INTEGRATED PLANNING OF BERTH ALLOCATION AND QUAY CRANE ASSIGNMENT PROBLEMS

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Certificated of Originality

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MA Hoi Lam

January 2014

Dedication

I would like to dedicate my work to my family, especially my dear father, mother and sister. Thank you very much for their endless love and support in my life. I have the warmest family so that I can concentrate on my work, and they give me strength to overcome all the difficulties to complete the study.

Abstract

Terminal operation efficiency is regarded as the most critical issue in sea-freight transportation network. Therefore, the ultimate objective of this research study is to improve the efficiency in terms of the total operating cost and total servicing time required, meanwhile the quay space utilization. Accordingly, three main research questions have been addressed, i) Defining customer importance and maximizing customer service level, ii) Optimizing quay crane assignment and utilization, and iii) Dealing with multi-continuous berth layout.

The thesis starts with Berth Allocation Problem (BAP) because it directly influences the customer service level represented by vessel waiting time, handling time, and completion time. To survive in the rigorous competitive environment nowadays, terminals strive to retain their customers by providing good service quality especially to those important ones. However, in literature customer importance is usually by using defined either by i) customer relationships or ii) handling volume. Both approaches have some drawbacks. Therefore, this thesis proposed a new defining approach to consider both factors simultaneously. Accordingly, a new Genetic Algorithm for BAP (GA-BAP) is proposed. Experimental results demonstrated that the proposed approach can serve many customers with good relationship, meanwhile maintaining a high handling volume.

To improve terminal operations efficiency, optimization of quay cranes

assignment is one of the key issues. Quay Crane Assignment Problem (QCAP) and BAP are highly interrelated. Therefore, integrated planning of berth allocation and quay crane assignment has been studied. However, holistically solving this problem is very complicated. Thus, decomposition approach is proposed. Moreover, a new methodology named Two-level Genetic Algorithm (TLGA) is proposed. Furthermore, for better Quay Crane (QC) utilization, variable-in-time quay crane assignment is further studied. In literature, time dimension is usually in hourly based. However, in transshipment terminal, vessel staying time is usually short (usually a few hours) comparing to traditional gateway terminals. Thus, hourly based approach may cause QC idling significantly. Therefore, a 15-minute based approach is proposed as suggested by industrial practitioners. A novel Three-level Genetic Algorithm (3LGA) with QC shifting heuristics is proposed to fulfill the research gap. The results show that the proposed 15-minute approach reduces QC idling remarkably. Meanwhile, the proposed 3LGA far outperforms the traditional GA in this problem.

Lastly, a novel multi-continuous berth layout is studied driven by the practical needs in real wharf layout. In literature, many researchers usually applied discrete or hybrid berth layout modeling approach. However, this induces low space utilization. Therefore, some researchers proposed continuous berth layout model. However, such modeling approach currently cannot be applied to berth layout with discontinuity. Accordingly, a novel Mixed Integer Programming approach is proposed. To bring further the model close to reality, yard storage assignment planning has also been considered. Ultimately, an integrated BAP with variable-

in-time QCAP and yard storage assignment in the multi-continuous berth layout is studied in this thesis. A Guided Neighbourhood Search (GNS) is developed to improve the optimization performance. Experiment results demonstrated that the proposed model can remarkably reduce the total terminal operating cost and computational time significantly.

Publications

International Journals:

1. H.L. Ma, Felix T.S. Chan and S.H. Chung, 2013. Minimising earliness and tardiness by integrating production scheduling with shipping information. *International Journal of Production Research*, 51(8), pp. 2253-2267.

2. H.L. Ma, Felix T.S. Chan and S.H. Chung, 2014. A fast approach for the integrated berth allocation and quay crane assignment problem. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, August 14, 0954405414544555.

3. H.L. Ma, Felix T.S. Chan and S.H. Chung. A Finer Time Modelling Approach for Berth Allocation with Quay Crane Assignment. *European Journal of Industrial Engineering*. (Under major modification)

Conference Papers:

1. H.L. Ma, Felix T.S. Chan, S.H. Chung and C.S. Wong, 2011. Maximizing the Reliability of Terminal Service by Vessel Scheduling and Quay Crane Assignment. *In proceedings of IEEE International Conference on Quality and Reliability*, September 14-17, Bangkok, Thailand, 85-89.

2. H.L. Ma, Felix T.S. Chan, S.H. Chung and C.S. Wong, 2011. Berth Allocation Problem with the Consideration of Customer Service Priority. *In proceedings of the 12th Asia Pacific Industrial Engineering and Management Systems Conference*, October 14-17, Beijing, China.

3. H.L. Ma, Felix T.S. Chan, S.H. Chung and C.S. Wong, 2012. Berth Allocation Planning for Improving Container Terminal Performances. *In proceedings of International Conference on Industrial Engineering and Operations Management Istanbul*, July 3-6, Turkey, 502-508.

4. H.L. Ma, Felix T.S. Chan and S.H. Chung, 2012. Integrating Production Scheduling and Limited Transportation. *In proceedings of the 13th Asia Pacific Industrial Engineering and Management Systems Conference*, December 2-5, Phuket, Thailand.

5. H.L. Ma, Felix T.S. Chan, S.H. Chung and B. Niu, 2013. Minimizing port staying time for container terminal with position based handling time. *The IEEE International Conference on Industrial Engineering and Engineering Management*, 10-13 December 2013, Bangkok, Thailand, 1339-1343.

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3LGA	3-Level Genetic Algorithm
AST	Average Service Time
BAP	Berth Allocation Problem
BA-QCAP	Integrated Berth Allocation and Quay Crane Assignment Problem
BA-VITQCAP	Integrated Berth Allocation and Variable-In-Time Quay Crane Assignment Problem
CBAP-VITQCA	Continuous Berth Allocation Problem and Variable-In-Time Quay Crane Assignment
CIFI	Customer Importance Fulfillment Index
Conf-15	Configuration with 15-minute based time segments
Conf-H	Configuration with an hourly based time segments
CS	Clustering Search
CSNS	Critical-shaking neighborhood search
DBAP-FCFS	Discrete berth allocation problem with first-come-first-served principle
DBAP-priority-H	Discrete berth allocation problem with priority considering handling volume
DBAP-priority-R	Discrete berth allocation problem with priority considering customer relationships
DBAP-priority-RH	Discrete berth allocation problem with priority considering customer relationships and handling volume
DBAP-QCA	Discrete Berth Allocation Problem and Quay Crane Assignment
DBAP-VITQCA	Discrete Berth Allocation Problem and Variable-In-Time Quay Crane Assignment
DS	Depth of Search

