devise crane work plans and vessel stowage plans that 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 decides on 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. Since 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 was previously carried out manually using spreadsheets. The daily berth planning begins at 10 am and must finish by 2 pm the day before execution. Because of the lack of KPIs, different planners would generate different plans following their own preferences and logics, leading to inconsistent resource utilization and vessel service. Moreover, making a berth plan involves respecting a number of practical restrictions. Because some of these restrictions are too complex for the planners to take into account,

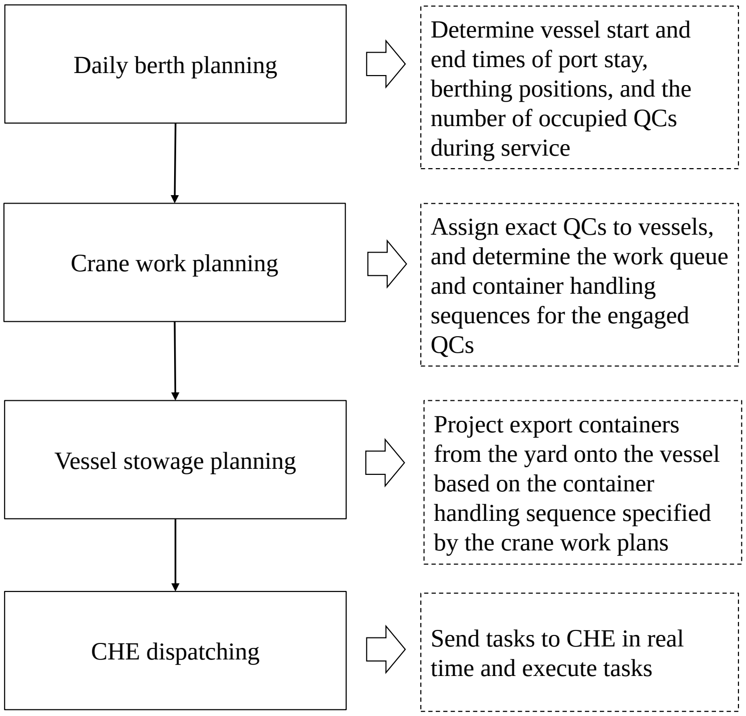

**Figure 2** **SGICT's daily operations are multi-layered, where the berth planning serves as the cornerstone.**

the only way for the planners to devise the plan is to rely on their personal experience. A typical example is that when determining the berthing and departure times of vessels, planners should take the berthing and departure time windows for different vessels into account. However, the planners are not clear about how a vessel's occupation of time windows could affect the berthing and departure times for other vessels. Consequently, most planners determine the berth stay intervals for vessels based on their knowledge from past vessel handling records without taking enough consideration of the time window requirements. As a result, most plans go awry during execution, and the operations department has to bear tedious workloads dealing with "planning" and execution simultaneously and reactively, which hindered the exploitation of the full terminal productivity. According to our evaluation, the initial planning process has the following limitations:

- The manual process is cumbersome and time-consuming.
- The resulting plans are unreliable and unexecutable.

- The lack of definitions of KPIs makes it difficult to evaluate the effectiveness of a plan.
- The manual process cannot 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 flexibility in decision making.
- Define KPIs that provide insights into the berth planning performances.

## Problem Description

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

### Time Periods of Vessel Port Stay

Figure 3 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 an anchorage where it is parked 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 arriving at the berth (period 2). Before QCs start handling a vessel, berthing and handling setup operations, including docking, tying ropes, removing twist locks, etc., 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 part in daily berth planning is to determine the vessels' berth stay intervals (i.e., periods 3 to 5 as shown in Figure 3), and the specific berthing locations assigned. QC utilization during this productive period must also be specified.

