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The Impacts of Time Segment Modeling in Berth Allocation and Quay Crane Assignment on terminal Efficiency

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Abstract

Purpose: The purpose of this paper is to study the impacts of time segment modeling approach for berth allocation and quay crane assignment on container terminal operations efficiency.

Design/methodology/approach: We model the time segment modeling approach in minutely-based, which can be in a minute, in 15 minutes, etc. Moreover, we divided the problem into three sub-problems and proposed a novel Three-level Genetic Algorithm (3LGA) with Quay Crane (QC) shifting heuristics to deal with the problem. Our objective function here is to minimize the total service time by using different time segments for comparison and analysis.

Findings: First, the study shows that by reducing the time segment, the complexity of the problem increases dramatically. Traditional meta-heuristic, such as Genetic Algorithm, Simulated Annealing, etc. becomes not very promising. Second, the proposed 3LGA with QC shifting heuristics outperforms the traditional ones. In addition, by using a smaller time segment, the idling time of berth and QC can be reduced significantly. This greatly benefits the container terminal operations efficiency, and customer service level.

Practical implications: Nowadays, transshipment becomes the main business to many container terminals, especially in Southeast Asia (e.g. Hong Kong and Singapore). In these terminals, vessel arrivals are usually very frequent with small handling volume and very short staying time, e.g. 1.5 hours. Therefore, traditional hourly based modeling approach may cause significant berth and quay crane idling, and consequently cannot meet their practical needs. In this connection, a small time segment modeling approach is requested by industrial practitioners.

Originality/Value: In existing literature, berth allocation and QC assignment are usually in hourly based approach. However, such modeling induces much idling time and consequently causes low utilization and poor service quality level. Therefore, a novel small time segment modeling approach is proposed with a novel optimization algorithm.

KEYWORDS: Transshipment, Berth Allocation, variable-in-time quay crane assignment, time steps, QC shifting heuristics.

1. INTRODUCTION

Transshipment hub is one of the most popular terminal models because of the changes in supply chain model. Examples can be found in Hong Kong, Singapore, Shanghai, Taiwan (Kaohsiung), South Korea (Busan), Malaysia (Tanjung Pelepas), Netherland (Rotterdam), etc. (Zhen et al., 2011; Lee et al., 2012; Liang et al., 2012; Tan and Hilmola 2012). Transshipment hub mainly deals with transshipment activities, in where the vessel turnaround is usually fast. Vessel arrival rate is relatively more frequent with smaller handling volume and shorter staying time comparing with those in traditional gateway terminal. The shortest vessel staying time can even be as short as only 1.5 hours including all the documentations, and loading and unloading operations. While in traditional gateway terminal, vessels are usually with larger handling volume and longer staying time (can be over days).

However, in the existing literature studying on the traditional gateway terminal, most papers applied hourly based time segment approach because the vessel staying time is usually long. For example the vessel handling time for a large vessel with 5,000 containers is about 40 hours (Queensland Government, 2014). In such situation, quay crane (QC) idling for an hour may become relatively insignificant and acceptable (Meisel and Bierwirth, 2009; Giallombardo et al., 2010). However, in transshipment hub, QC idling for an hour becomes significant, resulting in poor operation efficiency. For this reason, many terminals industrialists (example those in Hong Kong) are already changed to 30-minute based planning approach. In fact, the industrialists are seeking for 15-minute based planning approach to further enhance their efficiency by reducing the QC idling. However, to the best of the authors' knowledge, there are no existing papers working in the area of the integrated berth allocation problem (BAP) with variable-in-time quay crane assignment (QCA) that is using 15-minute based or 30-minute based. Therefore, the objective of this paper is to fulfill this research gap raised by the practical industrial needs in the terminal industries. The experimental results obtained by using the new time segment modeling approach showing that vessel-turnover can be faster by reducing vessel waiting time and handling time. This implies that the efficiency of transshipment hubs can be increased, similar to the customer service level as well.

Although one may expect that operation efficiency can be improved because of the reduction in QC idling, the problem complexity modeling in minutely based is in fact much higher than the traditional hourly based one, especially for the integrated BAP with variable-in-time QCA model. The increasing number of variables related to QCA increases the computational complexity. Meanwhile, the time unit is another factor that increases the problem complexity dramatically as well. For example, in a typical hourly based approach, a day is divided into 24 discrete time segments. However, if we model in a 15-mintue based approach, the number of the time segments will then increase four times to 96. This implies that the number of related variables will also increase exponentially. Therefore, traditional hourly based solution approaches (such as integer programming) may not be applicable in this case as the computational time will be too long. In this connection, a new optimization algorithm is required. Since it is known that solving an integrated BAP with variable-in-time QCA is more complicated than dealing with them separately, problem decomposition seems to be promising (Buhrkal et al., 2011; Ma et al., 2013; Cheng et al., 2016). In addition, GA is widely adopted for handling NP-hard scheduling problems (Damodaran et al., 2009). Therefore, we propose a novel 3LGA which decomposes the problem into three interrelated sub-problems: i) berth assignment, ii) quay crane assignment, and iii) vessels service sequence. To consider variable-in-time QCA, which is to allow idled QC to service another vessel, we also proposed a QC shifting heuristics combining with 3LGA for fine local search. The new approach aims to improve the operation efficiency of the transshipment hubs by minimizing the total waiting time and handling time. The rest of the paper is divided into the following sections. Section 2 gives a literature review. The corresponding problem formulation, the proposed 3-Level Genetic Algorithms (3LGA) and the QC shifting heuristics are described in Section 3. Section 4 presents and discussed the results, and Section 5 concludes the paper.

2. LITERATURE REVIEW

Studies of container terminal operations can generally be classified into Berth Allocation Problem (BAP), Quay Crane Assignment (QCA), Quay Crane Scheduling Problem (QCSP), Yard Storage Planning (YSP), etc. Among them, BAP is known to be one of the key elements as it controls and determines the incoming jobs (vessels). BAP consists of two main problems: (i) how to allocate different vessels to berths, and (ii) determine when a vessel should moor (Steenken et al. 2004; Bierwirth and Meisel 2010). In BAP studies, some solely focus on minimizing the total handling time, while some also include the total waiting time, defined as the total servicing time. Some studies investigate the deviation from the best berthing position and etc, (Imai et al., 2001; Imai et al., 2003; Imai et al., 2007; Nishimura et al., 2001; Mauri et al., 2008; Saharidis et al., 2010; Li and Yip, 2013; Li, 2014; Golias et al., 2011). In which, the vessel handling time can be defined as deterministic, such as a predefined and a committed time (Guan and Cheung, 2004; Wang and Lim, 2007), while some studies are defined by the berthing position (Nishimura et al., 2001; Imai et al., 2007).

In fact, vessel handling time can be influenced by many factors for examples, internal transport vehicle allocation, berth location to yard, interruptions during the loading or unloading operation, the ability of the crane driver using the crane, the operating rules for restricting the movement of cranes, etc., more important are the number of containers to be handled, the number of QCs assigned and its productivity rate (Zhou et al., 2006; Zhou et al., 2008; Theofanis et al., 2009; Golias, 2011; Raa et al., 2011; Meisel and Bierwirth, 2013). With a large the number of QCs being assigned to a vessel, obviously the handling time should be shorter. Therefore, BAP is commonly planned with QCA simultaneously in order to improve the feasibility and optimality in recent years (Bierwirth and Meisel, 2010; Zhang et al., 2010; Raa et al., 2011; Wang et al., 2014). QCA deals with the assignment of QCs to a vessel for carrying out the loading and unloading operations. According to Meisel and Bierwirth (2013), QCAs can generally be divided into two main types, (i) time-invariable assignment and (ii) variable-in-time assignment.

In time-invariable assignment, a vessel is assigned with a constant number of QCs over the whole service period. The utilization of QCs here is usually low because the QCs will not be reassigned to serve other vessels even they are idle after the completion of the current operation (Imai et al., 2008; Liang et al., 2009; Chang et al., 2010; Liang et al., 2011; Yang et al., 2012; Mario et al., 2013). To better improve the QC utilization, some researches consider proposed variable-in-time assignment, in which the number of QCs being assigned will vary through the whole service period (Park and Kim, 2003; Meisel and Bierwirth, 2009). The period applied ranged from an hour to a few hours. Although this modeling approach can simplify the problem complexity, this induce idling (Vacca et al., 2013). In this modeling approach, within the time segment, the idled QC cannot be reassigned to service other vessels until the next time segment start. For example, a vessel completed its task and left at 4:15 p.m. However, by using the hourly based interval approach, the QCs assigned to this vessel can only be released at 5 p.m. These QCs are idled for 45 minutes. Reducing this kind of idle can bring significant improvement on vessel waiting time and handling time, and it can be reduced by defining a 15-minute based time segment.

Park and Kim (2003) was the first one considered the integrated continuous BAP with variable-in-time QCA. The assignment was varied by every single time segment. They proposed a two-phase heuristic solution approach for the problem. The first phase was based on Lagrangean relaxation which determines the berthing time and position of each vessel as well as the number of QCs assigned to each vessel per each time segment. The second phase was based on dynamic programming; a detailed schedule for each quay crane was constructed according to the solution found in the first phase. For the reasons of simplicity, the productivity of the QC is always assumed directly proportional to the number of QCs that simultaneously serve a vessel by many researchers, including Park and Kim (2003). The assumption was criticized by Cordeau et al. (2005) and Hansen et al. (2008) as QCs may loss their productivity due to interference among QCs. Meisel and Bierwirth (2009) therefore focused on quay crane productivity in their studied model. The authors presented construction heuristic and local refinement procedures for feasible berth allocation and assignment of QCs and also developed two meta-heuristics to decide the priority list of vessels for improving the quality of berth plans. They compared their approach to the one proposed by Park and Kim (2003) using the same data sets and they always obtain better solution. Zhang et al. (2010) also further studied the integrated model introduced by Park and Kim (2003). They claimed that QCs could not cover the entire berth in reality, so they extended the model to restricting the moving the cranes by considering its coverage ranges.

