

A 15 Minute-Based Approach for Berth Allocation and Quay Crane Assignment

Hoi-Lam Ma, Sai-Ho Chung

Abstract—In traditional integrated berth allocation with quay crane assignment models, time dimension is usually assumed in hourly based. However, 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. Therefore, the traditional hourly-based modeling approach may cause significant berth and quay crane idling, and consequently cannot meet their practical needs. In this connection, a 15-minute-based modeling approach is requested by industrial practitioners. Accordingly, a Three-level Genetic Algorithm (3LGA) with Quay Crane (QC) shifting heuristics is designed to fulfill the research gap. The objective function here is to minimize the total service time. Preliminary numerical results show that the proposed 15-minute-based approach can reduce the berth and QC idling significantly.

Keywords—Transshipment, integrated berth allocation, variable-in-time quay crane assignment, quay crane assignment.

I. INTRODUCTION

IN the existing literature studying on the traditional gateway terminal, most papers applied hourly based 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 [1]. In the such situation, QC idling for an hour may become relatively insignificant and acceptable [2], [3]. However, in a 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 changing to a 30-minute-based planning approach. In fact, the industrialists are seeking for a 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 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 15-minute 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 model, a day is divided into 24 discrete time segments. However, in a 15-minute based model, the number of the time segments will then increase four times to 86. 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. Thus, we propose to develop a 15-minute based approach to tackle the abovementioned problem.

II. LITERATURE REVIEW

Studies of container terminal operations can generally be classified into BAP, 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 [4], [5]. 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. [6]-[14]. In which, the vessel handling time can be defined as deterministic, such as a predefined and a committed time [15], [16], while some studies are defined by the berthing position [17]-[19]. 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 [20]-[22]. With a larger 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 [23]-[25]. QCA deals with the assignment of QCs to a vessel for carrying out the loading and unloading operations. According to Meisel and

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Bierwirth [24], 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 if they are idle after the completion of the current operation [26]-[29]. 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 [30]. However, in these papers, the unit of time segment is usually hourly based and some even more than an hour [31]. 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 [30] were the first ones 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 QC 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 [30]. The assumption was criticized by Cordeau et al. [32] and Hansen et al. [33] as QCs may lose their productivity due to interference among QCs. Meisel and Bierwirth [2] therefore focused on QC 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 [30] using the same data sets and they always obtain better solution. Zhang et al. [25] also further studied the integrated model introduced by Park and Kim [30]. 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 [34] 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 time. 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. Meisel and Bierwirth [24] elaborated their previous model by including QCSP. They proposed a three-phase framework for the integration of BAP, QCA and QCSP. Giallombardo et al. [3] introduced a QC profile in their model which is similar to the concept of “mode” in Meisel and Bierwirth [34]. Each vessel required a certain amount of QC 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.

III. PROPOSED METHODOLOGY

A. Problem Formulation

In this section, a mathematical model for the BAP with QCA is presented. It is developed from the models presented by Meisel and Bierwirth [2] and Gialombardo et al. [3]. 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. In our model, we modify that into 15-minute-based time segment. Since QC interferences are usually only considered in QCSP [35], 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:

Input Data

- V : set of vessels ($V = 1, 2, 3 \dots I$)
- B : set of berths in terminal ($B = 1, 2, 3 \dots J$)
- U : set of 15-minute time steps ($U = 1, 2, 3 \dots T$)
- a_i : expected arrival time of the vessel $i \in V$
- 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 of the planning horizon of

berth $b \in B$.

Decision Variables

- 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 $q \in R_i$ QCs 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;
- $x_i^b \in \{0, 1\}$: 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:

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

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

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

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

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

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

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

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

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

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

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

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

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

$$(t + 1) \cdot y_{it} \leq c_i, \quad \forall i \in V, \forall t \in U \quad (15)$$

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

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

Constraint (2) ensures that every vessel must be served at a berth. Constraint (3) sets the relationship between the two variables. Constraint (4) and constraint (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 constraint (8) ensure the vessels will be served within the planning horizon. Constraint (9) and constraint (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. Constraint (14) – constraint (16) set the berthing time and completing time of the vessel without preemption.