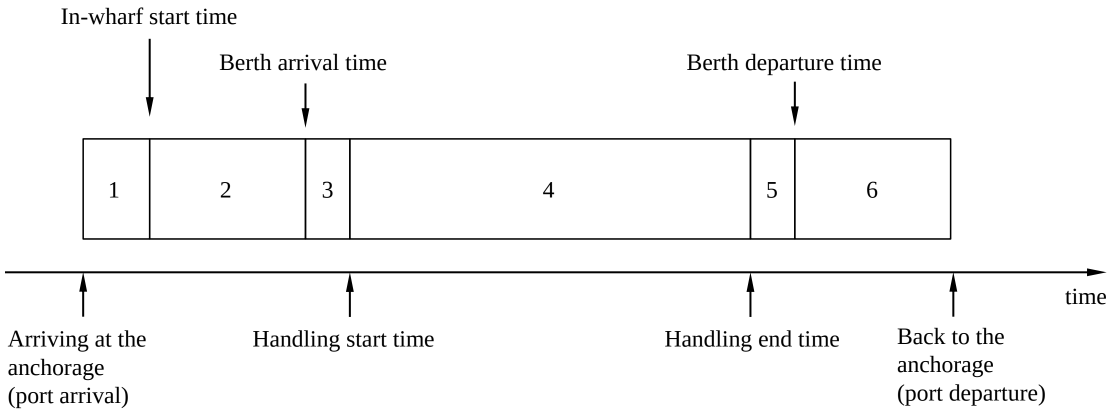

**Figure 3** **The vessel port stay interval consists of some important time periods.**

## Vessel Service

Shipping lines usually propose ETDs for vessels as part of the service requirements. Some vessels are also specified with a minimum number of QCs for handling. However, whether these requirements can be satisfied or not would depend on factors such as the deviations between actual arrival times and the ETAs, and the terms of service provided by the terminal. Nevertheless, the terminal often prefers completing vessel handling as quickly as possible in order to offer favorable service to shipping lines, while increasing berth productivity. When multiple vessels compete for limited berth space, planners often assign priorities to the vessels and decide on the order of service for them. For example, vessels of VIP customers are usually served before vessels of regular customers, since the former are given additional service guarantees and so are assigned with 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 due to huge mass of silt washed from the estuary of Yangtze River. As larger vessels usually require higher water levels to pass through the channel, their berthing and departure times depend on the tide.

The determination of vessel berthing and departure times is a time-consuming matter for planners because they have to decide carefully on whether the berth stay interval of a vessel should fall within a single tide cycle or multiple tide cycles. Figure 4 presents the variation of water levels over time, and the possible berth stay intervals of a vessel. In general, a single-tide-cycle berth stay interval guarantees a short vessel turnaround time, but results in high QC occupation in order to speed up the handling process, which may hinder the handling efficiency for other vessels. In contrast, a multi-tide-cycle berth stay interval requires fewer QCs but is unfavorable for maintaining high berth productivity, leading to possible delayed departure of subsequent vessels.

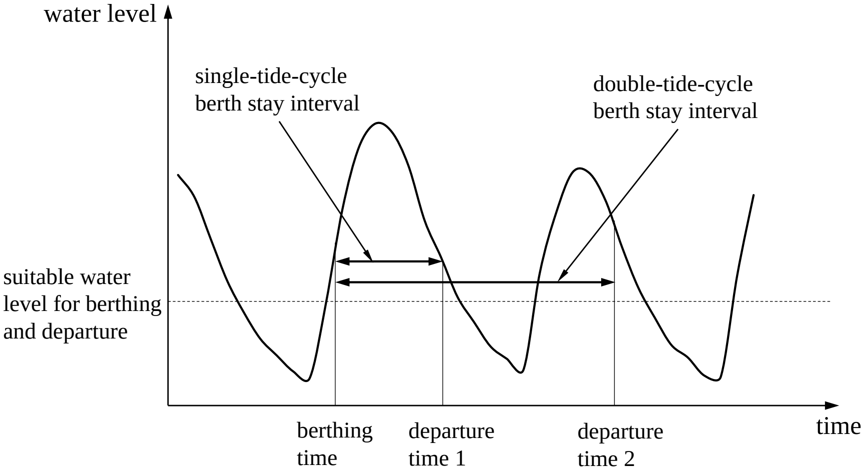

**Figure 4** **A vessel should berth and depart with satisfactory water levels.**

To improve the overall vessel handling capacity, one important issue in daily berth planning is to find the appropriate pace of handling for each vessel that accounts for the tide windows.

### Channel Flow Control

The navigation channel of SGICT is surrounded by many small islands (namely the Qiqu Archipelago), and is therefore under strict regulations of the pilot station for safety reasons. Vessels sailing in the channel must be guided by pilot ships to ensure safe sailing routes and speed. Because of the limited number of pilot ships, the berth plan is subject to the so-called channel flow control requirement, which limits the number of vessels that could simultaneously sail in the channel. Moreover, since SGICT shares the channel with a neighboring container terminal, the use of the navigation channel by the neighboring terminal must also be taken into account. This limitation is hard to quantify and is considered by planners based on their experience.

After lengthy discussions with the pilot station, we were allowed to surrogate the flow control by introducing additional berthing and departure time windows (proposed by the pilot station) for the incoming and outgoing vessels. The pilot station states whether each of these time windows can be used for berthing or departure, and the maximum number of vessels that can use it.

Once a plan is devised, it is sent to the pilot station to identify any potential incompliances with safety requirements. If violations are detected, the pilot station suggests plan revisions, or re-specifies the berthing and departure time windows such that the terminal can generate a satisfactory plan.

### Vessel Positioning

The 2,600-meter quaywall of SGICT is divided into seven berth segments, each assigned with 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 water depth up to 18 meters. These berths are generally dedicated to deep-sea vessels that are larger and carry more containers. Small ships, such as barges and shallow-draft feeders, usually share shorter berth segments and use fewer QCs as there are fewer containers to be handled.