Meisel and Bierwirth (2006) treated the integrated problem as a multi-mode resource-constrained project scheduling problem. Every vessel was represented as an activity which can be performed in different modes. Each mode represented a certain QC-to-vessel assignment over the planning horizon. The objective was to minimize the idle time of QCs. A priority rule based method was used to decide the mode, the berthing time and the berthing position of each vessel. Based on Meisel and Bierwirth (2006), Giallombardo et al. (2010) introduced a QC profile in their model which is similar to the concept of "mode". Each vessel required a certain amount of QC hours. In this study, the time segment for each QC profile is in 4 hours. For a given amount of QC hours, it could be possible to create different QC profiles. The profile consists of a number of working shifts occupied by a vessel and a number of QCs assigned to the vessel at each shift. They proposed a two-level heuristic for solving the integrated problem with the QC profile. A QC profile is initially assigned to a vessel, and a tabu search heuristics was adopted in the first level for berth allocation, and then the QC profile updating procedure was carried out in the second level which relied on the mathematical programming. Later on, Meisel and Bierwirth (2013) further elaborated their previous model by including QCSP. They proposed a three-phase framework for the integration of BAP, QCA and QCSP.

As a summary, in the existing literature regarding QC assignment, variable-in-time is proven to be better in QC utilization. It improves the efficiency of container terminal operations. However, majority of the existing work considers a relatively long time segment for each QC movement, which may result in poor QC utilization, due to the high problem complexity. Therefore, this paper studies the impacts of time segment modeling in berth allocation and QC assignment on the container terminal operations efficiency by proposing a new algorithm, which is able to handle 15 minutes time-segment efficiently.

3. METHODOLOGY

3.1 Problem Formulation

In this section, a mathematical model for the BAP with QCA is presented. In this model, the terminal is in discrete berth layout, and dynamic vessel arrivals are considered. Hence, vessels cannot berth before their arrival times. The handling time of the vessel varies depending on QCA. In traditional QCA models, a set of vessels is always served within a planning horizon which is divided into hourly based time segments. Since QC interferences is usually only considered in quay crane scheduling problem (Chung and Chan 2013), a constant QC productivity is used. QCs interference is assumed to be insignificant. The objective function (1) is to improve the operation efficiency of the terminal by minimizing the total waiting time and handling time. The notations used for the parameters in the mathematical model are shown in the following:

<u>Input data</u>

V set of vessels (V= 1, 2, 3…*I*)

B set of berths in terminal (B = 1, 2, 3…*J*)

U set of 15-minute time steps (U = 1, 2, 3…*T*)

a_i expected arrival time of the vessel (an expected value) $i \in V$

v_i handling volume of vessel $i \in V$

q_i^{max} maximum number of QCs can be assigned to vessel $i \in V$

q_i^{min} minimum number of QCs can be assigned to vessel $i \in V$

R_i range of the assignable number of QCs for vessel $i \in V$, where $R_i = [q_i^{min}, q_i^{max}]$

P QC productivity, expressed as the volume (TEU) handled by a QC at a time step

Q total number of QCs in terminal

N a sufficiently large positive constant

In addition, $o(b)$ and $e(b)$ are introduced as the starting node and ending node at berth $b \in B$. $s_{o(b)}$ and $s_{e(b)}$ represent the starting time and ending time (dummy nodes) of the planning horizon of berth $b \in B$. Moreover, q_i^{max} and q_i^{min} are used as given input modeling parameters to limit the choice of available QCs in each berth.

<u>Decision variables</u>

s_i berthing time of vessel $i \in V$

c_i completion time of vessel $i \in V$

$y_{itq} \in \{0, 1\}$, set to 1 if QCs with the range q, where $q \in R_i$, are assigned to vessel $i \in V$ at time step $t \in U$, and 0 otherwise;

$y_{it} \in \{0, 1\}$, set to 1 if at least one QC is assigned to vessel $i \in V$ at time step $t \in U$, and 0 otherwise;

$x_{ij}^b \in \{0, 1\}$, set to 1 if vessel $j \in V$ is scheduled after vessel $i \in V$ at berth $b \in B$, and 0 otherwise;

$x_i^b \quad \in \{0,1\},$ set to 1 if vessel $i \in V$ is assigned to berth $b \in B$, and 0 otherwise;

Objective:

$$Z_1 = \text{Min} \sum_{i \in V}(c_i - a_i) \quad (1)$$

Constraints:

$$\sum_{b \in B} x_i^b = 1, \quad \forall i \in V \quad (2)$$

$$\sum_{j \in \{V \cup e(b)\}} x_{ij}^b = x_i^b, \quad \forall i \in V, \forall b \in B \quad (3)$$

$$\sum_{j \in \{V \cup e(b)\}} x_{o(b)j}^b = 1, \quad \forall b \in B \quad (4)$$

$$\sum_{i \in \{V \cup o(b)\}} x_{ie(b)}^b = 1, \quad \forall b \in B \quad (5)$$

$$\sum_{j \in \{V \cup e(b)\}} x_{ij}^b - \sum_{i \in \{V \cup o(b)\}} x_{ji}^b = 0, \quad \forall i \in V, \forall b \in B \quad (6)$$

$$\sum_{b \in B} x_{ie(b)}^b \cdot (s_{e(b)} - c_i) \geq 0, \quad \forall i \in V \quad (7)$$

$$\sum_{b \in B} x_{o(b)j}^b \cdot (s_j - s_{o(b)}) \geq 0, \quad \forall j \in V \quad (8)$$

$$s_i - a_i \geq 0, \quad \forall i \in V \quad (9)$$

$$\sum_{j \in \{V \cup e(b)\}} s_j + N \cdot (1 - x_{ij}^b) \geq c_i \ , \quad \forall i \in V, \forall b \in B \quad (10)$$

$$\sum_{i \in V} \sum_{q \in R_i} (q \cdot y_{itq}) \leq Q, \quad \forall t \in U \quad (11)$$

$$\sum_{q \in R_i} y_{itq} = y_{it}, \quad \forall i \in V, \forall t \in U \quad (12)$$

$$\sum_{t \in U} \sum_{q \in R_i} P \cdot q \cdot y_{itq} \geq v_i, \quad \forall i \in V \quad (13)$$

$$\sum_{t \in U} y_{it} \leq c_i - s_i, \quad \forall i \in V \quad (14)$$

$$t \cdot y_{it} \leq c_i, \quad \forall i \in V, \forall t \in U \quad (15)$$

$$t \cdot y_{it} + N \cdot (1 - y_{it}) \geq s_i, \quad \forall i \in V, \forall t \in U \quad (16)$$

$$y_{itq},\ y_{it},\ x_{ij}^b,\ x_i^b \in \{0,1\}, \quad \forall i \in V,\ t \in U, b \in B, \quad (17)$$

Constraint (2) ensures that every vessel must be served at a berth. Constraint (3) sets the relationship between the two variables. Constraint (4) and (5) define the starting and the ending of the flow of the served vessels at each berth, while constraint (6) ensures the flow conservation for the remaining vessels at a berth. Constraint (7) and (8) ensure the vessels will be served within the planning horizon. Constraint (9) and (10) ensure no vessel should berth before its arrivals or the completion of the pervious vessel. Constraint (11) ensures the total number of assigned QCs at each time step must not exceed the total number of QCs in the terminal. Constraint (12) ensures the consistency of the variables. Constraint (13) ensures every vessel receives sufficient QC capacity for servicing. Constraints (14) – (16) set the berthing time and completing time of the vessel without preemption.

3.2 Proposed Optimization Methodology: Three-Level Genetic Algorithm (3LGA)

The problem involves three major decisions, including i) berth allocation, ii) vessel scheduling, and iii) quay crane assignment. With the reduction in the time unit from hourly to minutely, the problem complexity exponentially increases. Since GA is known to be a promising approach for solving large scale scheduling problems in the literature, we decided to use GA (Sakhuja et al. 2014; Chung et al. 2015). In fact, the abovementioned three decisions can be all represented by a single chromosome by using a three-dimensional chromosome as in the traditional GA modeling approach (This can be regarded as a single-level GA). However, in such modeling approach, the chromosome may consist of too much information, causing low genetic search ability and resulting in poor performance. We will test and demonstrate this in the numerical experiments in the later section.

To reduce the problem complexity, and improve the performance of the GA, a 3LGA is proposed. The idea is to decompose the highly complicated problem into different sub-problems so as to improve the solution optimality obtained in each sub-problem in order to increase the chances of optimality of the final solution (Chung and Chan 2012). This idea is demonstrated to be promising in economic lot scheduling problems. Therefore, we develop this proposed 3LGA based on this. The problem here is decomposed into three parts and solved at different levels, where the first level is aimed at allocating vessels to berths, the second level is aimed at sequencing vessels, and the third level is aimed at assigning QCs to vessel at different time along its operation. Accordingly, each GA can have a better focus and the genetic search in each part can be better.