FCFS	First-Come-First-Served
GA	Genetic Algorithm
GA-BAP	Genetic Algorithm for Berth Allocation Problem
GNS	Guided Neighborhood Search
GRASP	Greedy Randomized Adaptive Search Procedure
GSSP	Generalized Set Partitioning Problem
HV	Handling Volume
MBAP-VITQCA	Multi-continuous Berth Allocation Problem and Variable-In-Time Quay Crane Assignment
MOEA	Multi-Objective Evolutionary Algorithm
OBAP	Operational Berth Allocation Problem
PGA	Parallel Genetic Algorithm
QC	Quay Crane
QCAGA	Quay Crane Assignment Genetic Algorithm
QCAP	Quay Crane Assignment Problem
QCSP	Quay Crane Scheduling Problem
SA	Simulated Annealing
SGA	Single Genetic Algorithm
SSA	Storage Space Assignment
SSAP	Storage Space Assignment Problem
TBAP	Tactical Berth Allocation Problem
TLGA	Two-Level Genetic Algorithm
TS	Tabu Search
VITQCA	Variable-In-Time Quay Crane Assignment
VSGA	Vessel Scheduling Genetic Algorithm

Chapter 1 Introduction

1.1 Background on Container Terminal

Being a major channel of international trade, intercontinental maritime transport is getting busier. In 2012, there was about 601.8 million TEUs global container throughput (Twenty-foot Equivalent Unit) which contribute more than half in value of international seaborne trade (UNCTAD, 2012). Development of new container terminals has been announced by different governments to deal with increasing demand. Because of the global financial crisis, the throughput of the global container terminal had dropped down to 464 million TEUs in 2009. After that, it was rebound quickly to 531.4 million TEUs in 2010. Therefore, it can be foreseen that container throughputs will have a sustainable growth in the coming years. In view of the ever growing demand, proper planning and high degree of coordination of terminal operations to control efficiency is instrumental to terminals. Moreover, in Asia, because of the location of the terminals are geographically located near to each other. Therefore, competitions are even rigorous.

To maintain competitiveness, container terminals strive to improve their customer service quality to maintain good relationship with existing customer and attract more new customers. One of the approaches is to improve the operations efficiency by optimizing the utilization of existing facilities. Accordingly, a large amount of research work in the development of advance technology has been carried out in the last decade (Zaffalon *et al.*, 1998, Gunther and Kim, 2005). Later on, much more effort have been put on enhancing resources planning systems by developing different decision support technologies as resources allocation always determines the success and efficiency of the quayside and landside operations of the terminal (Steenken *et al.*, 2004). These planning systems include berth allocation plan, quay crane assignment plan, unloading and loading plan, yard storage plan, and import/ export container schedule through gate. All these will affect the turnaround time of the vessels (Lim *et al.*, 2004). More importantly, since penalty cost will be induced for late departure, minimization of late departure becomes one of the concerns. All the above mentioned plans are closely related and should be integrated into the terminal operating system. In reality, these plans should be perfectly match with each other, otherwise the whole system will collapse and induce negative impact on the overall operations.

1.2 Types of terminals

In general, there are two common types of terminals: i) container terminal, and ii) bulk cargo terminal. Container terminal is referred to which engages in handling of containerized cargo, while bulk cargo terminal is of non-containerized cargo in either dry or liquid form such as oil, petroleum, coal, etc. Container terminal, in more specific, is broadly classified into dedicated terminal or multi-user terminal. Dedicated container terminal is usually reserved for private cargo owners. Unlike dedicated terminal, multi-user container terminal is open to any cargo owner, and therefore, they will plan to optimize the vessel berthing position in order to achieve better utilization of berth space. In term of business natures, multi-user container terminals can further be classified into i) gateway terminal, or ii) transshipment hub. Gateway terminal is mainly focus on import and export activities, while transshipment hub is mainly focus on transshipment activities. According to Drewry Shipping Consultants Report, in 2009, about 72% of the world container terminal throughputs are from gateway terminal, while the remaining 28% are from transshipment hubs. Comparing to the results in 1990, a nearly 10% increase in the proportion of transshipment hubs has been recorded.

1.3 Container terminal systems

In maritime transport, vessels carry containers from one terminal to another. Once a vessel arrives, it enters to the harbor and waits for berthing at the prearranged terminal. The quay is known to be the platform projecting outward into the water for ease of loading and unloading containers operations. The location where berthing takes place is known as berth, which is equipped with quay cranes (QCs) that carry out the loading and unloading operations (Cordeau *et al.*, 2005). Vessels usually carry out the unloading operation followed by the loading operation. After the completion of loading operations, a vessel will generally depart in most situations. A fleet of internal tractors are responsible for transferring the containers to and from the yard where the containers are temporary stored until further usage.

Figure 1.1 shows a complete overview of the container terminal system. It comprises of quayside and landside. Quayside consists of the berth and the quay, while landside consists of the storage yard and the gate. The area connecting quayside and landside is called transportation area. Problems of the quayside operations include: (i) Berth Allocation Problem (BAP), (ii) Quay Crane Assignment Problem (QCAP), and (iii) Quay Cranes Scheduling Problem (QCSP), while problems of landside operations include: storage space assignment problem, dispatching and routing problem, and etc. Among them, BAP is well recognized as the leading problem as it can significantly affect the rest of the terminal operation.

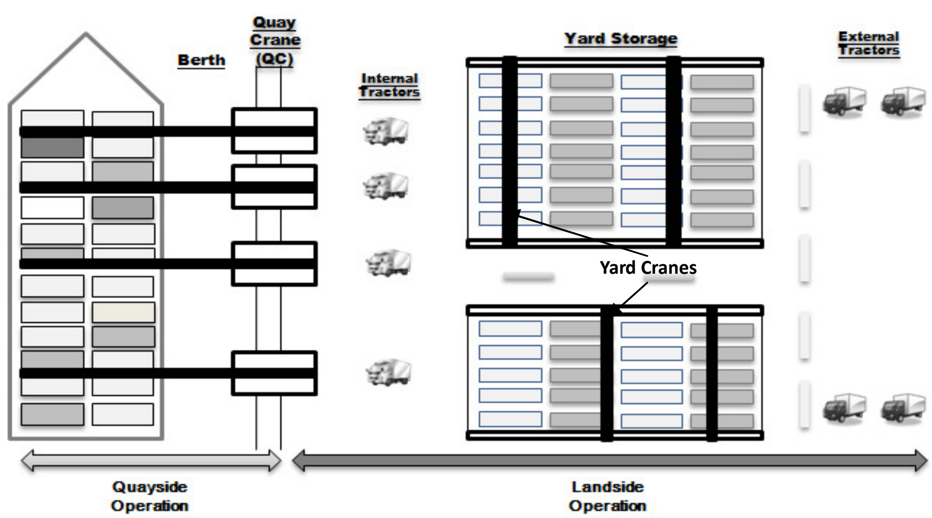

Figure 1.1 Overview of a container terminal system

BAP assigns incoming vessels to berths, requiring an expected vessel handling time, as input. In general, the vessel handling time is determined by QCAP, which is the assignment of the number of QCs to vessel. In addition, because of QC interference, vessel handling time becomes non-linear to the number of QCs assigned in practice. Therefore, QCAP just can provide preliminary handling time for BAP. Furthermore, BAP also influences the container storage space allocation inside the yard as it has a high impact on the internal travelling distance for transferring containers between quay and yard.