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, with reference to 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, and is used at the operational level by berth planners to determine the exact berthing positions for vessels such that the overall horizontal distance between the vessel and the 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; see Legato et al. 2013) are minimized.

### QC Allocation

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 hourly engaged QCs. This is beneficial for reducing the number of YCs, number of trailers, and manpower to be dispatched for each work shift, since the maximum hourly throughput would be lowered, leading to both improved CHE utilization and saving in operating costs.

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 vessel service. This arrangement often results in poor QC utilization and underestimation of QC capacity as it prevents vessels from sharing QCs during vessel handling. However, during execution, sharing QCs among vessels is very critical not only for making good use of idle QCs, but also for controlling the pace of the handling process.

To improve QC utilization, we propose a time-variant QC allocation scheme that allows flexible QC engagement. We adopt the concept of *QC-hours* (Meisel and Bierwirth 2009) to measure the vessel workload. Here, a QC-hour represents one hour of QC handling capacity. Adopting this concept allows us to assign different number of QCs to a vessel in different hours as long as the overall assigned QC capacity is sufficient to cover the vessel's workload.

When moving containers, the productivity of a QC (i.e., number of moves per hour) is dependent on both the vessel structure and the type of containers that are being handled. The QC productivity for each vessel is stored in an array called "QC productivity profile." This QC productivity 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 certain 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 is expected to be no less than the minimum number of QCs required by the vessel.

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

(3) The number of QC-hours allocated to a vessel is expected to be no less than the number required by the vessel.

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) pursues to achieve suitable handling efficiency for vessels by allocating adequate QC-hours. These three criteria may be violated in case problem infeasibility is encountered. For example, if the total number of available QC-hours is insufficient, then some vessels are allowed to be allocated fewer QC-hours than needed, resulting in a violation of criterion (3). In such case, the vessel should be handled with a higher efficiency in order to finish the service in time. However, such efficiency increase is undesirable as the system needs to run above their designed capacity, and imposes additional pressure on the yard operations in order to provide adequate support to the QCs.

**Objective Priorities**

The managers of SGICT would like our system to achieve the following objectives:

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

Due to the fierce competition from other domestic and international ports, improving vessel service is of paramount importance from the managers' perspective. Thus, OBJ 1 is considered to be the most compelling and should be highly prioritized. Improving performance in the resource utilization is also critical, since it has a major impact on container handling efficiency and operating costs. Therefore, OBJ 2 is prioritized just below OBJ 1 and above OBJ 3.

In multi-objective 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 rather 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 propose 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). Our solution approach is presented in the next section.

# Solution Approach

The problem 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 review of the related problems that have been studied. Researchers have studied berth allocation problems at both tactical level (Giallombardo et al. 2010) and 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 various business scenarios have been investigated in previous works, only a few articles have considered the impact of tidal effect on berth operation and navigation channel control; see, for example, Xu et al. (2012) and Du et al. (2015). The control of resource utilization during vessel handling has also received relatively little attention in the berth and quay crane allocation literature despite its practical significance on cost saving. To the best of our knowledge, no published work has provided satisfactory solutions that meet the demand of SGICT: The existing methodologies either cost excessive computational efforts in addressing an integrated problem, or fail to capture SGICT's berth planning business, which has multiple objectives and decision criteria.

In view of the problem complexity and the multi-objective nature of the problem, we develop a decomposition heuristic and address 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, the planning horizon is extended 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 in order to berth and depart within feasible time windows (normally, the duration of berth stay for a vessel cannot exceed two tide cycles in order to achieve acceptable berth productivity). In addition, depending on the length of the berth stay interval, each vessel is assigned an average number of QCs, which is derived 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, with a goal to balance the QC utilization within the extended planning horizon. The reallocation of QCs is performed 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 the reallocation, a post-processing step is invoked 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 described in the *QC Allocation* section). In case the QC capacities of some vessels become insufficient to cover their workloads, the subroutine suggests higher QC handling efficiency for these vessels in order to finish the service in time.

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, safety clearance between vessels, 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 can overlap with each other (see Appendix B for details). Because each vessel is 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 in a decomposition manner are threefold. First, the complexity of the problem is greatly reduced. The technique offers shorter computational time for solving each of the subproblems and enables fast generation of feasible solutions, which is very 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 remodeling the whole problem to deal with changed demand, the heuristic requires only the corresponding subproblem to be modified, which greatly facilitates the maintenance of the optimization engine. Despite some common weaknesses associated with decomposition approaches, such as weakened solution quality caused by the lack of connections among different subproblems, or infeasibility resulted by improper decomposition of the original problem, applying decomposition appears to be very attractive for solving many practical problems.