3.2.1 Mechanism of the 3LGA

The proposed 3LGA has three parts, i) Berth allocation, ii) Vessel scheduling, and iii) Variable-in-time Quay crane assignment, and are corresponding to the 1st level, the 2nd level, and the 3rd level GA. The relationship among these three levels is presented in Fig. 1. The starting point of the 3LGA is the generation of the Berth Allocation chromosome (BA-chromosome) (the initial pool) in 1st level GA as explained below and in Fig. 2:

1st level GA: With the structure of these BA-chromosomes, we will be able to know which vessel(s) are being assigned to which berth in each potential solution. Then we rely on the 2nd level GA to optimize the best vessel sequence at each berth for each individual BA-chromosome.

2nd level GA: This level aims to optimize the vessel sequence in each berth for each BA-chromosome. However, at this moment, the completion time of each vessel cannot be calculated without the information of the number of QCs assigned to each vessel at each time segment. Therefore, it is relied on the 3rd level GA.

3rd level GA: This level will optimize the number of QCs being assigned to each vessel at different time along its operation in the container terminal. Then the result will pass back to the 2nd level GA, and the optimized vessel sequence obtained in the 2nd level GA will pass back to the 1st level GA and so on. The iteration will stop until the stopping condition is reached at the 1st level GA."

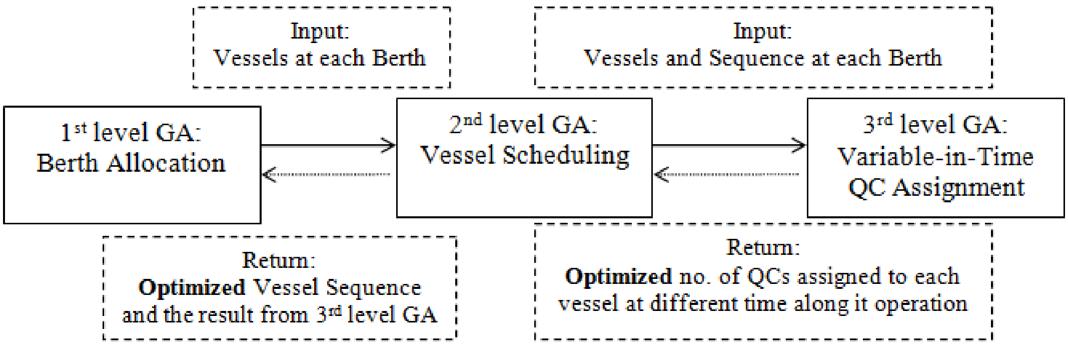


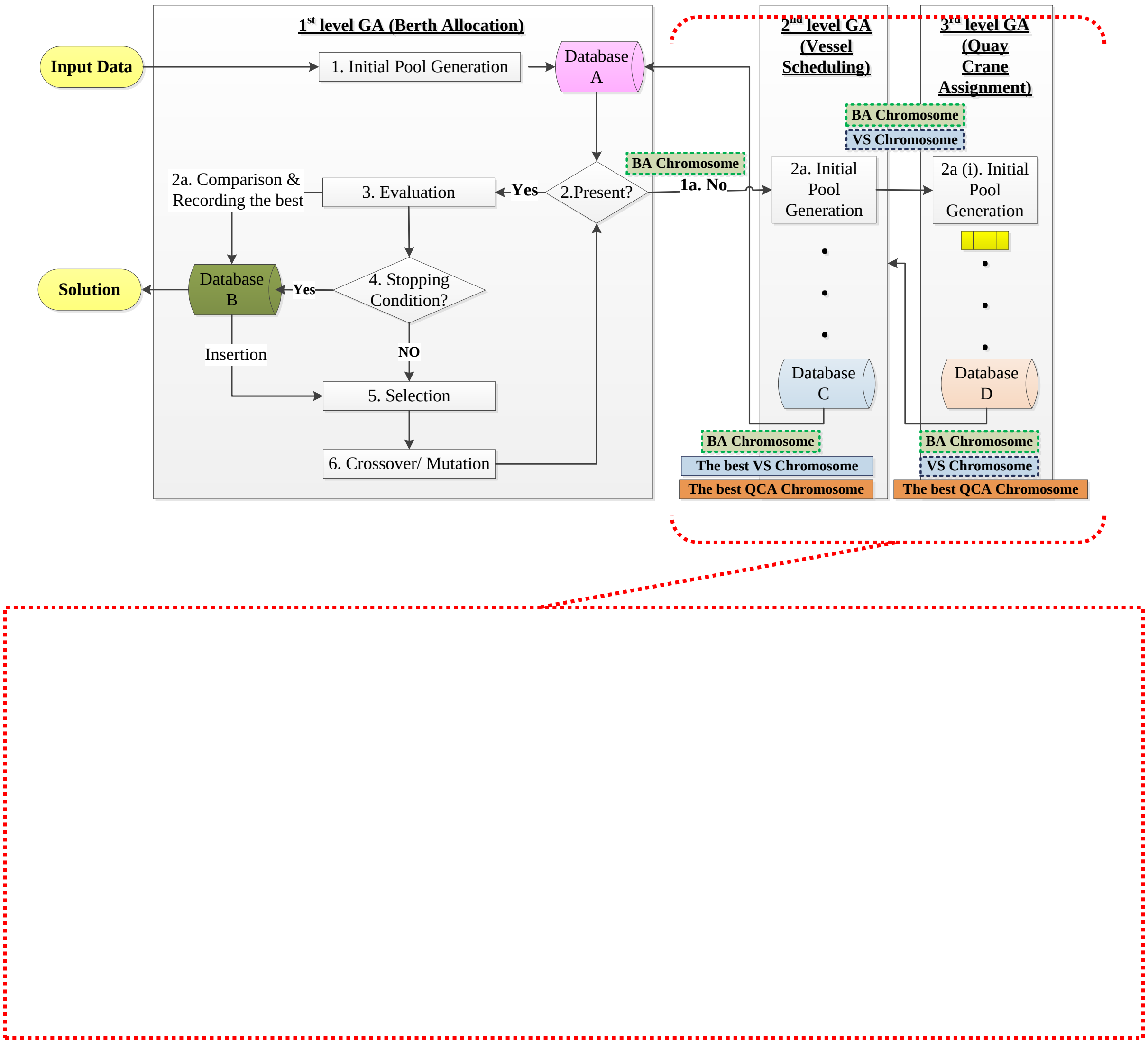
Fig. 1. The relationship between different levels in 3LGA

In more detail, the 3LGA framework is shown in Fig. 2. Four databases, Database A (DA), Database B (DB), Database C (DC) and Database D (DD), are involved. First of all, BA-chromosome is generated in the 1st level GA as mentioned before, the 2nd and 3rd level GA will be started. DA will record the BA-chromosome with its corresponding best Vessel Schedule chromosome (VS-chromosome) from DC and Quay Crane Assignment chromosome (QCA-chromosome) from DD as shown in Fig.2. If an identical BA-chromosome is generated again in the later iterations of the 1st level GA, the redundant 2nd and 3rd level GA processes will be skipped, and its corresponding best VS-chromosome and QCA-chromosome are directly obtained from DA. In this way, the efficiency of GA searching can be improved. DB, DC and DD are used to record the best chromosome in each GA, and to facilitate the elitist strategy (in section *3.2.4*). A QC shifting heuristics is proposed and implemented into the 3rd level GA to determine the complete variable-in-time QCA. The interaction among different levels of the 3LGA, and the detail steps please refers to the appendix.

3.2.2 Generation of initial pool and chromosome representation

A number of BA-chromosomes are randomly generated to form an initial pool of the 1st level GA. Fig. 3 shows an example of a BA-chromosome. It consists of I number of genes. The position of each gene corresponds to a vessel number, increasing from the left to the right. The value stored in the gene represents the berth where the vessel is assigned to. The example demonstrates that there are 3 berths being allocated for 8 vessels, in which Berth 1 is allocated for Vessels 1, 2 and 5, Berth 3 is allocated for Vessels 4 and 8 and so on.

Similarly, a number of VS-chromosomes are randomly generated to form the initial pool of the 2nd level GA. It consists of I number of genes. The position of each gene corresponds to a vessel number, and the value stored in the gene represents the service order (θ) of the vessel. An example of a VS-chromosome is shown in Fig. 4.



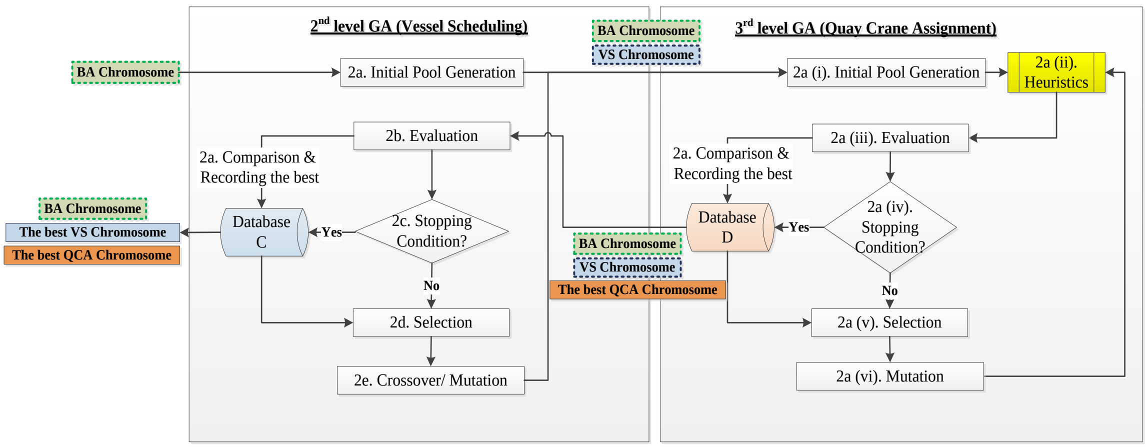


Fig. 2. 3LGA optimization methodology framework

i =	1	2	3	4	5	6	7	8
BA-chromosome:	1	1	2	3	1	3	2	3

Fig. 3. Chromosome of the 1st level GA

i =	1	2	3	4	5	6	7	8
VS-chromosome:	2	4	8	1	3	5	7	6

Fig. 4. Chromosome of the 2nd level GA

By combining the BA-chromosome with the VS-chromosome, the vessel schedule can be obtained. Fig. 5 shows an example of a vessel schedule formed by the BA-chromosome in Fig. 3 with the VS-chromosome in Fig. 4. To obtain the schedule, starting from the vessel with θ = 1 which is Vessel 4, it will be served as the first vessel (k = 1) at Berth 3. Then, for θ = 2, Vessel 1 will be served as the first vessel (k = 1) at Berth 1. For θ = 3, Vessel 5 will be served as the second vessel (k = 2) at Berth 1, and so on.

