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Optimal Quay Crane Assignment and Scheduling in Port's Container Terminals

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Abstract

Effective scheduling of quay cranes can increase throughput, and lead to higher revenues of container terminals. This research, therefore, proposes an optimization model to deal with quay crane assignment and scheduling problem (QCASP) considering multiple objective functions. The first objective minimizes the handling makespan in the terminal by sequencing the work of quay cranes on vessels' bays, while the second objective aims to maximize the number of containers being handled by each quay crane (QC) for all QCs in the container port to make sure that all QCs are utilized during the handling process. Finally, the third objective seeks to maximize satisfaction levels on handling completion times. The model takes into consideration the non-violence of non-crossing constraints and task completion without preemption constraints. Illustrations of the developed model were provided. The results showed that the proposed optimization model is found effective in optimizing terminal performance by optimizing the three stated objective functions concurrently. In practice, solving the QCASP helps in enhancing utilization of QCs, shortening service period at the terminal, and increasing the throughput at the terminal. In conclusion, the proposed optimization model can benefit planning engineers in determining optimal quay crane assignment and scheduling. Future research will focus on integrating berth allocation problem with QCASP.

Keywords: Optimization, Quay cranes, Scheduling and Assignment.;

1. Introduction

The ports irrespective of their location mainly face the problems of congestion, lost opportunities, high costs, and instability if not decreasing level of customer satisfaction. Seaports are complex dynamic systems consisting of numerous connecting elements, influenced by several random factors. Accordingly, full utilization of the obtainable resources and efficient management of operations are two major goals. Under these two goals numerous objectives can be accomplished; such as, increasing the port throughput and usage of resources (berths, cranes, quay, yards.), minimizing handling time, decreasing port congestion [1-2].

It is well known that the container terminal business is capital intensive. Therefore, effective scheduling of resources; especially quay cranes (QCs), can increase throughput and lead to higher revenues of container terminals [3-4]. Quay crane assignment and scheduling problem (QCASP) is a key task in seaside operations, where available quay cranes are assigned to vessels and their operations are scheduled. Therefore, this research develops an optimization model to deal with the QCASP with three main objectives including minimizing makespan, maximizing the number of operational QCs, and maximizing satisfaction level on bays' completion times. In practice, this model provides great assistance to planning engineers in ports in determining the optimal schedule of QCs and thereby improving terminal performance. The remainder of this research including the introduction is organized as follows. Section 2 reviews previous literature related to QCASP. Section 3 develops an optimization model to deal with QCASP. Section 4 illustrates the developed optimization models. Section 5 provides results and discussion. Finally, Section 6 presents the conclusions and future research.

2. Literature Review

Several studies have handled the QCASP. For example, Hu [5] studied the QCASP with the objective of minimizing the movements of QCs during the operations of each vessel in Ningbo Beilun Port in China using integer linear programming model. Lee and Wang [6] integrated berth allocation and QCASP to minimize makespan of handling all container ships, and reduce handling time of each container ship at each berth via genetic algorithm. Lee and Chen [7] optimized the QCSP with non-crossing constraints with two approximation algorithms, which are the best partition method and the enhanced partition method, to obtain optimal makespan for the QCSP. Zeng *et al*. [8] proposed a berth reallocation and quay crane rescheduling models to tackle irregular disruptions in container terminals, targeting the minimization of negative impacts of disruption. A Tabu search algorithm was used to solve

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the berth reallocation and QC rescheduling models. Data of numerical experiments were collected from the Tianjin Five Continents International Container Terminal. Chung and Chan [9] examined the QCSP aiming to minimize the makespan (completion time) of tasks. Workload balancing heuristics were applied in a Genetic Algorithm to solve the model and compare the workload balancing between the QCs. Diabat and Theodorou [10] developed a mathematical formulation for the integrated QCASP aiming to minimize the handling makespan of the ship while assuming that all QCs were identical with corresponding handling rates. Furthermore, a unidirectional movement for cranes was adopted so that QCs began handling the lowest-indexed bay out of the total bays, and the clearance conditions were enforced between adjacent QCs. Fu *et al.* [11] analyzed the integrated quay crane assignment and scheduling problem with the objective of maximizing the sum of the weighted work completion flag. A genetic algorithm was proposed to solve the problem, and different sizes instances were used to test the performance of the proposed model and the developed genetic algorithm. Al-Dhaheri *et al*. [12] studied the QCSP to minimize the absolute value of the sum of the differences in workload over time between all bays using mixed-integer programming. It was assumed that a QC could be assigned to at most one bay, a single QC could handle at most one task at an instant in time, QCs were mounted on a single rail so that the crossing of cranes was prevented, while the bi-directional movement was allowed. Identical service rates were assumed for all cranes, and the safety distance was implicitly taken into consideration. Msakni *et al.* [13] investigated the QCASP with the objective of minimizing the sum of selected QC-to-bay assignments required to achieve all container works (minimizing the makespan). A branch-and-price algorithm based on a set covering formulation was proposed to solve the problem. Chang *et al*. [14] studied the QCSP with the objective of minimizing the operation time of all ships at port and obtaining operation equilibrium of quay cranes using a genetic algorithm. The main assumptions were, all quay cranes had the same capacity and the same moving speed; the berthing time, berthing location and container stowage plan of every ship were all given and known. Chu *et al.* [15] studied the QCSP with the aim of minimizing the makespan of the ship handling operation, taking into account the constraint of the ship balance. Multi-Crane double cycling (double cycling means that a QC can unload the ship's container and load the ship's container in the same cycle) model was developed to optimize the operation sequence of each QC while considering ship stabilization during loading/ unloading operations. A Lagrangian relaxation heuristic algorithm was designed to solve the model, and one instance of a ship berthing in Tianjin Port in China was used to test the model validity.