1.3.1 Berth Allocation Problem

In general, BAP consists of two main decisions: (i) how to allocate different vessels to berths, and (ii) determine when a vessel should moor (Steenken *et al.*, 2004). Maximizing berth utilization and minimizing vessel service time are always the ultimate objectives of BAP. It can be categorized based on the configurations of berths, which is also regarded as spatial constraint in BAP. They are commonly known as i) discrete berth layout, ii) continuous berth layout, and iii) hybrid berth layout (Figure 1.2). In Discrete model, the entire quay is divided into a number of berths. Among which, one berth can only cater one vessel (Bierwirth and Meisel 2010). In Continuous model, the quay will not be divided into any berth (this is completely opposite to the discrete model approach). Vessels can be berth anywhere along the quay. Thus, it can provide much higher flexibility to berth allocation planning. In hybrid model, the quay again will be divided into a number of berths similar to discrete model. However, one vessel can occupy more than one berth. In addition, one berth can be shared by more than one vessel. The discrete model takes an advantage of easiness in scheduling, but leads to less efficiency resulting from low utilization, while the hybrid model makes some improvement on this, but yields another decision in determining the length of the berth segments. Continuous berth layout model, which is always suggested for better berth space utilization, becomes more common in practice.

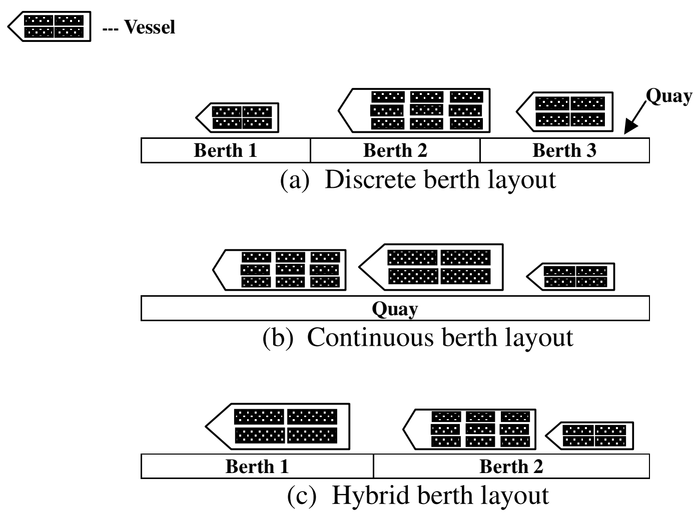

Figure 1.2 Three common berth layouts

To make the decisions, some vessels' information is required including vessel arrival time, vessel handling time, vessel length, etc. Some vessels may also be guaranteed to obtain the minimum number of resources, e.g. QCs, or maximum waiting time, etc.

In BAP, vessel arrival can be modeled in either static or dynamic arrival. Static model assumed that all vessels arrive at the terminal before the starting time of the planning horizon. In this case, the arrival time of a vessel can be ignored. However, nowadays, most of the vessels involve a numbers stops/ stations in every trip. They may arrive one terminal for loading up the containers and unload the containers in another terminal in the next or coming stations. An expected arrival time of the vessel to each terminal is estimated and will be given to the terminal for their arrangement. Therefore, dynamic arrival is closer to the reality, in which an expected arrival time will be given to each vessel, such that the vessels cannot berth before the estimated arrival time (Bierwirth and Meisel, 2010).

Vessel handling time is also critical as it directly affects the vessel departure time and may have great impact on the berthing time of the next vessel. In fact, vessel handling time can be influenced by many factors for examples, internal transport vehicle allocation, berth location to yard, loading or unloading operation, operating rules for restricting the movement of cranes, etc. More important are the number of containers being handled, the number of QCs being assigned, and the productivity rate (Zhou *et al.*, 2006; Zhou *et al.*, 2008; Theofanis *et al.*, 2009; Golias, 2011; Raa *et al.*, 2011; Meisel and Bierwirth, 2013). Moreover, it is very common that the vessel handling time can be shorter by assigning a larger number of QCs into the vessel. Therefore, BAP is commonly planned with QCAP simultaneously in order to improve the solution feasibility and optimality (Bierwirth and Meisel, 2010; Zhang *et al.*, 2010; Raa *et al.*, 2011).

1.3.2 Quay Crane Assignment Problem

QCAP deals with the assignment of QCs to vessel for carrying out the loading and unloading operations. According to Meisel and Bierwirth (2013), QCA 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 by this assignment type is usually low because the QCs will not be reassigned to serve other vessels even they are idle after the completion of its current operation (Imai *et al.*, 2008b; Liang *et al.*, 2009; Chang *et al.*, 2010; Liang *et al.*, 2011; Yang *et al.*, 2012; Mario *et al.*, 2013).

To improve the QC utilization, some researches proposed variable-in-time assignment in which a number of QCs will be assigned varying along the whole service period (Park and Kim, 2003; Meisel and Bierwirth, 2009). In the existing literatures, the unit of time segment is usually hourly based and some even more than an hour (Vacca *et al.*, 2013). In such 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. 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. Therefore, reducing this kind of idle can be a way to bring significant improvement on vessel waiting time and handling time in BAP.

1.3.3 Quay Crane Scheduling Problem

QCSP refers to the determination of the container loading and unloading sequence by a set of quay cranes. Both QCAP and the stowage plan of the vessel are the input of QCSP. The number of QCs being assigned to a vessel is derived from QCAP as mentioned before. The service sequence is derived from the stowage plan which contains the loading and unloading of the container information. First of all, the location of the discharged containers in each individual ship bay will be indicated. Secondly, the location of the loading containers will also be indicated according to the destination, weight, and type of containers.