Vessel schedule (v_{jk})			
Berth (j)	Service order at a berth (k)		
	1	2	3
1	1	5	2
2	7	3	---
3	4	6	8

Fig. 5. An example of the vessel schedule

For the 3rd level GA, QCA-chromosomes cannot be generated randomly as infeasible solutions may result easily. Therefore, we proposed QCA-chromosomes will be generated according to the follows:

i. Check the berthing time (s_i) = max {berth available time, vessel arrival time (a_i)} of the vessel *i* being served at each berth $b \in B$ with k =1. Since all vessels arrive after starting time of planning horizon, it starts by the vessel *i* with the earliest arrival time.

ii. Check the number of available QCs at s_i. If the number is smaller than q_i^{min}, s_i will increases until sufficient QCs are available.

iii. Randomly assign a number of QCs (q) for the vessel i range in [q_i^{min}, q_i^{max}] at s_i without violate the constraint (11).

iv. Calculate c_i of the vessel *i* by the eq. (18).

$$c_i = s_i + \frac{v_i}{P \times q} \qquad (18)$$

v. If c_i is not a multiplication of 15, c_i could increase to the nearest of the multiplication of 15 to get the actual value of c_i. Update $y_{itq} = 1$ form t = s_i to $t = c_i$, and the berth available time to $c_i + 1$.

vi. Check the next vessel with the earliest berthing time among berth $b \in B$ and repeat steps ii – v, until the all the vessels have been gone through the procedures.

For the first chromosome of the initial pool, all vessels will be assigned with the maximum available QCs instead of random assignment in step (iii). In the meantime, all the constraints will also be satisfied.

After completed the assignment procedures, a feasible QCA-chromosome is formed which is shown in Fig. 6. It consists of *I* number of genes. The position of each gene corresponds to the vessel number, increasing from the left to the right. The value stored in the gene represents the number of QCs being assigned to that vessel. Similarly, a number of QCA-chromosomes are then generated to form an initial pool of the 3rd level GA.

i =	1	2	3	4	5	6	7	8
QCA-chromosome:	2	4	5	3	3	6	2	4

Fig. 6. Chromosome of the 3rd level GA

3.2.3 Evaluation

Evaluation is based on a fitness value which represents the relative strength of a chromosome to the others in the same solution pool, and is calculated by eq. (19).

$$f(x) = 1 - \left(\frac{Z_3(x)}{\sum_{p=1}^{P} Z_3(p)}\right) \quad (19)$$

, where $Z_3(x)$ is the objective value of the chromosome x, and P is the initial solution pool size of GA. Since the objective is a minimizing function, an inverse function is needed to convert the objective value into a fitness value. Hence, the smaller the objective value, the higher the fitness can be.

3.2.4 Selection and elitist strategy

The selection methodology applied is the commonly used Roulette Wheel Selection approach. It gives to each chromosome a probability directly proportional to its fitness. The higher the fitness is, the higher the probability is for the chromosome to be selected. It is similar to the concept of “survival of the fittest”. Since it is not a deterministic choice, and remains a probability, a chromosome with a comparatively low fitness may still be chosen. To avoid the loss of the best chromosome, elitist strategy is also applied. Elitist strategy: The best chromosome is recorded and inserted back into the mating pool to replace the weakest chromosome in the next evolution.

3.2.5 Crossover and mutation

(i) Crossover operation

Uniform crossover with ratio (1/*I*) is applied in both the 1st level and 2nd level GA. Since a slight modification may cause dramatic changes to the 2nd level GA and to the 3rd level GA, a slow evolution approach is applied to avoid random searching. A pair of BA-chromosomes is required for the crossover operation. Fig. 7 shows an example of the crossover operation of the 1st level GA, in which the fourth gene is randomly being selected for crossover. After crossover, the berth allocated to Vessel 4 will change to 1 and 3 in the BA-chromosome (1) and (2) respectively.

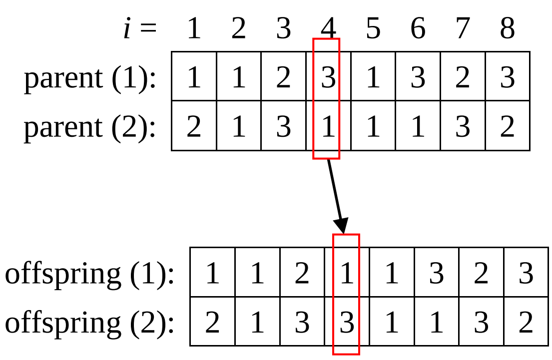


Fig. 7. Crossover operation of 1^{st} level GA

For the 2^{nd} level GA, a gene from a VS-chromosome will be randomly selected, and is swapped with the gene with the same position of another VS-chromosome. After that, a validation will be processed to ensure each vessel will be assigned to a θ once and only one. Fig. 8 shows an example in which the third gene is randomly selected for crossover. After crossover, in the VS-chromosome (1), both Vessels 2 and 3 are assigned to $\theta = 4$. Therefore, the validation will be carried out to assign Vessel 2 to $\theta = 8$.

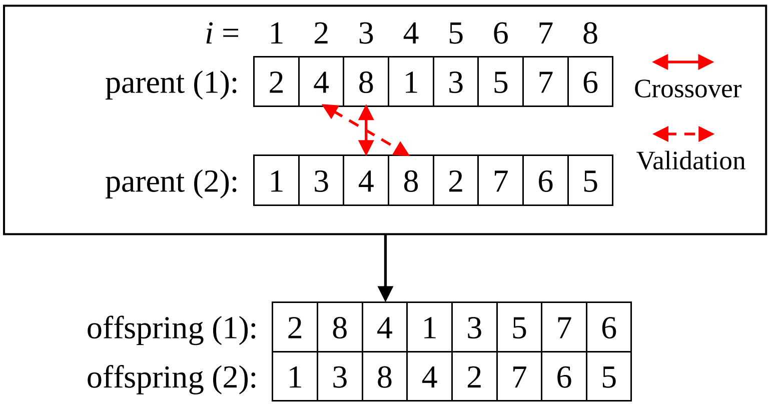


Fig. 8. Crossover operation of the 2^{nd} level GA

Given the BA-chromosome as the one shown in Fig. 3, the vessel schedules formed the BA-chromosome with the VS-chromosomes (1) before crossover and after crossover are shown in Fig. 9. In this case, the service order *k* at berth 2 of vessel 3 and 7 are swapped.

<u>Before crossover</u>

parent (1)			
Vessel schedule			
	$k = 1$	$k = 2$	$k = 3$
$j = 1$	1	5	2
$j = 2$	7	3	---
$j = 3$	4	6	8

<u>After crossover</u>

offspring (1)			
Vessel schedule			
	$k = 1$	$k = 2$	$k = 3$
$j = 1$	1	5	2
$j = 2$	3	7	---
$j = 3$	4	6	8

Fig. 9. Vessel schedule after crossover

(ii) Mutation operation

To avoid random searching, mutation with ratio (1/*I*) is applied in the 1^{st} level GA, the 2^{nd} level GA, and the 3^{rd} level GA. Only one chromosome is required for the mutation operation. For the 1^{st} level GA, a new value is randomly generated within set *B* to replace the value of the gene which is also randomly selected from a BA-chromosome. In an example shown in Fig. 10, the berth allocated to Vessel 2 is change from Berth 1 to the mutated value Berth 2.

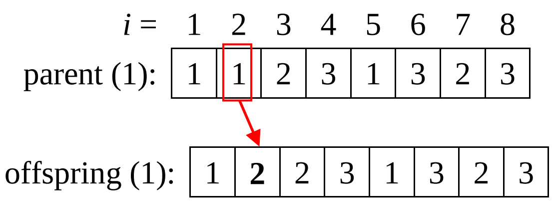


Fig. 10. Mutation of the 1st level GA

In the 2nd level GA, two genes of a VS-chromosome will be randomly selected and swap with each other. Fig. 11 shows an example in which the second gene and the sixth gene are randomly selected for swapping. After that, a new chromosome is formed. In which, the θ of Vessel 2 will change from 4 to 5, while the θ of Vessel 6 will do the change oppositely.