## System Implementation

SGICT is equipped with a terminal operating system (TOS), which is an IT system dedicated to the terminal's operations. The TOS connects directly to the operational database (ODB) and provides information for different departments to execute the corresponding business processes.

To support the berth planning process, we integrated our solution into the TOS and developed a DSS, called Berth Allocation Problem Optimizer (BAPOPT), with our decomposition heuristic embedded in its kernel. Figure 5 shows the integration framework of BAPOPT and the data flows between different module components. All the input data of our optimizer are originated from two databases—ODB and historical database (HDB). The ODB stores general terminal configurations (berth, QC, and yard configurations, etc.), tide tables, algorithm parameters (planning horizon, priority settings, etc.). It also stores the operational data (weekly plan, vessel information, container distribution in the yard, QC availability, etc.), which are filtered and organized in the TOS modules before feeding into the optimizer.

Old 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, in which time series analysis is applied to estimate the QC allocation profiles (i.e., the number of QCs used for different berth stay intervals) and the QC productivity profiles for different vessels.

Before the heuristic is invoked, all the input data should be handled by a preprocessor to perform data verification, time window calculation, and workload transformation. The preprocessor standardizes the necessary data for our algorithm and ensures 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.

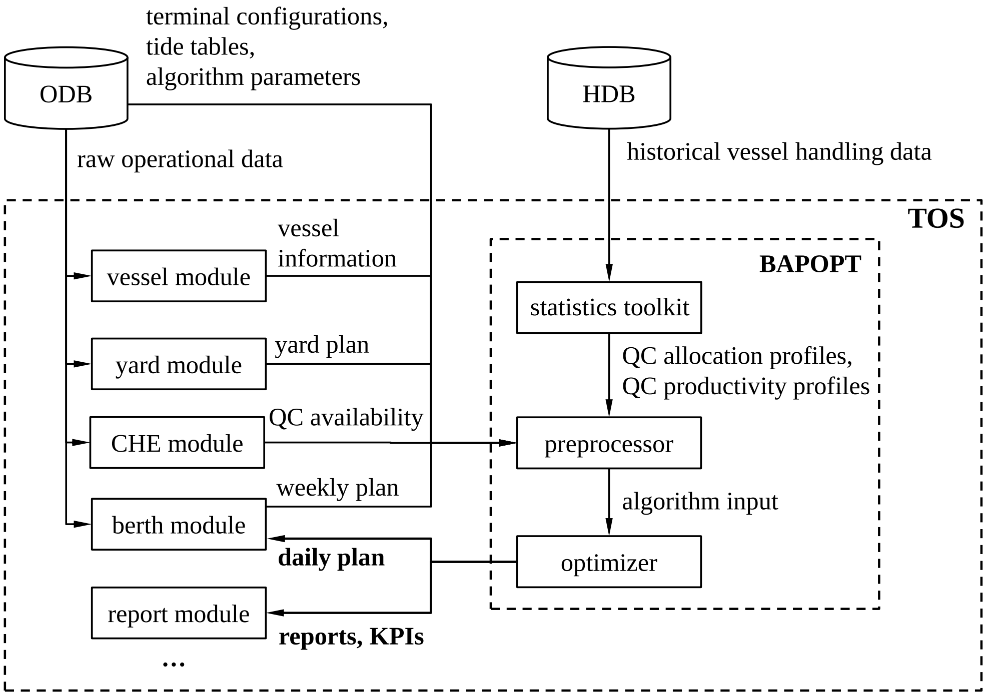

**Figure 5** **In the integration framework, BAPOPT receives data from the related TOS modules and the HDB, and outputs the daily berth plan, KPIs and reports to the berth module and report module.**

BAPOPT uses a software framework on which the TOS is based. Hence, without any data adapters, the berth plans generated by BAPOPT can be accessed by the berth module where they are visualized, making it convenient for planners to modify and evaluate their plans. In addition, the integration framework greatly facilitates uncertainty handling. If a daily berth plan cannot be executed successfully due to unexpected events, such as QC breakdowns, loading/unloading uncertainties, inaccurate ETAs and ETDs, etc., planners can perform re-planning by simply re-running the optimizer. In this case, BAPOPT is able to access the latest information from the TOS modules and generate a new berth plan quickly with the updated input data.

## Results

To evaluate the computational performance of our system, we extract typical busy-day instances from the HDB and summarize the corresponding performance characteristics.