In practice, a container can be loaded on the deck or in the hold. In addition, it is generally assumed that each ship bay can only be served by one QC regardless the size of the QC. Furthermore, since QCs are usually traveling on the same track when serving the same ship, crossing from one QC to another is not allowed. If a QC is blocked by another QC on the path it travels, it must wait until the completion of another QC's operation. QCSP was first described by Daganzo (1989), defining vessels could be partitioned longitudinally according to the number of ship bays (Daganzo and Peterkofsky, 1990).

1.3.4 Storage Space Assignment Problem

Storage Space Assignment Problem (SSAP) deals with assigning the best yard spaces to containers. A good storage space refers to the one that reduces the storage yard operations cycle time (i.e. the time to store, retrieve and reshuffle). Different characteristics, including the utilizing strategies (consignment strategy and housekeeping strategy), types of container flow (importing, exporting and transshipment), and the decision levels (strategic, tactical, operational and real-time), may have certain influences on the problem.

In the literature, many studies focused on the individual SSAP without simultaneously considering other resources' plan (Zhang et al., 2003, Bazzazi et al., 2009, Chen and Lu, 2012). However, from a practical point of view, there exist some interactions with other operational aspects. In the tactical point of view, yard management is also important. The decisions of assigning yard space to vessels may influence the BAP, meanwhile it affects the total traveling distance induced by the containers movement inside the terminal.

1.4 Scope of Research

This thesis studies on a scheduling problem related to container terminals. In practice, there are tremendous resources allocation and operations involved in a container terminal. It is widely known that many decisions in the operation planning are interrelated especially the integration of i) berth allocation planning with the quay crane assignment, and ii) the quay crane assignment with quay crane scheduling (Murty *et al.*, 2005). Among which, the integration of QC assignment with QC scheduling are always used to determine the vessel handling time for the BAP. When more vessels are berthed at the same time, the number of available QCs can be assigned to each vessel becomes lesser. As a result, an excessive long serving time on a vessel will be induced. In this thesis, the focus will be on BAP, and its closely related operations, including QCAP and SSAP.

1.5 Research Objectives

The main objective of this research is to maximize the terminal operations efficiency by improving the terminal resources utilization with the consideration of the customer service quality. To achieve that, an integrated model combining berth allocation problem, variable-in-time quay crane assignment, and storage space assignment problem is studied. The objective of this study can be further divided into the following sub-objectives:

(i) Develop a new vessel service priority to define customer importance with the consideration of both customer relationship and the corresponding handling volume.

(ii) Develop a new optimization methodology for the integrated BAP and QCAP by using QC-to-Berth allocation approach.

(iii) Develop a new optimization methodology for the integrated berth allocation and QCA by using variable-in-time QC assignment.

(iv) Develop a new mathematical modeling for multi-continuous berth layout to improve berth space utilization and address quay discontinuity in real environment.

(v) Develop a new optimization methodology for the integrated berth allocation, variable-in-time quay crane assignment, and storage space assignment model under multi-continuous berth layout.

1.6 Research Deliverables

Upon the completion of this project, some notable deliverables can be highlighted as follows:

(i) A new vessel service priority to define customer importance with the consideration of both customer relationship and the corresponding handling volume.

(ii) A new optimization methodology named Two-Level Genetic Algorithm (TLGA) is developed for the integrated BAP and QCAP by using QC-to-Berth allocation approach. It consists of 2 iterated GAs: i) designed for optimizing QC assignment, and ii) designed for optimizing the vessel sequencing.

(iii) A new optimization methodology named 3-Level Genetic Algorithm (3LGA) is developed for the integrated BAP and QCAP by using variable-in-time QC assignment. It consists of 3 iterated GAs with a heuristic algorithm. A Level 1 GA is designed for optimizing berth assignment. A Level 2 GA is designed for optimizing quay crane assignment. Lastly, a Level 3 GA is designed for optimizing vessel sequencing. A heuristic is also developed for the reassignment of idle QCs to shift from one vessel to service another.

(iv) A new mathematical model is developed for multi-continuous berth layout. A new idea named Virtual Quay Partition is developed to deal with quay discontinuity. Accordingly, a set of new constraints is also developed.

(v) A new Mixed Integer Programming combined with a new heuristic named Guided Neighborhood Search (GNS) is developed for the integrated berth allocation, variable-in-time quay crane assignment, and storage space assignment model under multi-continuous berth layout.

1.7 Outline of Thesis

This thesis is divided into 8 chapters. Chapter 1 is the introduction. Chapter 2 gives a literature review on the related works in the field, including the classification of BAP, the integration of berth allocation problems and quay crane assignment problems, and the corresponding proposed optimization methodologies. Chapter 3 studies vessel service priority in BAP and also proposes a new modeling approach to simultaneously consider both customer relationship with the terminal and the corresponding handling volume. Chapter 4 studies an integrated BAP and QCAP. A mathematical model is formulated. In addition, an optimization algorithm is developed to simultaneously determine the vessel schedule, berthing position, and the berthing time with quay crane assignment. Chapter 5 extends the quay crane assignment study to variable-in-time modeling approach. A 15-mintue based time unit approach as suggested by industrialists is proposed to maximize the QC utilization. An optimization algorithm is developed to deal with it. Chapter 6 studies the quay discontinuity layout problem. A discussion on the existing approaches for handling quay discontinuity is given, and the disadvantages are identified. Then, a new multi-continuous berth layout model is proposed, and the corresponding mathematical model is formulated. Chapter 7 introduces a new Mixed Integer Programming combined with a new heuristic named GNS to the integrated berth allocation, variable-in-time quay crane assignment, and storage space assignment model under multi-continuous berth layout. Lastly, Chapter 8 concludes all the achievements obtained in the research study. The limitations and suggestions for future works are also given.

Chapter 2 Literature Review

2.1 Introduction

In this chapter, a comprehensive literature review on BAP will be presented. It includes four main parts. Part 1 is the BAP classification, which includes the definition, types of berth layouts, vessel arrival modes, handling time determinations, decision levels and performance measures. Part 2 is about the integration of Berth Allocation and Quay Crane Assignment Problem (BA-QCAP), including the literature review on two main types of the integrated model. Part 3 is a review on the optimization methodologies applied in BAP and BA-QCAP, including approximation algorithms and exact algorithms. Lastly, Part 4 will highlight the identified research gap.