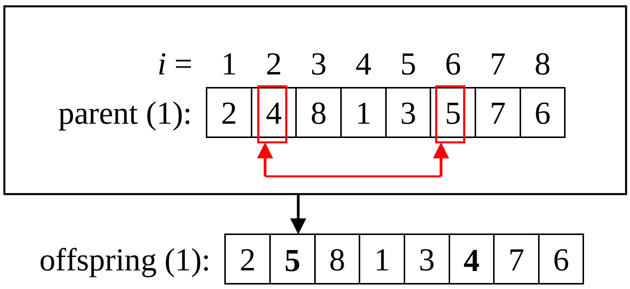


Fig. 11. Mutation of the 2nd level GA

In the 3rd level GA, a gene of a QCA-chromosome will be randomly selected, and the value stored in the gene will be mutated by adding 1. It means that one more QC is assigned to the corresponding vessel. Sometimes, the change may cause infeasible chromosome. Therefore, validation processes (Steps V1 – V3) are needed, and it will be started from the vessel *m* with the mutated gene.

Validation process

V1. Check if the new number of QCs $(\hat{q})$ assigned to the Vessel *m* is larger than q_m^{max} in the terminal. If yes, the value of the gene will be deduced 1 and quit the validation process. Otherwise, go to step V2.

V2. Calculate the new completion time $(\widehat{c_m})$ by eq. (19), and update $y_{mt\hat{q}} = 1$ form $t = s_i$ to $t = \widehat{c_m}$.

V3. Check the next vessel with the earliest berthing time among Berth $b \in B$, and repeat the Steps ii – vi of the QCA-chromosome Generating Procedures with the following remark to redo the assignment of the later vessels.

Remark:

In step (iii), the number of QCs assigned to the vessel in the parent chromosome will be used again instead of randomly generate a new value. If the number of QCs assigned to the vessel exceeds the number of available QCs, the maximum number of available QCs will be assigned to that vessel.

Fig. 12 shows an example of the mutation of the 3rd level GA. The third gene is being selected, and the value stored in the gene is 5. After mutation, the value changes to 6, and the chromosome becomes invalid. Therefore, the validation procedures are carried out to validate the chromosome by changing the number of QCs assigned to Vessel 5.

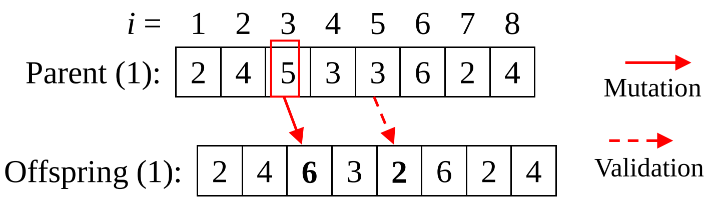


Fig. 12. Mutation of the 3rd level GA

3.2.6 QC shifting heuristics

In the 3rd level GA chromosome, a fixed number of QCs is assigned to a vessel during its entire operation. This QCA is in fact time-invariable assignment. In this assignment, QCs will not be released to join another even though they are idling. This reduces the QCs utilization. To improve this, a QC shifting heuristics is proposed and implemented, which changes the QCA from time-invariable into time-variable assignment. Since QC moving can be time consuming when QC interference exists, a number of QCs after the completion of their operation for a vessel will only be reassigned to its adjacent vessel. Therefore, no other QCs will be operating along the path during the movement. In addition, since too many movements in a short period of time are unrealistic, we forbid more than 2 times of QCs reassignment between each pair of vessels in order to make the algorithm more practical. Therefore, we suggest two situations for QC shifting in our proposed heuristics (Fig.13).

If QCs is released from Vessels A to B and no other incoming vessels is expected to be arrived at Berth 2 before the completion of Vessel B, this is regarded as Situation 1. In this situation, QCs released will operate there until the completion of Vessel B. The number of QCs involved in the shifting depends on the remaining QC capacity of the Vessel B. Otherwise for Situation 2, QCs released will return back to Berth 2 when the expected incoming Vessel C is arrived.

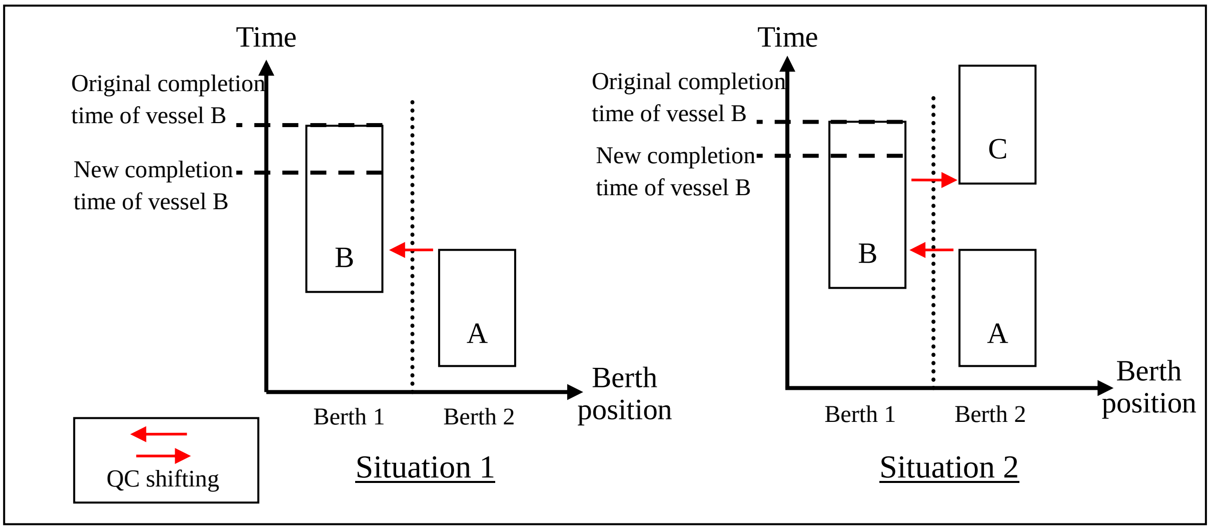


Fig. 13. Situations for QCs shifting

Summary of steps of the 3LGA

Start: Both the container terminal and the vessel information are required as the input data for the 3LGA.

1st level GA

Step 1: A number of BA-chromosomes, which indicates the berth allocation information, will be generated to form an initial pool (in section *3.2.2*).

Step 2: If an individual BA-chromosome is firstly generated, go to **Step 2a**. Otherwise, a record of the BA-chromosome can be found in DA, go to the **Step 3**.

2nd level GA

Step 2a: Each BA-chromosome, acted as an input data, is individually passed to the 2nd level GA. A number of VS-chromosomes, which indicates the service sequence of the vessels, will be generated to form an initial pool (in section *3.2.2*). Then, go to **Step 2a (i)**.

3rd level GA

Step 2a (i): A number of QCA-chromosomes, which indicates the initial QCA information, will be generated to form an initial pool based on the input BA-chromosome and VS-chromosome (in section *3.2.2*).

Step 2a (ii): They will go through the QC shifting heuristic (in section *3.2.6*) to obtain the complete QCA.

Step 2a (iii): Fitness evaluation for the QCA-chromosome with its completed QCA (in section *3.2.3*). The chromosome with the highest fitness value will be compared to the one stored in DD. If it has higher fitness value, it will replace that one stored in DD.

Step 2a (iv): Check if the stopping condition is reached. If yes, the best QCA-chromosome for the set of BA-chromosome & VS-chromosome will be recorded, and pass back to **Step 2b** of the 2nd level GA. If no, go to **Step 2a (v)**.

Step 2a (v): Formation of the mating pool by using the traditional roulette wheel selection approach, and the elitist strategy is applied (in section *3.2.4*).

Step 2a (vi): Genetics Operations – Uniform mutation (in section *3.2.5*). Go back to **Step 2a (ii)**.

Step 2b: Fitness evaluation for the VS-chromosome with its best QCA-chromosome (in section *3.2.3*). The chromosome with the highest fitness value will be compared to the one stored in the DC. If it has higher fitness value, it will replace that one stored in DC.

Step 2c: Check if the stopping condition is reached. If yes, the best VS-chromosome with its best QCA-chromosome for the BA-chromosome will be recorded, and pass back to **Step 3** of the 1st level GA. Otherwise, go to **Step 2d**.

Step 2d: Formation of the mating pool by using the traditional roulette wheel selection approach, and the elitist strategy is applied (in section *3.2.4*).

Step 2e: Genetics Operations – Uniform crossover and mutation (in section *3.2.5*). Go back to **Step 2a (i)**.

Step 3: Fitness evaluation of the BA-chromosome together with its best VS-chromosome & QCA-chromosome (in section 3.2.3). The chromosome with the highest fitness value will be compared to the one stored in DB. If it has higher fitness value, it will replace that one stored in DB.

Step 4: Check if the stopping condition is reached. If not, go to **Step 5**. Otherwise, go to **Step 7**.

Step 5: A number of BA-chromosomes will be selected to form the mating pool by using the traditional roulette wheel selection approach, and the elitist strategy is applied (in section 3.2.4).

Step 6: Genetics Operation – Uniform crossover and mutation (in section 3.2.5). Go to **Step 2**.

Step 7: Record the best BA-chromosome with its best VS-chromosome & QCA-chromosome.

End: The best solution of the berth allocation, vessel schedule and the QCA are obtained.