In the previously-presented studies, the most common objective function in the QCASP was minimizing the makespan of handling operations, completion time of tasks [5-6] and minimizing costs of handling [7].However, this research takes into consideration multiple objective functions; maximizing the number of operated QCs, minimizing the makespan, and maximizing satisfaction on completion times, with their more realistic conditions; such as, the non-crossing condition among operating QCs, and quay crane of distinct capacity, moving speed, and service rates.

3. The Proposed QCASP Optimization Model

The primary elements in the QCASP are the set of vessels that will be operated, and the set of quay cranes available in the terminal. Let Q denotes the set of QCs available to work in the terminal indexed by $q \in Q,\ q = (1,...,N)$, and B denotes the set of all bays belonging to berthing vessels in the terminal indexed by $b \in B,\ b = (1,...,S)$. In addition, let B_v denotes the subset of bays belonging to specific vessel $v \in V$ from the set of vessels berthing in the terminal. The QCASP model determines the number of quay cranes assigned to each vessel bays and their sequence of operations required to achieve the minimal handling period. The main assumptions and practical considerations of the proposed model are:

The length of each vessel is split into compartments for containers storage, which are termed as bays. Bay areas are assumed to be indexed sequentially along the quay, according to their position from left to right as shown in Fig. 1.

The bays of all berthing vessels are ordered from left to right in ascending order dealing with them as a single ship problem.

Safety margin between operating QCs working on the same vessel is not considered.

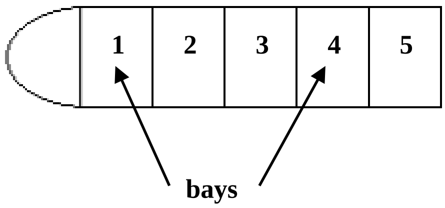

Figure 1. A vessel bays ordered from left to right in ascending order.

Each bay cannot be served by multiple cranes in the same time period. And, once a crane started its operation on a certain bay, it cannot leave until completing the loading and/ or unloading operations at that bay.

The quay cranes movement is bidirectional, giving them the freedom to travel in both directions left and right, as long as they do not cross each other. However, cranes can move from a vessel to another while serving it (dynamic allocation) as shown in Fig. 2.

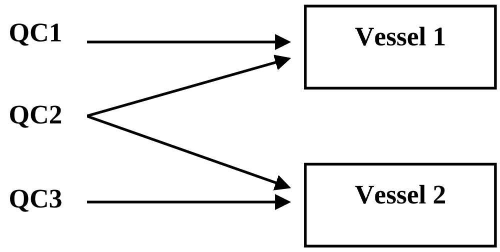

Figure 2. Dynamic allocation of QCs to berthing vessels.

The time required for quay cranes to travel between bays of vessels is small if compared to container handling times. Therefore, horizontal moving time of quay cranes is not considered in this model.

The quay cranes are positioned on a single track; therefore, they are not allowed to cross each other to shift position. Moreover, it is assumed that they are indexed in ascending order from left to right; this helps in preventing middle numbered QCs from serving bays at the ends. In other words, each bay has feasible quay crane or quay cranes, which can serve it.

The parameters of the proposed model are: (1) Total number of bays for the berthing vessels in the terminal (S), and their workload, the number of containers that should be loaded and/ or unloaded in each bay (ω_b). In addition to the number of bays belonging to each vessel (S_v) and (2) number of available quay cranes in the terminal (N), and their working rate in container/ hour (r_q).

The first objective function is to minimize the makespan, ψ, (latest completion time of all handling tasks for the bays of vessels in the terminal), which is represented as follows:

$$Min \quad \psi \tag{1}$$

The second objective function is to maximize the number of containers operated by each quay crane *q*, ζ_q, for better employment of all QCs in the terminal, this is represented as:

$$Max \sum_{q=1}^{N} \zeta_q \tag{2}$$

The objective functions are subject to the following constraints:

1. Let the binary decision variable λ_{bq} determines to which quay crane q a bay b is assigned, it equals 1 if quay crane $q \in Q$ is assigned to bay $b \in B$ (=0 otherwise). In order to meet all handling tasks of all bays in the terminal, each bay shall be assigned to only one quay crane in order to complete the loading and/ or unloading operations of it without preemption. Mathematically,

$$\sum_{q=1}^{N} \lambda_{bq} = 1, \qquad \forall b \in B \tag{3}$$

2. Let the binary decision variable $\upsilon_{bb'}$ determines the work precedence between bays, it equals 1 if the work on bay $b \in B$ is completed before the work on bay $b' \in B$ starts (= 0 otherwise). Also, if bays are being served simultaneously, the bays cannot be assigned to the same quay crane. Given that the quay cranes are moving on the same track, then the non-crossing constraint is formulated as given in Inequality (4).

$$\sum_{q=1}^{N} q\times\lambda_{bq} - \sum_{q=1}^{N} q\times\lambda_{b'q} + 1 \le M\times(\upsilon_{bb'}+\upsilon_{b'b}), \quad \forall b,\ b' \in B \mid b < b' \tag{4}$$

Fig. 3 shows how different berthing vessels are combined and served by QCs as a single ship problem. If bays numbers 3 and 4 are being served simultaneously, the right-hand side of inequality (4) will be zero. Accordingly, if the quay crane serving bay number 3, which is equivalent to (b) in the inequality, is of higher order than the one serving bay number 4 (b'); e.g. the crane serving bay number 3 is of order number 3, while the crane serving bay number 4 is of order number 2, the constraint will not be satisfied because after substituting the values in inequality (4), the result is (3-2+1=2, which is not less than or equal to zero). Consequently, the crossing between QCs moving on a single rail will be prevented.