2.2 Classification of Berth Allocation Problem

Kim and Park (2004) defined BAP as the first step in among all the terminal operations. BAP determines the berthing position of vessels along the quay. Similar idea was given by Steenken *et al.* (2004), Cordeau *et al.* (2005), Imai *et al.* (2007a), Wang and Lim (2007), etc. In general, BAP consists of two main decisions: i) "when", and ii) "where" a vessel should moor. In general, BAP can be classified according to different problem structures in terms of berth layouts, vessel arrival modes, vessel handling time determinations, and decision levels. In the literature, there are a number of measures for evaluating the performance of the berth allocation plan.

2.2.1 Introduction to different types of berth layouts

Berth layouts in BAP can broadly be classified into three main categories: i) discrete berth layout, ii) hybrid berth layout, and iii) continuous berth layout.

In discrete layout, the entire quay is divided into a number of berths (Bierwirth and Meisel 2010). Among which, one berth can only service one vessel. In hybrid layout, it is similar to discrete layout in dividing the quay into a number of berths. However, one vessel can occupy more than one berth. Meanwhile, one berth can be shared by more than one vessel. Lastly, in continuous layout, vessels can be allocated on to anywhere along the time. Comprehensive review on these three berth layout models can be found in Steebken *et al.* (2004), Bierwirth and Meisel, (2010) and Carlo *et al.* (2013).

In relating to berth layouts, length of the available berths and size of the vessels are always important and should be considered during the planning of berth allocation (Kim and Park, 2003; Boile *et al.*, 2006). In some studies considering discrete or hybrid berth layout, the quay is subdivided into a number of berth based on the size of vessel to ensure all vessels can be berthed and to optimize the utilization of the berth space (Cordeau *et al.*, 2005). In addition, this is also incredibly important for recognizing the position of the vessel and the remaining berth space in the terminal with continuous berth layout.

Comparing to the discrete and hybrid berth layout, the continuous layout in fact is much better in terms of berth space utilization (Giallombardo *et al.* 2010). Although natural or artificial quay discontinuity can be easily found in terminals, they are not addressed much in the continuous layout literature. Cordeau *et al.* (2005) and Cheong *et al.* (2010) have discussed about quay discontinuity in their studies. Cordeau *et al.* (2005) discussed a BAP of Gioia Tauro port, where discontinuity can be found in the middle of the quay. To deal with that, they modeled it as the hybrid berth layout model and then further divided the quay into a number of berth segments. In the model, a large vessel was allowed to occupy two or more adjacent berth segments. They proposed two formulations for the discrete case, and developed a heuristics for the hybrid case. Cheong *et al.* (2010) addressed the similar layout as discussed in this thesis. In their model, the entire quay consists of a number of discrete segments, and the space within each segment is treated as continuous. They mentioned this layout is even more practical. However, they did not propose a linear mathematical model for the layout, but developed a multi-objective evolutionary algorithm to optimize the berthing position for incoming vessels.

2.2.2 Vessel arrival modes in BAP: Static and Dynamic

In general, two vessel arrival modes can be found in the literature, which are known to be static arrival, and dynamic arrival. Static arrival (Figure 2.1) assumed incoming vessels will be arrived (ready) at the terminal before the start of the planning horizon. In such a situation, the arrival time of a vessel can be neglected (Imai *et al.*, 2007a). However, this type of vessel arrival may not be realistic nowadays as vessel waiting time is one of the critical factors in affecting the performance of the terminals. Therefore, Imai *et al.*, (2001) introduced another type of vessel arrival named as dynamic arrival. Dynamic arrival assumed vessels will only arrive at an expected time. Therefore, vessels cannot be serviced before that expected arrival time (Bierwirth and Meisel, 2010) as shown in Figure 2.2.

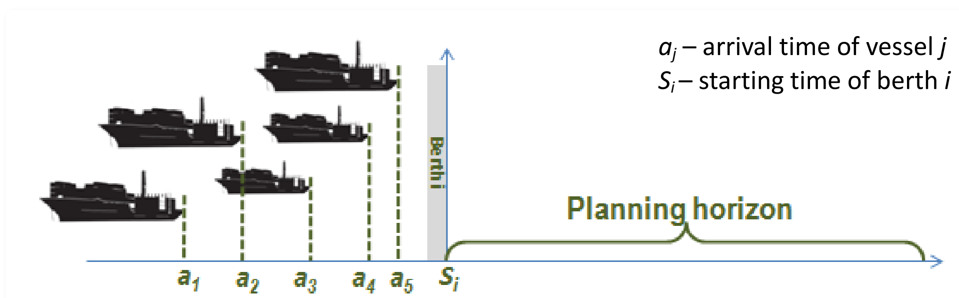

Figure 2.1 A static arrival mode

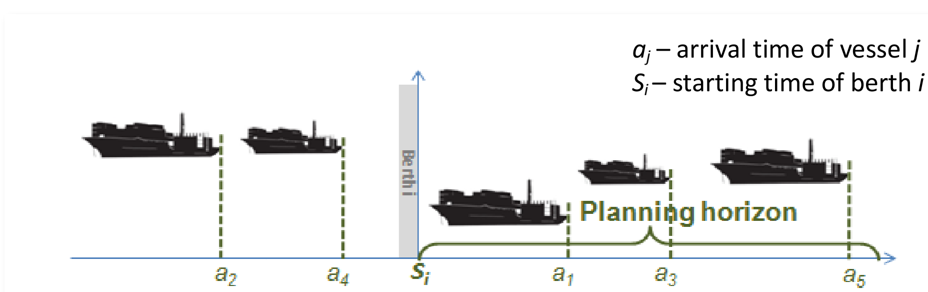

Figure 2.2 A dynamic arrival mode

2.2.3 Vessel handling time determinations in BAP

Researchers deal with vessel handling time by several approaches. Majority of their studies assumed deterministic handling time in their BAP models (Lim, 1998, Wang and Lim, 2007), while others determined by the berthing position, the volume handling size or the size of the vessels (Bierwirth and Meisel, 2010, Raa *et al.*, 2011). These studies always ignore the usage of QCs. However, these handling time determinations are still not enough for applying in the real situation. In practice, one of the critical factors affecting the vessel handling time is the number of QCs employed with its operation rate. Thus, Park and Kim (2003) introduced an integrated model to solve the integrated BAP and QCAP simultaneously. They assumed that the vessel handling time varies in a linear relationship with the number of QC being assigned. It provides a more satisfactory estimation on the vessel handling time. However, some researchers also claimed that the vessel handling time does not vary linearly as QC interference may occur during the operation. To obtain a more accurate vessel handling time, they proposed an integrated BA and QCSP model to consider the QCs schedule as well.