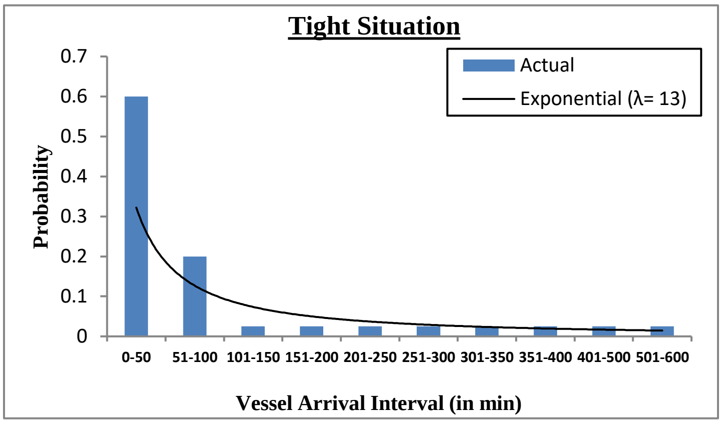
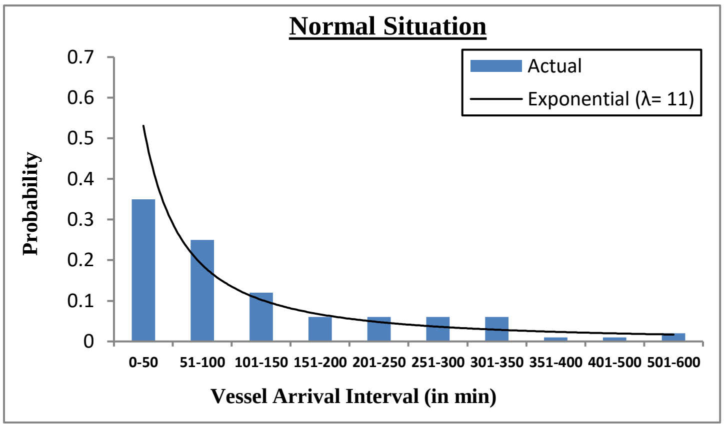
4. COMPUTATIONAL RESULTS

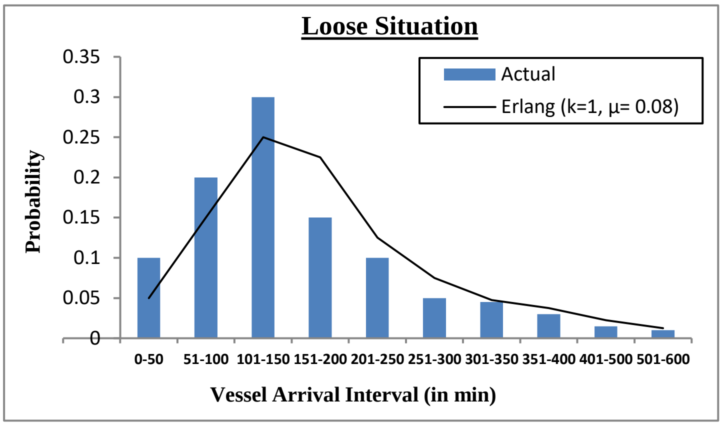
Numerical experiments are conducted to test the performance of the proposed algorithm. The generation of the test instances and the parameters setting are included in Section 4.1. To test the solution quality of the proposed 3LGA, it has been compared with commonly used approaches, Single-level GA, a Two-level GA, and Simulated Annealing (SA), in Section 4.2. To study the impacts of the time segment modeling approach on the operations efficiency of container port, a detail analysis will be given in Section 4.3.

4.1 Data Parameter Setting

In the experiments, the quay of the terminal is partitioned into 3 berths (B = 3) with a total of 8 QCs (Q = 8). We constructed 3 problem sizes: 10, 20 and 50 vessels, and 3 types of vessel arrival rate: Tight, Normal and Loose with a total of 9 instances as shown in Table 1. The vessel arrival patterns are generated by using Exponential distribution for the tight and normal situations, and Erlang distribution for the loose situation.

Table 1 – Proportions of vessel arrival intervals

Type	Proportions of the vessel arrival intervals (min)	%	Distribution
Tight (A)	0 ≤ V ≤ 100 101 ≤ V ≤ 300 301 ≤ V ≤ 600	80 10 10	
Normal (B)	0 ≤ V ≤ 100 101 ≤ V ≤ 300 301 ≤ V ≤ 600	60 30 10	

Loose (C)	0 ≤ V ≤ 100 101 ≤ V ≤ 300 301 ≤ V ≤ 600	30 60 10	

Each instance will follow the distribution to generate 3 set of data, with a total of 27 set of test data is generated (the data is available for readers, on request). The handling volume of each vessel is randomly generated within the range 100-3000 (TEUs), as shown in Table 2. It is assumed that all the containers are in TEU and no QC breakdown occurs. Therefore, the productivity of each QC is constant in 2 minutes per container. The minimum assignable number of QCs is from 1 to 3, while the maximum assignable number of QCs is from 4 to 6. The proposed single-level, two-level, and 3LGA are programmed in JAVA language and run on a PC with a CPU of 1.33GHz and 4GB RAM. The parameters setting for the Single-level GA, Two-level GA, and the proposed 3LGA are shown in Table 3. In order to have a fair comparison, the total number of chromosomes for the three approaches generated will be the same, i.e. for the number of vessels = 10, 20, and 50, the total number of chromosomes generated will be 1,600,000, 3,200,000, and 8,000,000 respectively. In addition, a low crossover and mutation rate will be used for the three approaches so that all the genetic evolution will grow slowly in order to avoid random search. The crossover and mutation rates used for the number of vessels = 10, 20, and 50 are 0.1, 0.05, and 0.02 respectively.

Table 2 – Proportions of the handling volume of vessels

Handling Volume (TEUs)	%
100 – 500	30
501 – 1000	40
1001 – 3000	30

4.2 Testing the solution quality of the proposed 3LGA

To demonstrate the significances of the proposed 3LGA, we compare it with another meta-heuristics approach SA, and two GA based approaches: the single-level GA and the two-level GA (Ma et al., 2014).

In SA, a feasible solution is represented by a string with an objective value E(x_i). The string is

randomly generated as an initial solution, and its neighborhood solution x_{i+1} will be determined after that. If E(x_{i+1}) $\leq$ E(x_i), the solution x_{i+1} will replace the current solution and the process iterates again until the stopping condition is reached. If E(x_{i+1}) $\geq$ E(x_i), a random number will be generated to see whether the solution x_{i+1} can be accepted to be the current solution with rand < $e^{(\frac{\Delta}{T_c})}$, where Δ = E(x_{i+1}) $-$ E(x_i), and T_c is the current temperature. T_c will be decreased by a cooling factor. In order to have a fair comparison between SA and GA, in this experiment, the maximum number of iterations is set as equal to the total number of chromosomes generated by GA approach, and the cooling factor is set as 0.9.
The Single-level GA used in this experiment represents the approach that without decomposing the studied integrated model into any sub-problem(s). All the BAP and variable-in-time QCA is determined by one single chromosome, detail of the methodology can be referred to (Ma et al., 2014). The chromosome, therefore, consists three kind of information, including berth allocation, vessel scheduling, and quay crane assignment. The idea of showing this approach is to demonstrate that the chromosome in such modeling approach may contain too many information. It may make the genetic search to be very difficult (results in Fig 14 showing that the solution converts difficultly).

The Two-level GA used in this experiment represents the approach that decomposing the studied integrated model into two sub-problems, which are i) BAP and Vessel Scheduling, and ii) Variable-in-time QCA, detail of the methodology can be referred to (Ma et al., 2014). In the literature, many studies decomposed the integrated problem of BAP and QCA into 2 sub-problems and solved them sequentially or by a two interacted loop. To simulate such problem decomposition practice, the two-level GA is created.

Fig. 14 demonstrates the convergence of the solutions obtained by the Single-level GA, Two-level GA, and 3LGA in the data set of 10 vessels. To compare the performance of these approaches, total number of chromosomes generated is set to be the same. Each test data is solved 10 times individually by the three algorithms. The results in Fig 14 show that Two-level GA performs better than the Single-level one. In this connection, we introduce the 3LGA, which decomposes the problem into i) BAP, ii) Vessel Scheduling, and iii) Variable-in-time QCA. From Fig 14, the results show that the performance is the best among the three approaches.

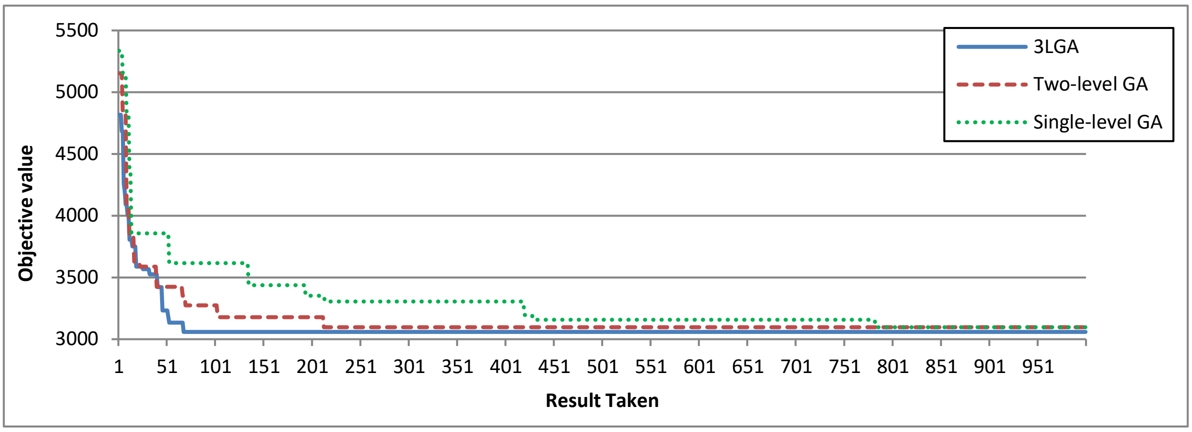


Fig. 14. Optimization performance of the three GA based approaches

Table 3 – GA parameters setting

	Single-level GA	Two-level GA		The Proposed 3LGA		
		BAP&VS	QCAP	1st level GA	2nd level GA	3rd level GA
Population Size	10	10	4	10	4	4
Result taken every	160	40	-	every	-	-
Number of Vessels = 10						
No. of evolutions	160,000	4,000	10	100	10	10
Total no. of chromosomes generated	1,600,000	1,600,000		1,600,000		
Number of Vessels = 20						
No. of evolutions	320,000	8,000	10	200	10	10
Total no. of chromosomes generated	3,200,000	3,200,000		3,200,000		
Number of Vessels = 50						
No. of evolutions	800,000	20,000	10	500	10	10