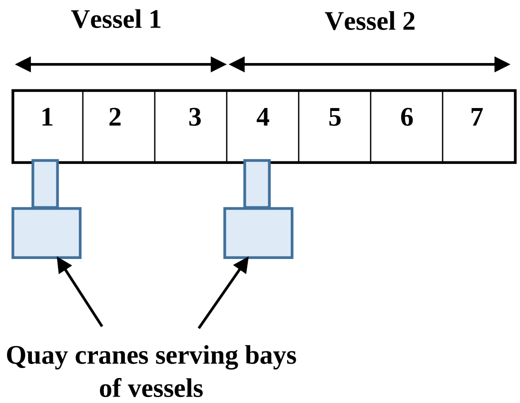

Figure 3. Quay cranes operating on bays of vessels.

3. To make sure that there is always enough space between any two quay cranes, in other words, a crane of order number 1 and another one of order number 3 will never be working on adjacent bays to make sure that there is enough space for quay crane number 2. This is represented as:

$$\sum_{q=1}^{N} q\times\lambda_{b'q} - \sum_{q=1}^{N} q\times\lambda_{bq} \le b' - b + M\times(\upsilon_{bb'}+\upsilon_{b'b}), \quad \forall b, b' \in B, b < b' \tag{5}$$

For more explanation to constraint (5), in Fig. 3 if bays numbers 2 and 3 are being serviced simultaneously, and the number of QCs serving them are 1 and 3, respectively. Such situation will not occur when applying this constraint because the term multiplied by the big M will be zero, however, ((3-1=2) which represents the QCs order numbers is not less than or equal to (3-2=1) which are the order numbers of bays $(b' - b)$ in the inequality). Accordingly, there will be always enough space for in between QCs.

4. The middle-numbered quay cranes shall not be assigned to end bays because this means that the quay cranes which are located on the bounds are pushed out of boundaries. For example, if in Fig. 3 the quay crane serving bay number one is QC number two, this will mean that quay crane number 1 is pushed out. Accordingly, equations (6) and (7) are used to define the feasible set of quay cranes that can be assigned to each bay:

$$\lambda_{bq} = 0, \quad \forall b \in B, q \in Q, q > b \tag{6}$$

$$\lambda_{bq} = 0, \quad \forall b \in B, q \in Q, S - b < N - q \tag{7}$$

Assume that there are 4 QCs in a certain MCT, then applying constraints (6) and (7) on the 7 bays in Fig. 3 gives the set of feasible QCs that can serve each bay as shown in Fig. 4. Total number of bays for the berthing vessels in the terminal (S), number of available quay cranes in the terminal (N).

Bay number	1	2	3	4	5	6	7
Feasible quay cranes	1	1 2	1 2 3	1 2 3 4	2 3 4	3 4	4

Figure 4. Bays and feasible quay cranes.

5. Given the number of containers, ω_b, that need loading/unloading in bay $b$and the working rate, r_q, of each quay crane, the processing time, ρ_b ,for bay b needed to complete the tasks can be calculated:

$$\rho_b = \sum_{q=1}^{N} \frac{\lambda_{bq} \times \omega_b}{r_q}, \qquad \forall b \in B \quad (8)$$

6. The completion time of every bay processing is greater than or equal to its processing period. Moreover, let the decision variable h_v denotes the handling time of vessel $v \in V$, then the handling time of each vessel can be calculated as the latest completion time of its bays; mathematically:

$$C_b \geq \rho_b, \quad \forall b \in B \quad (9)$$

$$h_v \geq C_b, \quad \forall b \in B_v, v \in V \quad (10)$$

7. The work of QCs on bays is without preemption, this means that a quay crane shall complete its work on the current bay before moving to any other bay. This is assured by inequality (11), which determines the work sequence of every QC:

$$C_b \leq C_{b'} - \rho_{b'} + M \times (1 - \upsilon_{bb'}), \quad \forall b, b' \in B, b \neq b' \quad (11)$$

8. The number of containers (size of workload) handled by each quay crane equals the sum of containers that need loading/unloading in the bays which the QC was assigned to; this is determined by equation (12):

$$\zeta_q = \sum_{b=1}^{S} \lambda_{bq} x\, \omega_b, \qquad \forall q \in Q \quad (12)$$

9. The makespan of processing jobs on all bays in the terminal is calculated as the largest completion time among all processed bays; that is:

$$\psi \geq C_b, \qquad \forall b \in B \quad (13)$$

10. Non-negative and binary variables are determined in constraints (14) and (15):

$$\psi, C_b, \rho_b, \zeta_q, h_v \geq 0, \quad \forall b \in B, q \in Q, v \in V \quad (14)$$

$$\lambda_{bq}, \upsilon_{bb'} \in \{0,1\} \quad (15)$$

Further, let SC_b denotes the satisfied completion time for bay b. It is also important to maximize the satisfactions on the bays' completion times. Ideally, the satisfaction will be 100% if the completion time meets the satisfied completion time; while the satisfaction decreases when the completion time exceeds the satisfied target [16-20]. Let $\mu_b$denote the membership function that represents the satisfaction on bays' completion times. Let Δ^+_b denotes the maximal positive permitted deviation from SC_b. The *STB* function is shown in Fig.5.

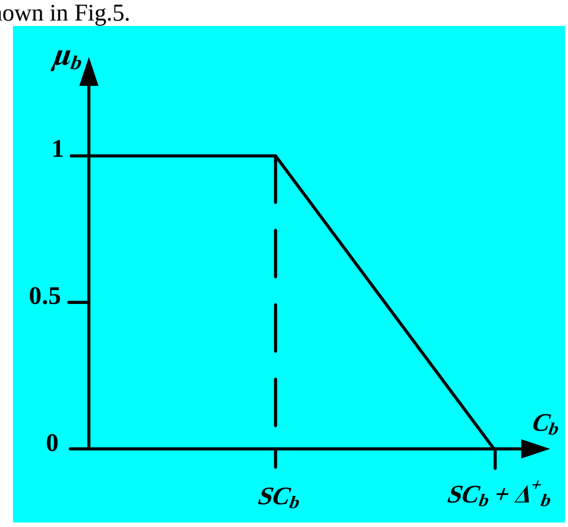

Figure 5. The (*STB*) type satisfaction.