The tests were performed on an i5-2450M processor with 8GB RAM. As can be seen from Table 1, the majority of the computational efforts are expended 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 2 seconds) because efficient solution strategies are applied. The fast generation of solutions is critical to SGICT as it enables planners to perform re-planning whenever necessary (e.g., when the arrival plan of a vessel is cancelled unexpectedly), and to perform what-if analysis based on different scenario configurations to support better decisions.

| 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 | 21426 | 2.1 | 8.2 | 1.2 | 0.5 |
| 10 Feb 2015 | 8 | 4 | 29230 | 2.5 | 10.7 | 1.0 | 0.5 |
| 12 Feb 2015 | 6 | 6 | 21141 | 1.8 | 9.1 | 0.8 | 0.4 |
| 13 Feb 2015 | 7 | 5 | 25144 | 2.0 | 10.8 | 1.5 | 0.5 |
| 18 Feb 2015 | 7 | 6 | 25627 | 2.0 | 9.2 | 1.6 | 0.5 |
| 22 Feb 2015 | 8 | 6 | 29377 | 1.5 | 11.5 | 1.5 | 0.3 |
| 25 Feb 2015 | 7 | 7 | 26302 | 2.1 | 10.1 | 1.1 | 0.4 |
| 28 Feb 2015 | 6 | 8 | 24672 | 2.4 | 8.9 | 0.8 | 0.6 |
| 29 Feb 2015 | 7 | 6 | 25320 | 1.8 | 9.6 | 1.1 | 0.4 |

**Table 1 BAPOPT runs efficiently on real-world problems.**

In response to SGICT's lack of knowledge about the 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 available QC-hours.
- KPI 3: Berth utilization rate—measured by meter-hours for vessel handling divided by the total available meter-hours.
- KPI 4: Service level by vessel—measured by total number of hours of lateness.

KPI 1 reflects the overall QC productivity. A higher value of KPI 1 indicates higher vessel handling efficiency accomplished by the terminal. KPIs 2 and 3 reflect the performance of the terminal resource utilization. If the overall workload (i.e., the total number of containers to be handled) of the terminal is 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) due to better berth plans, then the values of KPIs 2 and 3 will increase with increased value of KPI 1. Therefore, improving KPIs 1–3 simultaneously is desirable from the terminal's perspective. As for KPI 4, lower values usually indicate better vessel service that is provided by the terminal.

Figure 6 depicts SGICT's average planning performance of 2014 (i.e., before adopting BAPOPT) and that of the first quarter of 2015 (i.e., after adopting BAPOPT). As shown in the figure, 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 appropriate vessel handling paces and resource utilization, and eventually allows more vessels to be served than in plans generated manually. Because of the improved KPIs 1–3, managers from SGICT are confident to expect at least 15% of improvement in overall terminal productivity.

Before using BAPOPT, planners tended to reserve as many QCs as possible for large vessels to achieve short turnaround times while paying little attention to the sufficiency of QC capacities for feeders and barges. In our view, over-emphasizing 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 on comprehensive instances and compared our solutions with manually generated

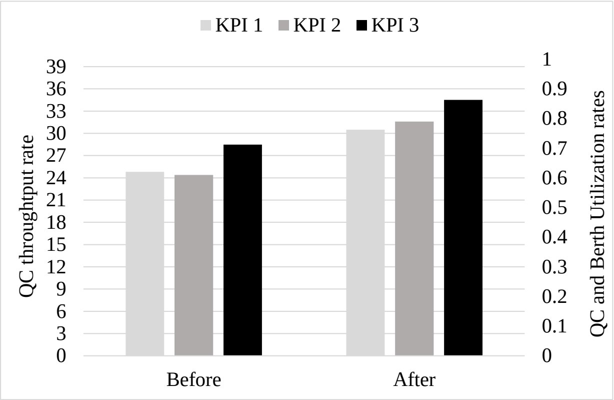

**Figure 6** **SGICT realizes tangible improvements in KPIs 1–3 by using BAPOPT.**

ones. The simulation results showed that our solution was able to make KPI 4 to be at the same level as the manual solution did for deep-sea vessels with the addition of improved service for feeders and barges. Moreover, our solution was able to handle two more vessels per day on average than the manual solution. This productivity enhancement corresponded to an increment in monthly throughput of about 80,000 TEUs.

Owing to the effective underlying heuristic, BAPOPT has considerably improved the work efficiency of the planning department—it has reduced the time spent on daily berth planning from 4 hours to less than 1 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 in a rolling-horizon fashion. In addition, the availability of a reliable solution has relieved the control room from frequent plan revisions during execution. The new method is superior to previous empirical method in the following aspects:

- It enables fast generation of solutions, making the execution of berth planning much simpler.
- It accounts for various practical restrictions and produces executable plans.
- It improves terminal productivity and yields better resource utilization.

The managers of SGICT have realized that the decomposition heuristic satisfies their requirements in pursuing different goals, and BAPOPT is of great value as it lays a solid foundation for technological innovation in decision-making 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 is a significant progress in container terminal management.