2.2.4 Decision levels in BAP: Tactical BAP and Operational BAP

Berth allocation planning decisions can be made at two levels: i) tactical level, and ii) operational level, depending on the length of the planning horizon. Tactical level decisions regarding medium to short term decisions on resource allocation in berth and yard management. At this level, the decisions can be practically based on ‘‘rules of thumb’’ in which the experience of the terminal managers plays an significant role, or it could be alternatively based on some more scientific approaches like operations research methods. Operational level decisions involves making daily and real time decisions such as crane scheduling and last minute changes in response to disruptions in the existing schedule. BAP decides when and where the vessels should moor. Generally, the decisions can also be made at these two levels. Operational berth allocation problem (OBAP) is exercised in a short planning horizon covering a few days by taking real time operational constraints into consideration, while tactical berth allocation problem (TBAP) is exercised in a longer planning horizon covering maybe a month to support terminal managers in making decisions during their negotiations with shipping lines, and also served as a reference for OBAP.

(i) Operational Berth Allocation Problem

OBAP has received much attention in the literature. It can be modeled as a discrete berth layout model (Cordeau *et al.*, 2005) if a quay is partitioned into a finite set of berths and each berth can only be assigned with one vessel. Some others (Cheong *et al.*, 2010; Wang and Lim, 2007; Lee and Chen, 2009, Meisel and Bierwirth, 2009; Yang *et al.*, 2012) are modeled at a continuous berth layout model in which vessels can be berthed anywhere along the quay. The remaining (Cordeau *et al.*, 2005; Turkogullari *et al.*, 2014) are modeled as a hybrid berth layout model, in which the quay is divided into a number of berths. Each berth can be shared by more than one vessels or one vessel can occupy more than one berth. Related studies can be found more comprehensive in (Bierwirth and Meisel, 2010).

(ii) Tactical Berth Allocation Problem

In the literature, only a small amount of papers study on TBAP, including (Cordeau *et al.*, 2007; Moorthy and Teo, 2006; Zhen *et al.*, 2011a; Giallombardo *et al.*, 2010). In fact, berth allocation has great impact on yard planning and vice versa. Terminal managers, before negotiating with the shipping lines, has to understand the overall situation of assigning certain amount of existing resources, i.e. berth, QCs, yard storage space, to the shipping lines. Therefore, TBAP usually combines various resources planning problems (e.g. SSAP, QCAP) in a single large scale optimization problem.

Moorthy and Teo (2006) firstly introduced the concept of berth template and yard template in transshipment hubs. They also address the problem of quay discontinuity in their paper. To deal with that, the quay is considered as hybrid berth layout by dividing it into a number of linear sections which are further subdivided into berths. They developed a sequence pair approach to pack the vessels in berths with a fixed handling time, and used the standard simulated annealing approach to search the solution space of sequence pairing. It aimed to minimize the total expected delays and the connectivity cost, which is regarded as the travelling distance between the berthing positions of vessels for the same group of transshipment. Cordeau *et al.* (2007) studied the tactical problem in the terminal located at Port of Gioia Tauro utilizing housekeeping strategy, which dedicates specific position of yard and the quay to a shipping company. The problem is formulated in a generalized quadratic assignment model to minimize the re-handling operations of containers inside the yard, and an evolutionary heuristics was developed for solving it. Same as Cordeau *et al.* (2005), the terminal studied in this paper presented discontinuities in the middle of the quay. Therefore, the authors created an additional constraint to avoid a service requiring two berth spaces is allocated to a pair of berths showing discontinuity. Giallombardo *et al.* (2010) extended the study by Cordeau *et al.* (2007) to consider the usage of QCs. They modeled the terminal in discrete berth layout instead of hybrid. They also introduced the concept of QC-profile. For each vessel, a set of feasible QC-profile are generated, and each QC-profile consists of a number of working shifts occupied by a vessel and a number of QCs being assigned to vessel for each shift. They aimed to maximize the total value of the selected QC-profiles and minimize the housekeeping costs generated by transshipment flows between vessels simultaneously. A heuristics combining mathematical programming techniques and Tabu search is proposed to solve the problem. Comparing to Cordeau *et al.* (2007) and Giallombardo *et al.* (2010), Hendriks *et al.* (2013) explicitly modeled the transportation of container to and from their storage block in the yard, and determined the best block for storage by a heuristics approach. They considered the terminal as the conventional continuous berth layout and also took into account the periodic nature of the schedule and container types, while the total QC capacity devoted to each vessel is given. Apart from these, some papers also focused on tactical planning. For examples Lee *et al.* (2012) considered terminal allocation for a container port with multi-terminals instead of considering the exact berthing position of a particular terminal. Robenek *et al.* (2014) studied the tactical berth allocation problem and yard assignment in the context of bulk ports. Lee and Jin (2013) focused on adopting a proactive management strategy for feeder schedule in the point of view of container terminals. They considered an integrated quay and yard operations of a transshipment terminal by simultaneously considering the berth and yard templates.

2.2.5 Performance Measures in BAP

In the literature, there are different measurements to evaluate the performance of the berth allocation plan, such as vessel waiting time, vessel handling time, total service time (comprising the waiting time of berthing, the vessel handling time required, and the total delay time) (Liang *et al.*, 2009; Liang *et al.*, 2012; Eduardo *et al.*, 2012), berthing position (Li and Yip, 2013; Li, 2014; Golias *et al.*, 2011), customer satisfaction, etc. (Imai *et al.*, 2001; Imai *et al.*, 2003; Imai *et al.*, 2007a; Nishimura *et al.*, 2001; Mauri *et al.*, 2008; Saharidis *et al.*, 2010). Some of the studies solely focused on one objective, while some other used multi-objective for measurement. Details are explained as the follows:

(i) Waiting time

When a vessel arrive its destination (terminal), it firstly waits at harbor before mooring to the berth. Generally, the wait is caused by unavailability of the quay resources (e.g. all the berths are occupied by other vessels at that moment) or handling documents. The time duration between vessel arrival and vessel mooring is called waiting time. Long waiting time may cause delays in vessel departures. Hence, minimizing the vessel waiting time is crucial to terminals (Imai *et al.*, 2003).

(ii) Handling time

Handling time refers to the time duration from vessel berthing to its completion. Once a vessel berthed, the unloading and loading operations will start. Thus, handling time is more related to the operation efficiency. As mentioned before, in BAP, handling time can be simplified to a deterministic value according to the handling volume, vessel size or the result from other individual resource plan (e.g. QCAP). In this case, vessel handling time is treated as an input value without making contribution to the optimality of berth allocation plan. However, in some other cases, it can be modeled as an adjustable value. For example, it can be determined according to the berthing position. Actually, certain positions are more favorable to a vessel, for example, the position with more QCs or close to its storage location. It is always assumed that a shorter handling time is estimated for a vessel if it can berth at its favorable position. To estimate more accurately, it can be determined simultaneously with QCAP, QCSP and SSAP in an integrated approach.