Total no. of chromosomes generated	8,000,000	8,000,000	8,000,000

The averages solution values obtained by the four approaches are summarized in Table 4. The table shows that the overall performance of the Single-level GA is slightly better than SA in average. The results also show that 3LGA obtains the same or a better solution than Single-level GA and Two-level GA. For the small size problems (*V*=10), about 0 to 2.5% reduction can be achieved by 3LGA. 0% reduction means the performances of these approaches are the same. It occurs only in small size problems. Since small size problem is less complicated, all approaches are capable to solve it effectively. However, it is observed that the improvement obtained by 3LGA becomes more significance as the increment of the problem sizes. For *V*=20, the percentage range is 0.9 to 3.9%, and for *V*=50, the reduction can up to 11%. It demonstrated that the proposed 3LGA outperforms the Single-level GA and Two-level GA in solving large problems faster and better.

4.3 Studying the impacts of time segment modeling on operations efficiency

To study the impacts of time segment modeling on operations efficiency, 27 test data sets are generated for representing various situations. Two different time-unit configurations in the proposed 3LGA: 1) an hourly based time segment (Conf-H) is used to simulate the traditional modeling in the literature, and 2) a 15-minute based time segment (Conf-15) which is suggested by industrialists in Hong Kong, are used for comparisons. A small size problem (10A-1) is used as an example, and the detail of the best results obtained by 3LGA with Conf-H and Conf-15 are illustrated in the space-time diagram as shown in Figs. 15 and 16. In the diagrams, a rectangular block represents a vessel, and the height of the block represents the maximum QC capacity of the vessel. Each QC is marked with a number for the ease of arrangement, and the shifting of the QCs is indicated by an arrow sign. The dotted line shows the waiting time of the vessel, and the shadowed area shows the time of the idled QCs occupied by a time segment.

Table 4 – Experiment results of SA, single-level GA, two-level GA and 3LGA

	Instance	SA	Time (s)	(1) Single - level GA	Time (s)	(2) Two - level GA	Time (s)	Proposed 3LGA	Time (s)	Compare to (1) % change	Compare to (2) % change
V=10	10A-1	3207	4.12	3180	4.13	3105	4.13	3098	4.26	-2.57	-0.22
	10A-2	4232	5.02	4180	5.04	4172	4.22	4120	4.86	-1.36	-1.24
	10A-3	3560	4.81	3535	4.73	3529	4.87	3519	4.32	-0.4	-0.28
	10B-4	3998	4.25	3962	4.1	3962	4.86	3971	5.01	-1.29	-1.29
	10B-5	3920	4.16	3892	4.51	3845	4.11	3825	4.36	-1.72	-0.52
	10B-6	2392	4.11	2370	4.61	2348	4.71	2348	4.7	-1.1	0

	10C-7	3297	4.27	3279	4.24	3275	4.15	3275	4.56	-0.18	0
	10C-8	3740	4.3	3724	4.28	3722	4.19	3722	4.27	-0.11	0
	10C-9	3601	4.21	3572	4.3	3572	4.29	3572	4.29	0	0
V=20	**20A-1**	12255	10.53	12040	10.22	11842	10.62	11644	10.42	-3.29	-1.69
	20A-2	11292	10.28	11190	10.68	10945	10.76	10842	10.15	-3.1	-0.94
	20A-3	12537	10.76	12328	10.62	12139	10.81	11979	10.77	-2.83	-1.31
	20B-4	13894	10.82	13741	10.71	13499	10.53	13269	10.21	-3.43	-1.7
	20B-5	12631	10.17	12522	10.92	12261	10.26	12061	10.92	-3.68	-1.63
	20B-6	14468	10.87	14329	10.34	14100	11.1	13762	11.04	-3.96	-2.4
	20C-7	11206	10.13	11060	10.43	10910	10.21	10783	10.37	-2.5	-1.11
	20C-8	11411	10.77	11240	10.23	10931	10.3	10812	10.38	-3.8	-1.08
	20C-9	9662	10.41	9645	10.48	9401	10.25	9305	10.26	-3.53	-1.02
V=50	**50A-1**	45786	67.52	44985	68.18	43712	68.22	40527	67.12	-9.91	-7.29
	50A-2	41130	64.31	40759	65.74	39040	68.1	37116	68.42	-8.94	-4.93
	50A-3	33733	65.26	33170	65.55	32605	64.63	31536	65.21	-4.93	-3.28
	50B-4	38687	66.01	38261	67.25	37451	65.93	34328	66.13	-10.28	-8.34
	50B-5	51309	63.27	51105	66.17	49013	66.13	46603	65.63	-8.81	-4.92
	50B-6	38702	67.8	38197	65.52	37406	65.88	35397	65.1	-7.33	-5.37
	50C-7	60957	66.12	59982	65.18	58544	65.27	55886	66.21	-6.83	-4.54
	50C-8	67165	66.25	65989	65.64	62786	65.19	58468	65.35	-11.40	-6.88
	50C-9	40988	65.33	40636	65.66	39882	65.23	38133	65.86	-6.16	-4.39

In the example, both configurations of our 3LGA show good assignment of QCs, such that either all QCs have been assigned or the maximum QC capacity of the vessel is reached. However, 3LGA with the proposed Conf-15 shows better performance than that with Conf-H in both waiting time and handling time. From which, the improvement of the total waiting time is significantly reduced from 417 min to 80 min (about 80% improvement), and the handling time is reduced from 3264 min to 3018 min (about 7.5% improvement). In addition, the makespan for the whole set of vessel can also reduce from 27 hours to around 25 hours by using the Conf-15.

Berth position

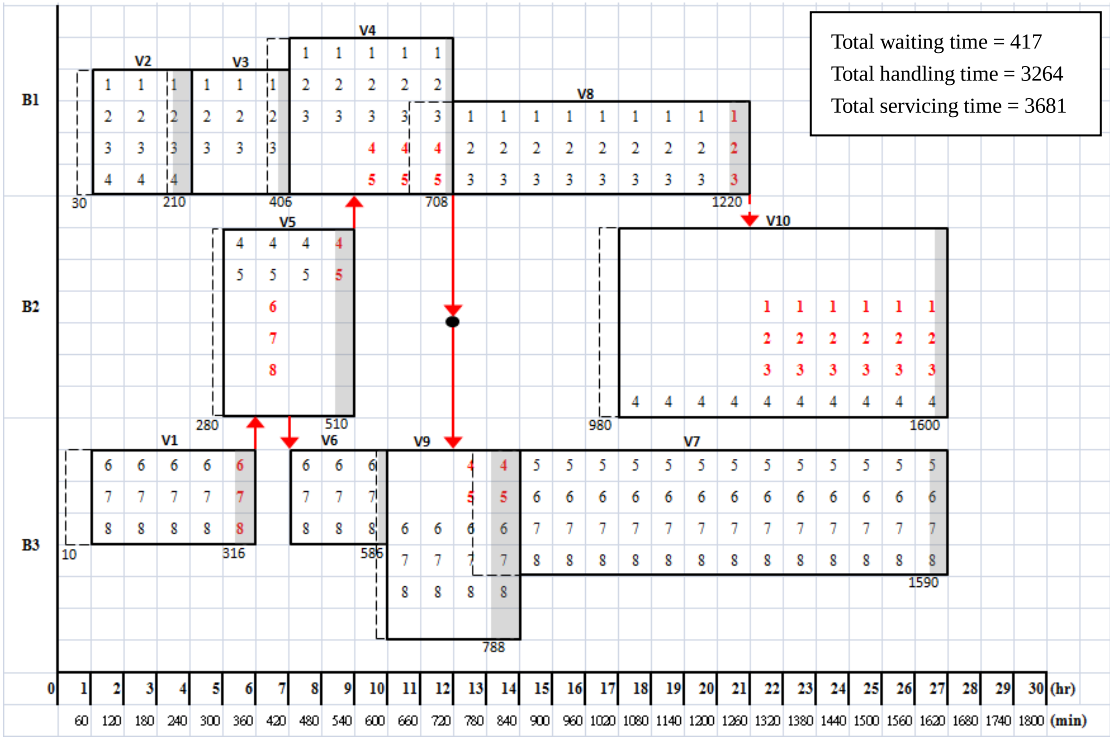


Fig. 15. Space-time diagram of the result from the 3LGA with traditional conf-H

With Conf-H, it is observed that many idled QCs are occupied in a time segment (Fig.15). It not only affects the utilization of the QCs, but also hinders the berthing of the latter vessels and thus affects waiting time (i.e. Vessels 3, 4, 7, 8 and 9). Moreover, a large proportion (about 35%) of the total waiting time is induced by waiting for berth as the berthing time of vessels can only in hours. This waiting time can be reduced greatly from 140 min to 30 min by using the proposed Conf-15 (Fig. 16). Furthermore, using the proposed configuration, the idled QCs can be released earlier after task completion, and can shift to another vessel for supporting. It enhances the operation efficiency and therefore, the handling time can be reduced from 3264 min to 3018 min.