Then, the objective function is to maximize the satisfaction on completion times of bays; or, mathematically

$$Max \sum_{b=1}^{S} \mu_b \quad (16)$$

Let δ^+_b denotes any positive deviation from the target value, SC_b. the value of δ^+_b is always positive and less than the maximum allowed deviation as in Eq. (17).

$$0 \leq \delta^+_b \leq \Delta^+_b \;, \forall b \quad (17)$$

Furthermore, the amount of any positive deviation is determined by observing how far the difference between SC_b and the actual completion time, C_b, is expressed as:

$$C_b - \delta^+_b = SC_b \;, \forall b \quad (18)$$

Also, the value of the membership function is calculated using Eq. (19).

$$\mu_b + \frac{\delta^+_b}{\Delta^+_b} = 1 \;, \forall b \quad (19)$$

Finally, the value of each membership should not be less than the minimum allowable satisfaction θ_b which is expressed as:

$$\mu_b \geq \theta_b, \quad \forall b \quad (20)$$

The cranes assignment schedule and sequence of operations on bays in order to minimize the time required to complete all handling processes are obtained by solving the complete optimization model, which is written as:

$$Min = \psi$$

$$Max = \sum_{q=1}^{N} \zeta_q + \sum_{b=1}^{S} \mu_b$$

Subject to:

$\sum_{q=1}^{N} \lambda_{bq} = 1, \forall b \in B$	[QCs assignment to bays]
$\sum_{q=1}^{N} q \times \lambda_{bq} - \sum_{q=1}^{N} q \times \lambda_{b'q} + 1 \le M \times (\upsilon_{bb'} + \upsilon_{b'b}), \forall b, b' \in B, b < b'$	[Non-crossing constraint]
$\sum_{q=1}^{N} q \times \lambda_{b'q} - \sum_{q=1}^{N} q \times \lambda_{bq} \le b' - b + M \times (\upsilon_{bb'} + \upsilon_{b'b}), \forall b, b' \in B, b < b'$	[Keeping enough space between QCs]
$\lambda_{bq} = 0, \forall b \in B, q \in Q, q > b$ $\lambda_{bq} = 0, \forall b \in B, q \in Q, S - b < N - q$	[Defining the feasible QC or QCs for working on each bay]
$\rho_b = \sum_{q=1}^{N} \frac{\lambda_{bq} \times \omega_b}{r_q}, \forall b \in B$	[Processing period for each bay]
$C_b \ge \rho_b, \forall b \in B$	[Completion time for work on each bay]
$h_v >= C_b, \forall b \in B_v, v \in V$	[Handling time of each vessel]
$C_b \le C_{b'} - \rho_{b'} + M \times (1 - \upsilon_{bb'}), \forall b, b' \in B, b \ne b'$	[Precedence between bays]
$\zeta_q = \sum_{b=1}^{S} \lambda_{bq} x \, \omega_b, \forall q \in Q$	[Number of containers handled by each QC]
$\psi \ge C_b, \forall b \in B$	[Makespan]
$\psi, C_b, \rho_b, \zeta_q, h_v \ge 0, \quad \forall b \in B, q \in Q, v \in V$	[Non-negative variables]
$0 \le \delta_b^+ \le \Delta_b^+ \ , \forall b$	[The deviation always positive]
$C_b - \delta_b^+ = SC_b \ , \forall b$	[The amount of any positive deviation]
$\mu_b + \frac{\delta_b^+}{\Delta_b^+} = 1 \ , \forall b$	[The value of the membership function]
$\mu_b \ge \theta_b, \ \forall b$	[The minimum allowable satisfaction]
$\lambda_{bq}, \upsilon_{bb'} \in \{0,1\}$	[Binary variables]

4. Results and Discussion

The proposed model was applied on three cases. The results and discussion of these cases are presented as follows.

4.1. Case I: Small sample size (3 vessels, 6 quay cranes, and 12 bays)

Consider three vessels that have already arrived and berthed in the terminal, then the load profile of each vessel (number of bays belonging to each vessel and the number of containers in each bay) is summarized in Table 1. The heterogeneous working rates of the quay cranes in the MCT are presented in Table 2.

Solving the proposed QCASP optimization model of 224 variables and 328 constraints using Lingo 11.0 (Processor: Intel (R) Core (TM) i5-4210U; CPU @ 1.70GHz, 2.40 GHz, elapsed time = 6.15 minutes), the total makespan, handling time periods for each vessel, processing and completions times for operations on each bay are obtained as summarized in Tables 3. Further, the calculated number of containers operated per crane is shown in Table 4.

Table 1. Berthing vessels' load profile.

Input	Value											
Vessel number	1			2					3			
Number of bays	3			5					4			
Total number of bays for all vessels (B)				12								
Bays numbers from left to right sequentially (b)	1	2	3	4	5	6	7	8	9	10	11	12
Number of containers in each bay (ω_b)	100	200	125	150	250	150	100	175	125	200	250	150

Table 2. Quay cranes working rates.

Quay crane number	Working rate (containers per hour) (r_q)
1	30
2	15
3	35
4	15
5	30
6	35

Table 3. Optimal results for QCASP model (Case I).

Variable		Final value											
ψ		14.29											
$\sum_{q=1}^{N} \zeta_q$		1975											
Vessel number		1			2					3			
h_v		14.29			14.29					11.43			
Processing and completion times of bays	Bay number	1	2	3	4	5	6	7	8	9	10	11	12
	ρ_b	3.33	6.67	4.17	10	7.14	4.29	2.86	11.67	4.17	6.67	7.14	4.29
	C_b	7.62	14.29	4.17	14.29	11.43	4.29	14.29	14.29	4.17	11.43	7.14	11.43

Table 4. Number of containers operated by each QC.