## Extensions and Future Research

Although successfully deployed and used, our BAPOPT needs further extensions as several issues remain to be addressed based on user feedback: (1) Because the heuristic is unable to determine whether a vessel should be served or not, it suffers from infeasibility when excessive vessels are imported into the optimizer. Thus, it relies on planners' preferences and tuning efforts to perform vessel selection under hectic conditions (i.e., when too many vessels are waiting at the anchorage). (2) The time-variant QC allocation scheme allocates the number of QCs to each vessel at each hour. However, it does not explicitly specify which QCs should be allocated to a vessel. This has made the allocation and scheduling of exact QCs rather complex to perform manually.

Tackling these problems will be the focus of development in the future. First, we intend to introduce additional binary variables in our model to enable automated vessel selection. However, this decision is subject to several factors, such as the requirements of balancing service for various VIP customers, coordinating the vessel handling time with the arrival times of export containers, and the trade-off between increasing berth throughput and controlling the density of tasks in the yard. More investigations are needed to quantify these requirements in order to make our model applicable in practice. 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 in our solution framework, as was studied by Meisel and Bierwirth (2013). The main challenge in this regard is to deal with the QC scheduling efficiently while respecting the resource restrictions in a multi-vessel environment.

Besides the above issues, another possible weakness of our decomposition solution approach could be weakened solution quality caused by the lack of connections among different subproblems as mentioned in the *Solution Approach* section. Our heuristic decomposes the problem into three phases, and executes the three phases only once. One possible way to improve the effectiveness of our solution method would be to develop an iterative heuristic that returns to phase 1 after executing phases 2 and 3, and continues to search for improvement until it reaches certain stopping criterion. This approach, however, will increase the computational time.

Another weakness of our decomposition approach is that it uses the weekly berth plan to generate the berth allocation solution in phase 1 without taking into account the actual 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. However, this assumption may not hold in practice since yard allocation is changed 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 may not generate a good solution in the third phase. In view of this, further investigation in integrating berth allocation, QC allocation, and yard allocation could be an interesting future direction for academic research.

## 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 cranes |
| 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 described in the *Solution Approach* section, the original problem is decomposed into three subproblems, which are solved in a sequential manner.

**Phase 1:** In this phase, we solve a discrete berth allocation problem (problem **M1**) as an MILP. In this discrete berth allocation problem, the planning horizon, which is normally 48 hours long, covers a set of non-overlapping time windows during which vessels can berth and a set of non-overlapping time windows during which vessels can depart. These two sets of time windows, denoted $\Omega^1$ and $\Omega^2$, are imposed by the pilot station for the purpose of traffic control for the navigation channel (as described in the *Channel Flow Control* section). For each vessel $i$, there is also a set $\Omega_i$ of non-overlapping time windows during which vessel

$i$ can berth or depart with satisfactory water level as the water level goes up and down according to the tide cycles. Vessel $i$ may either berth and depart within the same time window in $\Omega_i$ (called "single-tide-cycle handling") or berth and depart in two consecutive time windows in $\Omega_i$ (called "double-tide-cycle handling"). The start time of each time window in $\Omega_i$ is no less than the ETA of vessel $i$. If vessel $i$ has no water level requirement, then $\Omega_i$ 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 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 $i \in V$.

$\Omega^1$: Set of time windows during which vessels can berth.

$\Omega^2$: Set of time windows during which vessels can depart.

$\Omega_i$: Set of time windows during which vessel $i$ can berth or depart with satisfactory water level.

$\Gamma_i = \{(\omega, \omega') \mid \omega \text{ and } \omega' \text{ are consecutive time windows in } \Omega_i\}$.

Input:

$w_i$: Service priority of vessel $i$ (note: a larger value indicates 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 $i$.

$\alpha_u^1$, $\beta_u^1$: Start and end times of time window $u \in \Omega^1$.

$\alpha_v^2$, $\beta_v^2$: Start and end times of time window $v \in \Omega^2$.

$N_u^1$: Maximum number of vessels that may use time window $u \in \Omega^1$ simultaneously.

$N_v^2$: Maximum number of vessels that may use time window $v \in \Omega^2$ simultaneously.

$Q_i^1$: 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.

$\tau^1$: Berthing setup time.

$\tau^2$: Departure setup time.

$\tau^3$: 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 $i$.

$\varepsilon^1_{i\omega}$: $=1$ if vessel $i$ berths during time window $\omega\in\Omega_i$; 0 otherwise.

$\varepsilon^2_{i\omega}$: $=1$ if vessel $i$ departs during time window $\omega\in\Omega_i$; 0 otherwise.

$\lambda^1_{iu}$: $=1$ if vessel $i$ berths during time window $u\in\Omega^1$; 0 otherwise.

$\lambda^2_{iv}$: $=1$ if vessel $i$ departs during time window $v\in\Omega^2$; 0 otherwise.

$\sigma_i$: $=1$ if vessel $i$ uses single-tide-cycle handling; 0 if it uses double-tide-cycle handling.