Berth position

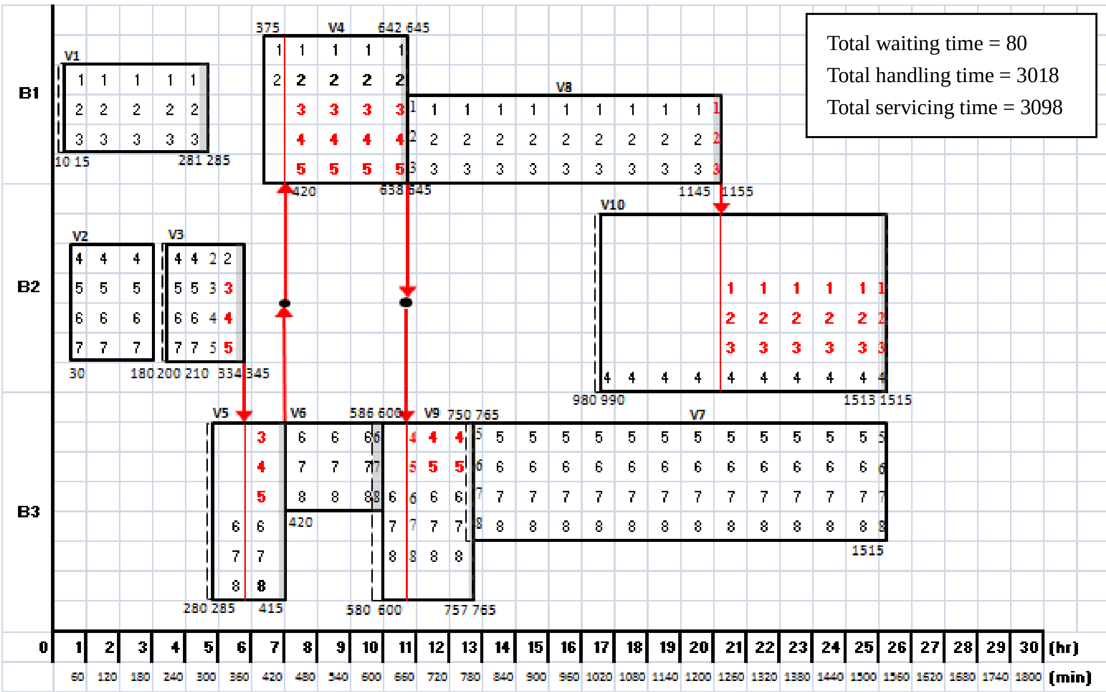


Fig. 16. Gantt chart of the results from the 3LGA with proposed conf-15

Our proposed 3LGA with the traditional Conf-H and the proposed Conf-15 are tested by 27 test data sets. Similarly, each data set is solved 10 times individually, and the averages values of the results are summarized in Table 5.

As expected, results show that Conf-15 performs better than Conf-H in all instances. The percentage of the improvement is shown in Fig. 17. Up to 20% improvement can be achieved by using Conf-15. The variation may depend on the arrival time of vessels, the number of QC shifting involved, the arrival time interval between vessels, etc. In general, the improvement are around 10%, 12%, and 16% in average for the small (V=10), medium (V=20) and large (V=50) problem sizes, and a trend which shows that the improvement may increase with tight arrival situation.

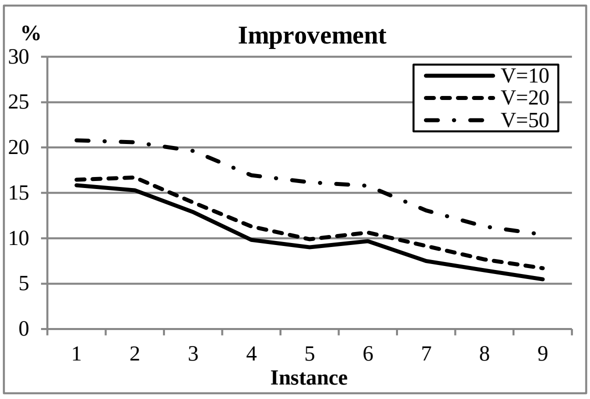


Fig. 17. Improvement percentage (conf-15)

Table 5 – Experiment results of conf-H and conf-15

V=10				
Instance	**conf-H**	**t(s)**	**conf-15**	**t(s)**
10A-1	3681	4.12	3098	4.26
10A-2	4989	4.70	4227	4.86
10A-3	4186	4.21	3646	4.32
10B-4	4404	4.12	3971	5.01
10B-5	4332	3.88	3941	4.36
10B-6	2670	4.01	2412	4.70
10C-7	3628	4.50	3356	4.56
10C-8	4074	3.98	3811	4.27
10C-9	3868	4.00	3656	4.29
V=20				
Instance	**conf-H**	**t(s)**	**conf-15**	**t(s)**
20A-1	13934	10.52	11644	10.42
20A-2	13015	10.12	10842	10.15
20A-3	13922	10.62	11979	10.77
20B-4	14959	9.79	13269	10.21
20B-5	13385	10.71	12061	10.92
20B-6	15399	10.55	13762	11.04
20C-7	11868	10.20	10783	10.37
20C-8	11709	10.01	10812	10.38
20C-9	9973	9.80	9305	10.26
V=50				
Instance	**conf-H**	**t(s)**	**conf-15**	**t(s)**
50A-1	51163	66.32	40527	67.12
50A-2	46736	70.21	37116	68.42
50A-3	39238	66.87	31536	65.21
50B-4	41330	64.12	34328	66.13
50B-5	55582	65.07	46603	65.63
50B-6	42034	64.12	35397	65.10
50C-7	64276	63.55	55886	66.21
50C-8	65920	65.12	58468	65.35
50C-9	42562	65.22	38133	65.86

5. CONCLUSIONS

Operation efficiency and fully utilization of resources is crucial to terminal industries as it directly affects the profitability. In traditional modeling approach(es), berth allocation problems and quay crane assignment problems are usually modeled in hourly-based approach. However, this limitation and assumption reduces the utilization of the quay cranes significantly and induces unnecessary vessel waiting time. Accordingly, a new 15-minute based modeling approach is proposed. As this increases the problem and computational complexity dramatically, a new algorithm named 3LGA is proposed. To further enhance the utilization of the quay crane resources by modeling the variable-in-time quay crane assignment, the 3LGA is embedded with a QC shifting heuristics for fine local searching. The 3LGA decomposes the problem into berth allocation, vessel scheduling, and quay crane assignment and solves them iteratively for the best solution. In order to test the solution quality of the proposed algorithm and demonstrate the significance of minutely based approach, numerical experiments have been conducted. For testing the solution quality, SA and two additional approaches based on some commonly used approaches found in the literature, named Single-level GA and Two-level GA, have been created for comparison. The results demonstrate that the proposed 3LGA outperforms those by obtaining better solutions. For demonstrating the significance of minutely based approach, another experiment is conducted. The results demonstrated a significant improvement on waiting time and handling time obtained by using the 15-minute based time segments comparing with the traditional hourly based approach. It is concluded that the proposed 3LGA can improve the performance of the terminal operations, and provide better QCs utilization.

From the numerical experiments, one can see that the vessel waiting time and the handling time are improved significantly. This improvement is particularly important nowadays because transshipment becomes more important to many container terminals, especially in Southeast Asia (e.g. Hong Kong and Singapore). In these terminals, vessel arrivals are usually very frequent with small handling volume and very short staying time, e.g. 1.5 hours. Therefore, traditional hourly based modeling approach may cause significant berth and quay crane idling as demonstrated, and consequently cannot meet their practical needs. In this connection, a small time segment modeling approach, such as the 15-minute based approach, can help these terminals to further enhance their operation efficiency and increase the facility utilization.

In this study, the productivity of QC is assumed to be 2 minutes per container regardless of the QC movement. This is a common assumption in literature and also a common practice in terminal planning because this is at the planning level, while QC movement is the concern of the operational level. Although by considering QC movement, such as QCSP, the planning accuracy can be further increased, the problem complexity will dramatically increase as well. This makes the problem becomes unsolvable. However, nowadays, due to the availability of the recorded historical data, this 2 minutes assumption can be estimated by conducting a decent data analytics. As a result, this assumption can be reflected more precisely rather than solving QCSP with BA and QC assignment. This provides a new research direction for future studies.

APPENDIX

An example of QCA-chromosome generation

Given an example, followed by the vessel schedule in Fig. 5, assuming that vessel 1 has the earliest arrival time among the vessels with k = 1, including vessel 1, 7 and 4. Hence, vessel 1 will do the assignment first. Since the available time of the berth 1 at the beginning of the planning horizon is “0” which is smaller than the arrival time of vessel 1 “30”, and the number of QCs available at t = 30 is 4 which is larger than the minimum number of QCs required by vessel 1, the vessel can berth at the terminal at its arrival time. Given that the maximum and minimum QC capacity of the vessel are 5 and 1. The number of QCs assigned to vessel 1 will be a random number within the range [1 - 4], for example 2 QCs. By using eq. (18) with $v_i = 300$ TEU and $P = 0.5$, the $c_1 = 30 + \frac{300}{0.5 \times 2} = 330$ will be calculated. Since 330 is the multiplication of 15, it is the actual value of c_1. Next, the available time of the berth will be updated to 331, and the available number of QCs from t = 30 to t = 330 will change from 4 to 2. Then, the above procedures are repeated for the next berthing vessel until the QCA-chromosome (Fig. 6) is generated.

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