Quay crane number	Number of containers loaded/ unloaded (ζ_q)
1	425
2	150
3	500
4	175
5	325
6	400

In Table 3, it is noted that the total sum of operated containers (= 1975) equals the number of containers that shall be loaded/ unloaded from all bays of berthing vessels. This means that all required handling operations are accomplished. The optimal makespan is found 14.29 hours. The optimal values of the binary decision variable (λ_{bq}) determines which QC (q) is assigned to bay (b) when it takes the value of 1 $(\lambda_{bq} = 1)$ are listed in Table 5. The time precedence relations between bays, which define what bay shall complete its operation before the start of the job on another bay, are taken from the value of the binary decision variable $(\upsilon_{bb'})$; it equals 1 if the job on bay b completes before the start of operation on bay b'. Table 6 defines the precedence relations between tasks by summarizing the variables that took the value 1 $(\upsilon_{bb'} = 1)$

Table 5. The bays assigned to each quay crane.

Assignment Variable	Value meaning
$\lambda_{11}=1$	QC number (1) is assigned to bay number (1)
$\lambda_{21}=1$	QC number (1) is assigned to bay number (2)
$\lambda_{31}=1$	QC number (1) is assigned to bay number (3)
$\lambda_{42}=1$	QC number (2) is assigned to bay number (4)
$\lambda_{53}=1$	QC number (3) is assigned to bay number (5)
$\lambda_{63}=1$	QC number (3) is assigned to bay number (6)
$\lambda_{73}=1$	QC number (3) is assigned to bay number (7)
$\lambda_{84}=1$	QC number (4) is assigned to bay number (8)
$\lambda_{95}=1$	QC number (5) is assigned to bay number (9)
$\lambda_{105}=1$	QC number (5) is assigned to bay number (10)
$\lambda_{116}=1$	QC number (6) is assigned to bay number (11)
$\lambda_{126}=1$	QC number (6) is assigned to bay number (12)

Table 6. Time precedence relations among bays.

Output	Value meaning	Output	Value meaning
$\upsilon_{12}=1$	Operation on bay No. (1) completes before the start of operation on bay No. (2).	$\upsilon_{610}=1$	Operation on bay No. (6) completes before the start of operation on bay No. (10).
$\upsilon_{17}=1$	Operation on bay No. (1) completes before the start of operation on bay No. (7).	$\upsilon_{612}=1$	Operation on bay No. (6) completes before the start of operation on bay No. (12).
$\upsilon_{31}=1$	Operation on bay No. (3) completes before the start of operation on bay No. (1).	$\upsilon_{910}=1$	Operation on bay No. (9) completes before the start of operation on bay No. (10).
$\upsilon_{32}=1$	Operation on bay No. (3) completes before the start of operation on bay No. (2).	$\upsilon_{912}=1$	Operation on bay No. (9) completes before the start of operation on bay No. (12).
$\upsilon_{34}=1$	Operation on bay No. (3) completes before the start of operation on bay No. (4).	$\upsilon_{117}=1$	Operation on bay No. (11) completes before the start of operation on bay No. (7).
$\upsilon_{57}=1$	Operation on bay No. (5) completes before the start of operation on bay No. (7).	$\upsilon_{1112}=1$	Operation on bay No. (11) completes before the start of operation on bay No. (12).
$\upsilon_{65}=1$	Operation on bay No. (6) completes before the start of operation on bay No. (5).	$\upsilon_{127}=1$	Operation on bay No. (12) completes before the start of operation on bay No. (7).
$\upsilon_{67}=1$	Operation on bay No. (6) completes before the start of operation on bay No. (7).		

For the third objective function which aims to maximize satisfactions on the bays' completion times, the minimum allowable satisfaction for each bay (θ_b) and the maximum allowable deviation (Δ^+_b) were decided values of 85% and 3, respectively. The optimal values of the satisfaction levels and positive deviations are summarized in Table 7. It is obvious that all the satisfaction levels on the completion times are larger than the threshold of 85%. In addition, the satisfaction level is 100% for 9 bays out of 12. The above results reveal the effectiveness of the proposed models in solving the QCASP. Finally, Table 8 shows the optimal sequence of QCs operations on bays over the planning horizon based on the defined precedence relations among bays and the results of assignment, processing and completion times.

Table 7. The optimal satisfaction levels on completion times.

Bay, b	Satisfied completion times, SC_b	Actual completion times, C_b	δ^+_b	μ_b
1	7.5	7.62	0.12	96%
2	14	14.29	0.29	90%
3	5	4.17	0	100%
4	15	14.29	0	100%
5	13	11.43	0	100%
6	6	4.29	0	100%
7	15	14.29	0	100%
8	15	14.29	0	100%
9	5	4.17	0	100%
10	11	11.43	0.43	86%
11	8	7.14	0	100%
12	13	11.43	0	100%

Table 8. Sequence of QCs operations (time periods x bays).

<table>
<tr><th rowspan="2">Time period</th><th colspan="12">Bay number</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th></tr>
<tr><td>1</td><td></td><td></td><td rowspan="4">QC1</td><td></td><td></td><td rowspan="4">QC3</td><td></td><td></td><td rowspan="4">QC5</td><td></td><td rowspan="7">QC6</td><td></td></tr>
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<tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td rowspan="12">QC4</td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td rowspan="3">QC1</td><td></td><td></td><td rowspan="10">QC2</td><td rowspan="7">QC3</td><td></td><td></td><td></td><td rowspan="7">QC5</td><td></td></tr>
<tr><td>6</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>7</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td></td><td rowspan="7">QC1</td><td></td><td></td><td></td><td></td><td></td><td rowspan="4">QC6</td></tr>
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<tr><td>12</td><td></td><td></td><td></td><td></td><td rowspan="3">QC3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>13</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>14</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>15</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

4.2. Case II: Large sample size (6 vessels, 12 quay cranes, and 24 bays)

Assume that six vessels have arrived and berthed in the terminal, then the load profile of all vessels are presented in Table 9. Twelve QCs are available with working rates (containers per hour) as shown in Table 10.