$\delta_{ij}$: $=1$ if vessels $i$ and $j$ are assigned to the same berth, and $i$ is served earlier than $j$; 0 otherwise.

Formulation:

$$\textbf{M1}:\quad \text{minimize} \quad \sum_{i\in V} w_i l_i \tag{1}$$

$$\text{subject to} \quad \sum_{b\in B_i} y_{ib}=1,\quad i\in V \tag{2}$$

$$h_i\ge S_b y_{ib},\quad b\in B_i;\, i\in V \tag{3}$$

$$\alpha_{i\omega}\varepsilon^1_{i\omega}+\tau^3\le h_i\le M(1-\varepsilon^1_{i\omega})+\beta_{i\omega},\quad \omega\in\Omega_i;\, i\in V \tag{4}$$

$$\alpha_{i\omega}\varepsilon^2_{i\omega}\le l_i\le M(1-\varepsilon^2_{i\omega})+\beta_{i\omega}-\tau^3,\quad \omega\in\Omega_i;\, i\in V \tag{5}$$

$$\sum_{\omega\in\Omega_i}\varepsilon^1_{i\omega}=1,\quad i\in V \tag{6}$$

$$\sum_{\omega\in\Omega_i}\varepsilon^2_{i\omega}=1,\quad i\in V \tag{7}$$

$$\alpha^1_u\lambda^1_{iu}\le h_i\le M(1-\lambda^1_{iu})+\beta^1_u,\quad u\in\Omega^1;\, i\in V \tag{8}$$

$$\alpha^2_v\lambda^2_{iv}\le l_i\le M(1-\lambda^2_{iv})+\beta^2_v,\quad v\in\Omega^2;\, i\in V \tag{9}$$

$$\sum_{u\in\Omega^1}\lambda^1_{iu}=1,\quad i\in V \tag{10}$$

$$\sum_{v\in\Omega^2}\lambda^2_{iv}=1,\quad i\in V \tag{11}$$

$$\sum_{i\in V}\lambda^1_{iu}\le N^1_u,\quad u\in\Omega^1 \tag{12}$$

$$\sum_{i\in V}\lambda^2_{iv}\le N^2_v,\quad v\in\Omega^2 \tag{13}$$

$$l_i-h_j\le M(1-\delta_{ij}),\quad i,j\in V;\, i\ne j \tag{14}$$

$$1-\delta_{ij}-\delta_{ji}\leq M(2-y_{ib}-y_{jb}),\quad b\in B_i\cap B_j;\, i,j\in V;\, i\neq j \tag{15}$$

$$\varepsilon^2_{i\omega}-\varepsilon^1_{i\omega}\leq 1-\sigma_i,\quad \omega\in\Omega_i;\, i\in V \tag{16}$$

$$\varepsilon^2_{i\omega'}-\varepsilon^1_{i\omega}\leq M\sigma_i,\quad (\omega,\omega')\in\Gamma_i;\, i\in V \tag{17}$$

$$l_i-h_i\geq\frac{W_i\sigma_i}{Q^1_i}+\frac{W_i(1-\sigma_i)}{Q^2_i}+\tau^1+\tau^2,\quad i\in V \tag{18}$$

$$l_i,h_i\geq 0,\quad i\in V \tag{19}$$

$$y_{ib},\varepsilon^1_{i\omega},\varepsilon^2_{i\omega},\lambda^1_u,\lambda^2_v,\sigma_i,\delta_{ij}\in\{0,1\},\quad b\in B_i;\,\omega\in\Omega_i;\,u\in\Omega^1;v\in\Omega^2;\,i,j\in V;\,i\neq j \tag{20}$$

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 (1), the constant term "$\sum_{i\in V}w_iD_i$" has been omitted. Constraint (2) states that each vessel must be assigned a berth segment. Constraint (3) ensures that each berth cannot be occupied before it becomes available. Constraints (4)–(7) ensure that all vessels can berth and depart with satisfactory water level. Constraints (8)–(11) ensure that the berthing and departure times of all vessels fall within the feasible time windows provided by the pilot station. Constraints (12) and (13) limit each time window in $\Omega^1$ and $\Omega^2$, respectively, to be used by a maximum number of vessels. Constraints (14) and (15) 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 (16) and (17) determine whether a vessel requires single-tide-cycle handling or double-tide-cycle handling. Constraint (18) 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 (19) and (20) 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 $i$ also gets 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. Certain requirements must be satisfied: (i) The number of QC allocated at any hour $t$ must not exceed the number of QCs available in that hour, $\bar{Q}_t$. (ii) 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 $i$. But whether this requirement can be satisfied or not depends on the availability of QCs. This phase is conducted by executing a heuristic subroutine (procedure **P**). The following are inputs of 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.

$(v_1^t, v_2^t, \ldots, v_{m_t}^t)$: 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).

$\pi_i$: 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 $i$.