(iii) Total Service time / Vessel turnaround time/ Port staying time of a vessel

Total service time is comprised of the vessel waiting time and vessel handling time of all incoming vessels. Terminals concern about productivity and customer satisfaction, while vessels concern more on its departure time. Therefore, individual waiting time or handling time may not be so important to them comparing to the combined one. Minimizing the total service time represents improving the operation efficiency of the terminal, which means that the terminal can have a larger service capacity. Therefore, it is always the aim of BAP from terminal's point of view (Cordeau *et al.*, 2005; Hansen *et al.*, 2008).

Vessel turnaround time, also named as port staying time of a vessel, which comprises waiting time and handling time. Since vessel turnaround time directly affects vessel departure time, it is always treated as one of the critical measures for rating the performance of a terminal from customers' point of view (Murty *et al.*, 2005). Monaco and Sammarra (2007) have also pointed out the objective function can be the weighted sum of vessel turnaround time. The weighting can be defined based on the vessels priority or the penalty cost induced by delay departure as signed on the contracted.

(iv) Earliness and Tardiness

Completion earlier than the completion time is known to be an important performance measure in some studies [see Park and Kim (2003), Imai *et al.*

(2007a), Hansen et al. (2008), Liang *et al.* (2009)] because delay departure may cause delay arrival to the next port and so on (Imai *et al.*, 2007a). The propagation effect is fatal, and therefore, it is crucial for terminals to achieve the committed departure time. In addition, delay the departure time will also induce huge penalty costs. Imai *et al.* (2005) and Hansen *et al.* (2008) studied the modeling of penalty costs, which consists of the cost induced by the early starting time of vessel handling against the expected vessel arrival time, and the late departure time deviated from the committed departure time. Sometimes, arrival and departure time are specified in the contract. If the vessel handling operations are completed earlier than the expected departure time, a premium will be paid by the vessel owners to the terminal. On the other hands, if the operations are completed after that date, penalty cost will be paid by the terminal to the ship owners. One can see that, such premiums or penalties can be used to indicate the importance of delays vary toward different vessels, depending on both the vessel size and the commitments to the vessel owners such as the scheduled arrival date to the next port. As a summary, it is critical for terminals to ensure the departure time will not be violated in order to minimize their total operating cost.

(v) Berthing position

According to Park and Kim (2003), there is an optimal berthing position for vessels, which is the nearest position to the marshalling yard. In yard, marshaling yard is a storage place to stack all the outbound containers. Vessels berthing near to these storage locations to be loaded onto the vessel can minimize the delivery distance and time for the containers. Therefore, Kim and Moon (2003) and Park and Kim (2003) have added a factor in their optimization model to penalize the distance from the berthed location to its ideal berth location. Moreover, it is also known that some planners will increase the expected vessel handling time accordingly. Cordeau *et al.* (2005) stated a similar idea with Park and Kim (2003) and Kim and Moon (2003), emphasizing that minimization of travelling distance between vessels and the outbound containers is important. In addition, the most favorable location can also be determined by the resources availability, the strength, the depth of water, and direction of waves, etc.

(vi) Vessel rejection/ Vessel transfer

With the increase of cargo shipments, some studies recently found that the major hub terminals, such as those in the Indian Ocean and Hong Kong, are now facing problems of congestion. In practice, vessels usually are assigned with a maximum waiting time limitation, i.e. 2 hours (Dai *et al.*, 2008). If the vessel has to wait more than this limitation, it will be transferred to another terminal. Although this activity can effectively save the waiting time of the vessel, it may induce some extra transshipment between the terminals, increase costs and affect the reputation of the terminal (Imai *et al.*, 2008a).

In the literature, some papers are focusing on the minimization of the number of vessel rejection. Wang and Lim (2007) firstly considered the cost of unallocated vessels in the BAP model. However, they did not explain details of the cost. Imai *et al.* (2008a) proposed another BAP mode. In this model, vessels will be assigned to external terminal for uploading and unloading operations if they cannot be handled within a predefined time limit. The paper aimed to minimize the total vessel servicing time at the external terminal. According to Bierwirth and Meisel (2010), vessel rejection or transfer will happen when a vessel cannot be served within a maximum acceptable waiting time. In such case, the terminals would transfer these vessels to other terminals, ensuring the vessel can depart within the due date. However, the terminal will suffer the extra cost for these transfers, which is called rejection cost. By minimizing the rate of vessel rejection, the external terminal usage can be reduced. Customer loyalty is one of a critical factor on affecting the long-term revenue of a terminal. However, it may not directly proportion to the rejection cost because the rejection cost normally depends on the volume of the containers to be handled of the vessel, the extra cost caused by employing external terminal, etc. Some important customers may not have the highest volume of container in every time, however, they provide higher container traffic volume to the terminal in a long term. These customers usually desire higher service priority from the terminal because they require very stable port service. Terminals therefore have to make a trade-off between these factors when they make decision on allocating berths to the vessels.

(vii) Customer Satisfaction: Order of service and Service priority

Order of Service relates to the service sequence. Traditionally, the vessel should be received the service by First-Come-First-Served (FCFS) basis. Imai *et al.* (1997) have concluded that high port throughput can be achieved without considering the FCFS basis. However, they also concluded that this may result in customer dissatisfaction because of the service ordering.

Moreover, terminals always want to provide good service quality to all the vessels (Cordeau *et al.*, 2005), however, many terminals, for example those in Hong Kong, are subject to many constraints, such as berth space, number of quay cranes, etc. It may be difficult to provide the same service quality to all incoming vessels, and some may have to suffer long waiting times or handling times, or they may be transferred to other terminals. Some researchers stated that vessel servicing priority is important, and this can help in providing good service quality to important customers (Cordeau *et al.*, 2005; Imai *et al.*, 2003; Dai *et al.*, 2008; Legato and Mazza, 2001). Moreover, the reasons for prioritization are varied, i.e. emergencies, number of containers to be handled, tide restrictions, transshipment aspects between vessel, etc. (Raa *et al.*, 2011).