The optimization model for Case II includes 826 variables and 1234 constraints. Using Lingo 11.0 (Processor: Intel (R) Core (TM) i5-4210U; CPU @ 1.70GHz, 2.40 GHz, elapsed time = 17.19 minutes), the assigned QC for each bay are obtained as shown in Table 11, where it is found that the optimal makespan and number of operated containers are 15 hour and 3995, respectively. Further, the optimal satisfaction values on completion times are shown in Table 12. It is seen that the smallest satisfaction value is 83%, which is larger than the satisfaction threshold value. Furthermore, the number of containers operated by each QC is displayed in Table 13, where it is found that the largest number of loaded/unloaded containers (=525) corresponds to QC number 9.

Table 9. Berthing vessels' load profile for Case study II.

Input	Value					
Vessel number	1	2	3	4	5	6
Number of bays	3	5	4	4	4	4
Total number of bays for all vessels (*B*)	24					
Bay number (*b*)	1	2	3	4	5	6
Number of containers in each bay (ω_b)	100	200	125	150	250	150
Bay number (*b*)	7	8	9	10	11	12
Number of containers in each bay (ω_b)	100	175	125	200	250	150
Bay number (*b*)	13	14	15	16	17	18
Number of containers in each bay (ω_b)	200	120	100	200	175	150
Bay number (*b*)	19	20	21	22	23	24
Number of containers in each bay (ω_b)	125	250	175	200	100	225

Table 10. Working rates for QCs (Case II).

Quay crane number	Working rate (containers per hour)	Quay crane number	Working rate (containers per hour)
1	30	7	30
2	15	8	15
3	35	9	35
4	15	10	15
5	30	11	30
6	35	12	35

Variable	Final value											
The optimal makespan ψ	15											
The optimal number of operated containers $(\sum_{q=1}^{N} \zeta_q)$	3995											
Vessel number	1			2					3			
Bay number	1	2	3	4	5	6	7	8	9	10	11	12
Processing time in hours	3.33	6.67	4.17	10	7.14	10	3.33	5	3.5	6.67	8.33	4.26
Completion time	14.17	6.67	10.83	15	10.71	13.57	15	13.33	3.57	15	8.3	4.29
Handling time	14.17			15					15			
Vessel number	4				5				6			
Bay number	13	14	15	16	17	18	19	20	21	22	23	24
Processing time in hours	6.67	8	6.67	5.71	5	4.28	8.33	8.33	5	6.67	2.86	6.43
Completion time	6.67	15	6.67	15	9.29	4.29	15	15	15	6.67	2.86	9.29
Handling time	15				15				15			

Table 11. Optimal results for QCASP model (Case II).

Table 12. The satisfaction on completion times for Case study II.

Bay, b	Satisfied completion times, SC_b	Actual completion times, C_b	δ^+_b	μ_b	Bay, b	Satisfied completion times, SC_b	Actual completion times, C_b	δ^+_b	μ_b
1	14	14.17	0.17	94%	13	6.67	6.67	0	100%
2	6.5	6.67	0.17	94%	14	15	15	0	100%
3	10.5	10.83	0.33	89%	15	6.5	6.67	0.17	94%
4	15	15	0	100%	16	15	15	0	100%
5	10.5	10.71	0.21	93%	17	9	9.29	0.29	90%
6	13.33	13.57	0.24	92%	18	4	4.29	0.29	90%
7	15	15	0	100%	19	14.5	15	0.5	83%
8	13	13.33	0.33	89%	20	15	15	0	100%
9	3.5	3.57	0.07	98%	21	15	15	0	100%
10	15	15	0	100%	22	6.5	6.67	0.17	94%
11	8	8.3	0.3	90%	23	2.5	2.86	0.36	88%
12	4	4.29	0.29	90%	24	9	9.29	0.29	90%

Table 13. Number of containers operated by each QC in case study II.

Quay crane number	Number of containers loaded/ unloaded (ζ_q)	Quay crane number	Number of containers loaded/ unloaded (ζ_q)
1	425	7	400
2	150	8	220
3	375	9	525
4	150	10	125
5	350	11	450
6	325	12	500

Finally, the optimal sequence of QCs operations on bays over the planning horizon for case study II is developed and then displayed in Table 14.

Sensitivity analysis on the arrangement and service rates of QCs was conducted and then obtained optimization results are summarized in Table 15. It is noted that the arrangement of high rates QCs at the sides results in the largest makespan (= 27.02 hours) but the largest minimal satisfaction level (= 88%). Although the base arrangement corresponds to the smallest minimal satisfaction level, however it provides the best optimal results on the remaining objective functions.

Table 14. Sequence of QCs operations in case study II.