B. Three-Level Genetic Algorithm (3LGA)

The problem involves three major decisions, including i) berth allocation, ii) vessel scheduling, and iii) QCA. With the reduction in the time unit from hourly to 15-minutes, 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. 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. To reduce the problem complexity, and improve the performance of the GA, a 3LGA is proposed. The problem 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 clearer focus and the genetic search in each part can be better.

The proposed 3LGA has three parts, i) Berth allocation, ii) Vessel scheduling, and iii) Variable-in-time QCA, 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.

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 aim 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 QC 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 this 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.”

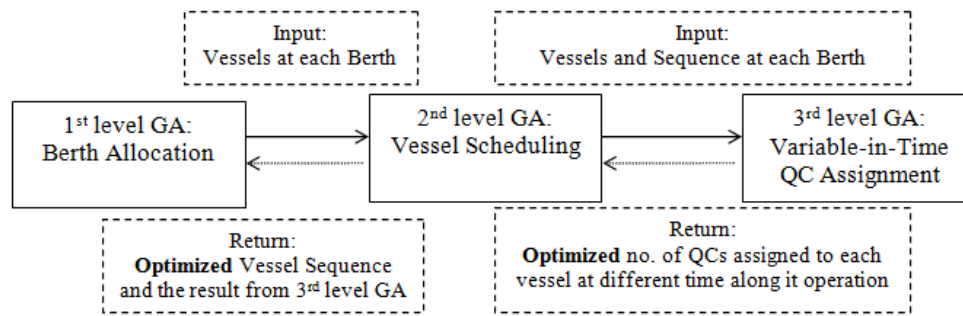


Fig. 1 Outline of the proposed 3LGA

TABLE I
 PRELIMINARY RESULT OF THE HYPOTHETICAL PROBLEM

Instance	SA	Time (s)	Single - level GA	Time (s)	Two - level GA	Time (s)	3LGA	Time (s)
A-1	3207	4.12	3180	4.13	3105	4.13	3098	4.26
A-2	4232	5.02	4180	5.04	4172	4.22	4120	4.86
A-3	3560	4.81	3535	4.73	3529	4.87	3519	4.32
B-4	3998	4.25	3962	4.1	3962	4.86	3971	5.01
B-5	3920	4.16	3892	4.51	3845	4.11	3825	4.36
B-6	2392	4.11	2370	4.61	2348	4.71	2348	4.7
C-7	3297	4.27	3279	4.24	3275	4.15	3275	4.56
C-8	3740	4.3	3724	4.28	3722	4.19	3722	4.27
C-9	3601	4.21	3572	4.3	3572	4.29	3572	4.29

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 QCA-chromosome from DD. 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. A QC shifting heuristics is proposed and implemented into the 3rd level GA to determine the complete variable-in-time QCA. For the interaction among different levels of the 3LGA and the detail steps, please refer to the appendix.

IV. PRELIMINARY NUMERICAL RESULTS

To test the importance of the proposed a 15-minute-based approach, we first conduct preliminary numerical experiment by creating a hypothetical situation for a small scale problem. We compare two time modeling approaches: i) 15-minute-based approach, and ii) hourly-based approach. The preliminary results are summarized as in Table I.

The preliminary results show that 15-minute-based approach performs better than the hourly-based approach. The percentage of the improvement has up to 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 overall averaged improvement is still around

10%.

V. CONCLUSIONS

Operation efficiency and full utilization of resources is crucial to terminal industries, as it directly affects the profitability. In the traditional modeling approach, BAPs and QCA problems are usually modeled hourly based. However, this limitation and assumption reduces the utilization of the QCs significantly and induces unnecessary vessel waiting time. Accordingly, a 15-minute-based modeling approach is proposed. As this increase the problem and computational complexity dramatically, an algorithm named 3LGA is proposed. To further enhance the utilization of the QC resources by modeling the variable-in-time QCA, the 3LGA is embedded with a QC shifting heuristics for fine local searching. The 3LGA decomposes the problem into berth allocation, vessel scheduling, and QCA and solves them iteratively for the best solution. For demonstrating the significance of a minutes-based approach, a preliminary numerical experiment is conducted. The results demonstrated a significant improvement on waiting time and handling time obtained by using the 15-minute-based time segments compared with the traditional hourly-based approach. It is concluded that the proposed 15-minute-based approach can improve the performance of the terminal operations, and provide better QCs utilization.

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