$Q_t^{\text{sum}} = \sum_{i\in V} q_{it}$: QC utilization at the $t$-th hour.

$T^1$: Set of hours with the highest QC utilization; i.e., $T^1 = \big\{t_1 \in T \mid Q_{t_1}^{\text{sum}} = \max_{t\in T}\{Q_t^{\text{sum}}\}\big\}$.

$T_i^2$: Set of hours at which vessel $i$ is served and the QC utilization is not the highest; i.e., $T_i^2 = \big\{t_2 \in T \mid t_2 \in [h_i + \tau^1, l_i - \tau^2]$ and $Q_{t_2}^{\text{sum}} < \max_{t\in T}\{Q_t^{\text{sum}}\}\big\}$.

$T^3$: Set of hours at which the number of allocated QCs exceeds the number of available QCs; i.e., $T^3 = \{t_3 \in T \mid Q_{t_3}^{\text{sum}} > \bar{Q}_{t_3}\}$.

$\pi_i'$: 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 $Q_t^{\text{sum}}$ 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 $\varphi$ 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 $T_i^2 := T_i^2 \setminus \{t_2\}$. If $T_i^2 \neq \emptyset$, 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 $T^1 := T^1 \setminus \{t_1\}$. If $T^1 \neq \emptyset$, then go to Step 1.2.
Step 3: (Post-processing)
    3.1: If $Q_t^{\text{sum}} \leq \bar{Q}_t$ for all $t \in T$, then set $\pi_i' := \frac{W_i}{W_i'}\pi_i$ for all $i \in V$, terminate the procedure, and output $\pi_i'$
         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 $\varphi := \left\lceil \frac{Q_{t_3}^{\text{sum}} - \bar{Q}_{t_3}}{m_{t_3}} \right\rceil$.
    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 $T^3 := T^3 \setminus \{t_3\}$. If $T^3 \neq \emptyset$, then go to Step 3.2; otherwise, go to Step 3.1.
```

The above procedure attempts to reduce the QC engagement at peak hours iteratively (Steps 1 and 2). It also revises the handling efficiency for the vessels in order to guarantee feasibility of the QC allocation solution (Step 3). In Steps 1 and 2, in order to avoid having a large variation in 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 $\rho$. In Step 1.3, the value of $\varphi$ is selected in such a way 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 $\varphi$ is selected in such a way 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 described in the *QC Allocation* section). In Steps 3.2–3.3, when a time 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 in order to finish the service in time. The indicator $\pi'_i$ is used to inform planners about how fast vessel $i$ should be handled in order to achieve the given solution.

In Steps 1–3, we always begin with revising the QC allocation for vessels with lower service priority. 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 solution that results in the minimum peak QC utilization will be kept as the final solution. In case more than one solution obtain the same maximum QC utilization, planners will decide on which solution to accept based on their preferences on QC allocation pattern 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

$$O_{ij} = \begin{cases} 0, & \text{if } l_i \le h_j \text{ or } h_i \ge l_j; \\ 1, & \text{otherwise}; \end{cases} \tag{21}$$

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 $i$.

$\mu$: Safety clearance between two vessels that are simultaneously served 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 $k$.

$$\textbf{M2}: \quad \text{minimize} \quad \sum_{i \in V} \sum_{k \in K_i} C_{ik} d_{ik} \tag{22}$$

$$\text{subject to} \quad p_i \geq P_i^1, \quad i \in V \tag{23}$$

$$p_i + L_i \leq P_i^2, \quad i \in V \tag{24}$$

$$p_i = P_i, \quad i \in V' \tag{25}$$

$$p_i + L_i + \mu - p_j \leq M(1 - X_{ij}), \quad i, j \in V \cup V'; i \neq j; O_{ij} = 1 \tag{26}$$

$$d_{ik} \geq \left(p_i + \frac{L_i}{2}\right) - U_k, \quad k \in K_i; i \in V \tag{27}$$

$$d_{ik} \geq U_k - \left(p_i + \frac{L_i}{2}\right), \quad k \in K_i; i \in V \tag{28}$$

$$p_i, d_{ik} \geq 0, \quad k \in K_i; i \in V \tag{29}$$

Objective function (22) minimizes the total horizontal container transportation distance covered by the trailers. Constraints (23) and (24) ensure that all vessels are positioned within their suitable berthing ranges. Equation (25) fixes the berthing positions for vessels that are already at berth. Constraint (26) imposes safety clearance between vessels. Constraints (27) and (28) imply that $d_{ik} \geq \left|\left(p_i + \frac{L_i}{2}\right) - U_k\right|$, where $\left|\left(p_i + \frac{L_i}{2}\right) - U_k\right|$ is the horizontal distance between vessel $i$ and YB $k$. Constraint (29) specifies the nonnegativity requirements of the decision variables.

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