Time period	Bay number 1	2	3	4	5	6	7	8	9	10	11	12
1		QC1		QC2		QC4			QC3		QC5	QC6
2		QC1		QC2		QC4			QC3		QC5	QC6
3		QC1		QC2		QC4			QC3		QC5	QC6
4		QC1		QC2		QC4			QC3		QC5	QC6
5		QC1		QC2	QC3	QC4		QC6			QC5	
6		QC1		QC2	QC3	QC4		QC6			QC5	
7		QC1		QC2	QC3	QC4		QC6			QC5	
8			QC1	QC2	QC3	QC4		QC6			QC5	
9			QC1	QC2	QC3	QC4	QC5	QC6		QC7		
10			QC1	QC2	QC3	QC4	QC5			QC7		
11			QC1		QC3		QC5			QC7		
12	QC1									QC7		
13	QC1									QC7		
14	QC1									QC7		
15										QC7		

Time period	Bay number 13	14	15	16	17	18	19	20	21	22	23	24
1	QC7		QC8			QC9	QC10			QC11	QC12	
2	QC7		QC8			QC9	QC10			QC11	QC12	
3	QC7		QC8			QC9	QC10			QC11	QC12	
4	QC7		QC8			QC9	QC10			QC11		QC12
5	QC7		QC8		QC9		QC10			QC11		QC12
6	QC7		QC8		QC9		QC10			QC11		QC12
7	QC7		QC8		QC9		QC10			QC11		QC12
8		QC8			QC9		QC10	QC11				QC12
9		QC8			QC9			QC11				QC12
10		QC8		QC9				QC11	QC12			
11		QC8		QC9				QC11	QC12			
12		QC8		QC9				QC11	QC12			
13		QC8		QC9				QC11	QC12			
14		QC8		QC9				QC11	QC12			
15		QC8		QC9				QC11				

Table 15. Optimal results of sensitivity analysis for Case II.

Crane	1	2	3	4	5	6	7	8	9	10	11	12	Makespan	Total containers	Minimum satisfaction
Base case	30	15	35	15	30	35	30	15	35	15	30	35	15	3995	83%
Ascending order	15	15	15	15	30	30	30	30	35	35	35	35	20	3995	88%
High rates at the middle	15	15	30	30	35	35	35	35	30	30	15	15	17.86	3995	86%
High rates at the sides	35	35	30	30	15	15	15	15	30	30	35	35	27.02	3995	88%

4.3. Case III: Large sample size (6 vessels, 12 quay cranes, and 40 bays)

Six vessels were assumed to be arrived and berthed in the terminal. The load profile of all vessels in this case is presented in Table 16. The optimization model for Case III includes 2074 variables and 3330 constraints. Using Lingo 11.0 (Processor: Intel (R) Core (TM) i5-4210U; CPU @ 1.70GHz, 2.40 GHz, elapsed time = 129.43 minutes). The optimal loaded/unloaded containers for Case III are displayed in Table 17, where it is noted that QC number 12 loaded/unloaded the largest number of containers (= 870).

The optimization results for Case III are then displayed in Table 18, where it is noted that the makespan and total loaded/unloaded containers are 16.52 hours and 5940, respectively.

The optimal sequence of QCs operations is then developed as shown in Table 19. Finally, the sensitivity analysis on the arrangement of QCs is conducted and then the results are shown in Table 20. Clearly, the best arrangement of QCs corresponds to the base case.

Table 16. Input data for Case III.

Input	Variable									
Vessel number	1		2		3		4	5		6
Number of bays	6		7		6		6	8		7
Total number of bays for all vessels (B)	40									
Bay number (b)	1	2	3	4	5	6	7	8	9	10
Number of containers in each bay (ω_b)	100	125	75	100	75	75	100	100	75	50
Bay number (b)	11	12	13	14	15	16	17	18	19	20
Number of containers in each bay (ω_b)	100	200	225	100	170	25	500	75	75	350
Bay number (b)	21	22	23	24	25	26	27	28	29	30
Number of containers in each bay (ω_b)	450	175	200	175	150	75	100	50	50	100
Bay number (b)	31	32	33	34	35	36	37	38	39	40
Number of containers in each bay (ω_b)	150	50	25	25	50	275	275	290	230	350

Table 17. Optimal QCs' loaded/unloaded containers for Case III.

Quay crane number	Number of containers loaded/ unloaded (ζ_q)	Quay crane number	Number of containers loaded/ unloaded (ζ_q)
1	475	7	700
2	500	8	275
3	695	9	300
4	175	10	100
5	500	11	550
6	800	12	870

Table 18. Optimization results for Case III.

Variable	Final value									
ψ	16.52									
$\sum_{q=1}^{N} \zeta_q$	5940									
Vessel number	1					2				
Bay number	1	2	3	4	5	9	10	11	12	13
ρ_b	3.33	6.67	8.33	4.29	5	4.17	5.71	2.86	4.29	6.67
C_b	3.33	7.81	16.52	8.64	8.64	6.14	7.36	4.52	5.98	9.02
Bay number	6	7	8	-	-	14	15	-	-	-
ρ_b	10	2.86	5.83	-	-	3.43	6.67	-	-	-
C_b	7.51	9.79	7.36	-	-	3.43	6.62	-	-	-
Handling time	16.52					9.02				
Vessel number	3					4				
Bay number	16	17	18	19	20	23	24	25	26	27
ρ_b	5.71	11.67	10	3.57	8.33	3.33	3.57	3.33	6.67	4.17
C_b	7.35	11.67	13.19	9.93	14.12	7.36	4.19	14.52	6.67	4.36
Bay number	21	22	-	-	-	28	-	-	-	-
ρ_b	5	5	-	-	-	4.29	-	-	-	-
C_b	8.33	9.62	-	-	-	14.52	-	-	-	-
Handling time	14.12					14.52				
Vessel number	5					6				
Bay number	29	30	31	32	33	35	36	37	38	39
ρ_b	8.33	10	2.86	5.83	4.17	5.71	4.29	5.71	3.43	2.86
C_b	14.12	14.02	5.54	7.95	6.71	9.02	4.29	5.71	3.43	8.57
Bay number	34	-	-	-	-	40	-	-	-	-
ρ_b	5.71	-	-	-	-	6.67	-	-	-	-
C_b	7.95	-	-	-	-	7.31	-	-	-	-
Handling time	14.12					9.02				

Table 19. Optimal QC operations sequence for Case III.

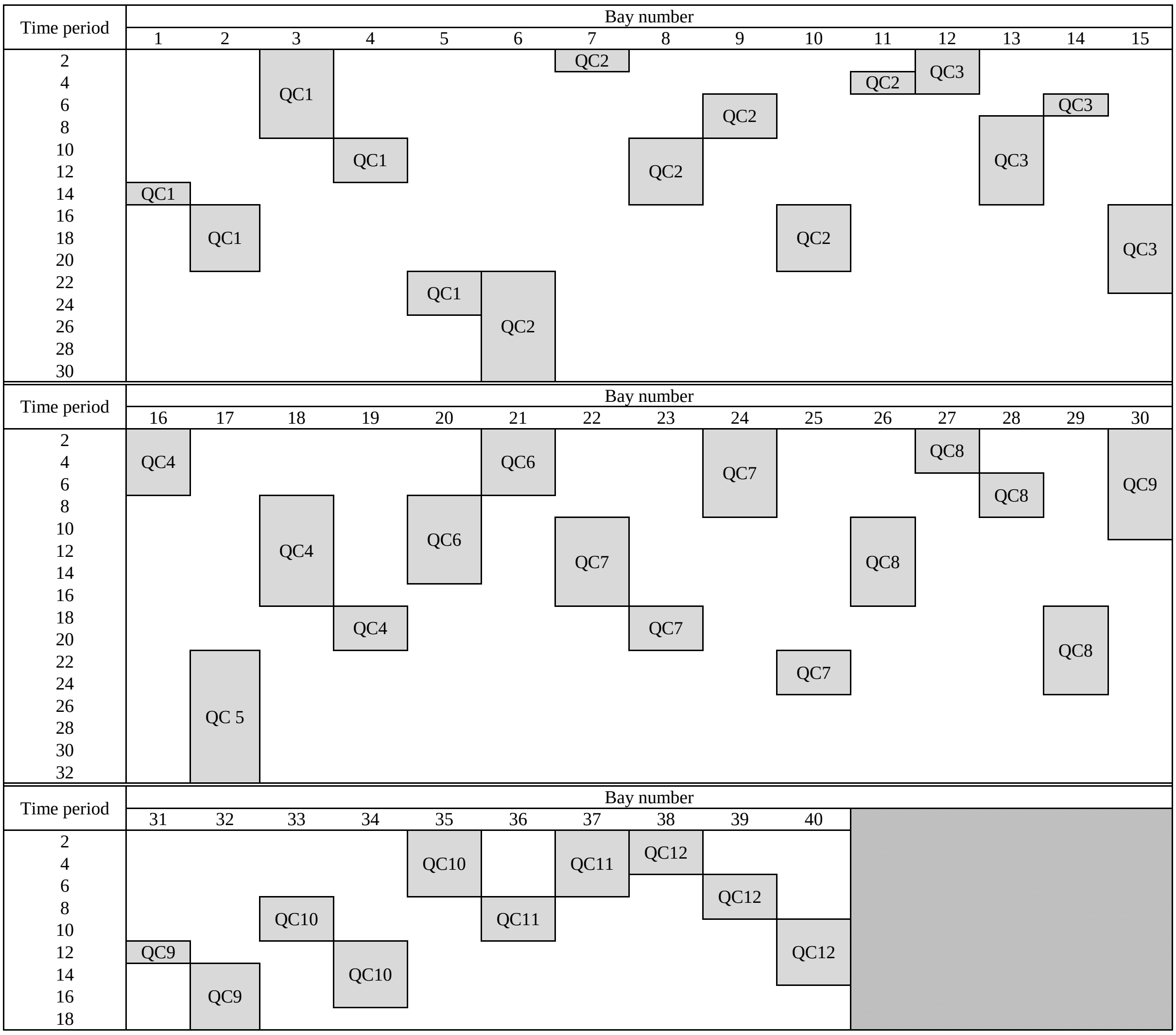

Table 20. Optimal results for sensitivity analysis for Case III.

Crane	1	2	3	4	5	6	7	8	9	10	11	12	Makespan	Total containers	Minimum satisfaction
Base	30	15	35	15	30	35	30	15	35	15	30	35	16.52	5940	81%
Ascending order	15	15	15	15	30	30	30	30	35	35	35	35	21.33	5940	84%
High rates in the middle	15	15	30	30	35	35	35	35	30	30	15	15	31.11	5940	80%
High rates in the sides	35	35	30	30	15	15	15	15	30	30	35	35	29.11	5940	83%

From the previous studies, it is found that:

- The proposed optimization model is found effective in scheduling and sequencing quay cranes operation to achieve stated multiple objectives. Moreover, it considers satisfaction levels on completion times.
- The proposed model can be utilized in determining the optimal quay cranes arrangements. It is found that having the same service rates for all quay cranes provides the best results.
- The proposed model considers more realistic constraints; such as, cranes crossing.

In these regards, the optimization model can provide valuable support to planning engineers in terminal in scheduling and sequencing quay cranes operations in a way that achieves terminal goals.

5. Conclusions

This research proposed an QCASP model to determine the optimal schedule and sequence of quay cranes operations on bays of vessels so that the makespan (latest completion time) of handling all bays is minimized and the utilization of all QCs in the marine container terminal is maximized. The proposed QCASP model was solved for three case studies. The assignment was made for bays of vessels assuming that all bays are ordered from left to right in ascending order. The locations of QCs obtained from solving the model exhibited that the non-crossing condition was not violated at any time, which is an essential requirement in real life as cranes are working on the same rail or track. Also, the cranes process their work on all bays without preemption, meaning that the QC finishes its job on the assigned bay before moving to another one. The results of the model also showed that the tasks on bays were distributed among the available QCs to better utilize them and achieving the shortest possible service time for all vessels so that the terminal could serve additional vessels. In conclusion, utilizing the QCASP model helps in making better utilization of the QCs and shortening the service period by the terminal, which consequently increases the terminal's throughput. Future research will consider developing a heuristic solution to solve large scale quay crane scheduling and sequencing problems.

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