Different researchers have different views on defining an important customer (Buhrkal *et al.*, 2011). In general, the views can be classified into two streams. The first stream is volume oriented. Imai *et al.* (2003) stated that vessel servicing priority is critical to customer service quality and terminal efficiency especially when there is different vessel size with different container handling volumes. For instance, some terminals in China may consider small feeder vessels as important customers and give them high priority, since the handling work associated can be completed in a short period. Therefore, large vessels will have a longer waiting time. However, some terminals in Singapore give higher priority to large vessels because they believe these vessels may provide more profit (Imai *et al.*, 2003; Golias *et al.*, 2009). Another stream of research defines important customers by using their relationship with the terminals, such as long-term partnerships (Imai *et al.*, 2008a; Wang and Lim, 2007; Oliver, 2005; Notteboom and Winkelmans, 2001; Soppe *et al.*, 2009). Dai *et al.* (2008) also stated that berth-on-arrival service (i.e. within two hours of arrival) has been guaranteed for some particularly important customers in their contract.

Therefore, they will be served with higher priority. Treating good customers with higher service priority without consider their handling volume can gain a long-term profit but may induce a short-term business loss. However, the long-term and short-term profits may not always be compatible. To the best of our knowledge, no research output has been found that considers both views in assigning the service priority.

(viii) Multi-objective measurement

Container terminals work under multiple operation objectives, choosing a suitable objective function is not a trivial tasks. Various objectives may help in improving the terminal operations, viewed from different aspects. To maximize the performance of the terminal operations from the point of view of both the terminal and vessel operators, researchers recently considered multi-objectives in their studied models (Wang and Lim, 2007; Saharidis *et al.*, 2010; Chang *et al.*, 2010; Zhen and Chang, 2012; Karafa *et al.*, 2013). However, different objectives are sometimes non-commensurable, in other words the improvement achieved on one objective may cause downgraded on the others (Saharidis *et al.*, 2010). Researchers therefore have employed different techniques in solving such problems. Weighted method is a popular approach for transforming multi-objective models into single objective one. The solution accuracy of this approach depends on the proper assigning the weight to each objective. It is difficult to justify the appropriated weights in a scientific way, but practically may depend on the experience and the view point of the decision makers. Some other researchers also proposed different algorithm to find the non-dominated solutions named Pareto Front. Saharidis *et al.* (2010) mentioned the turnaround time of all the vessels is an important measure that influences the competitiveness of a container terminal. Meanwhile, in their objective, the turnaround time of a specific group of customers is also important. They used a k-th best algorithm to solve the proposed multi-objective problem. Cheong *et al.* (2009) incorporated a Multi-Objective Evolutionary Algorithm (MOEA) with Pareto optimality to simultaneously solve three objectives, makespan, vessel waiting time, and degree of deviation from a predefined vessel priority schedule. Zhen and Chang (2012) also utilized a multi-objective optimization method to find a tradeoff between two conflicting objectives, which are cost and robustness. In their methods, they used a Pareto optimal set, which is known as a form of alternate tradeoffs between different objective components. In this, when any objective component of any non-dominated solution improves, at least one of the other objective components will be degraded. Thereby, they applied this to discover the Pareto-optimal set for decision makers to select a more desirable solution based on the particular situation faced (Cheong *et al.*, 2009).

2.3 Classification of integrated berth allocation with quay crane assignment problem

Many BAP studies assumed deterministic handling time or berthing position based handling time because berthing position is highly related to the number of the QCs being assigned in the operation, and also container transportation time spending between the berth and the yard. Examples can be found in Cordeau *et al.*, 2005, Imai *et al.*, 2007a, Imai *et al.*, 2008a, Golias *et al.*, 2009. However, detail studies related to the determination procedure are usually being ignored. In practice, the number of QCs being assigned can directly determine the vessel handling time. Therefore, much more research work are developed in the integration of berth allocation and quay crane assignment models nowadays. There are two types of the integrated models, one with time invariable quay crane assignment and another with variable-in-time quay crane assignment.

2.3.1 Time invariable quay crane assignment

Imai *et al.* (2008b) studied a problem of simultaneous berth-crane allocation and scheduling with considering some physical constraints of QC. They mentioned that QCs cannot move freely among berths. A GA based heuristic was developed to minimize the total servicing time. However, in this paper, the relationship between the number of QCs assigned and the handling time was ignored. Liang *et al.* (2009) introduced a formulation for simultaneous berth and QC assignment problem, and solved a dynamic scheduling problem by using a hybrid evolution algorithm. They aimed to minimize total waiting time, total handling time and delay time of vessels. Liang *et al.* (2011) extended the study by investigating the number of QC movements among berths. They believed that too many movements may reduce the efficiency of loading and unloading operations. Therefore, they proposed a multi-objective mathematical model to trade-off between the numbers of movements and the total servicing time. A multi-objective hybrid GA approach was developed for solving the problem. Chang *et al.* (2010) firstly addressed green transportation in its integrated model. They aimed to minimize the deviation berthing position, total penalty and energy consumption of QCs by employing a hybrid algorithm which involves the heuristic rules and Parallel Genetic Algorithm (PGA) to solve BA-QCAP. Raa *et al.* (2011) presented a model for BA-QCAP with consideration of vessel priorities, preferred berthing locations and vessel handling time. Yang *et al.* (2012) developed an evolutionary algorithm with nested loops to minimize the average service time of the incoming vessels. Mario *et al.* (2013) presented a model that took into account the QCs and the hold of vessel in determining the handling time. They proposed a Greedy Randomized Adaptive Search Procedure (GRASP) meta-heuristic and compared it to some usual scheduling methods employed in container terminal i.e. FCFS, first come maximum priority, maximum weighed waiting time, earliest weighed mooring time. The results showed great improvement was obtained by the proposed approach. In these approaches, the QCAP is involved in determining the vessel handling time. Therefore, the integrated approaches can generate more efficient schedules than separated ones.

2.3.2 Variable-in-time quay crane assignment

Park and Kim (2003) firstly studied an integrated continuous BAP with variable-in-time quay crane assignment. The assignment was varied by every single time segment. They suggested a two-phase heuristic solution approach for the problem. First of all, they applied Lagrangean relaxation to determine the berthing position and time for individual vessel and the number of QCs being assigned for each time segment. After a detail schedule of each QC was determined. Then they applied dynamic programming to solve the rest. For the reasons of simplicity, the productivity of the QC is always assumed to be directly proportional to the number of QCs being assigned, including Park and Kim (2003). However, such 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 Park and Kim (2003) by using the same data sets and obtained better results. 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 scheduling problem. They modeled vessel as an individual activity performing in different modes with a certain number of QC being assigned over the planning horizon. The objective was to minimize the idle time of QCs. The adoption of mode was determined by a priority rule based method. Later on, Meisel and Bierwirth (2013) elaborated their previous model by including QCSP. They proposed a three-phase framework for the integration of BAP, QCAP and QCSP.

Giallombardo *et al.* (2010) introduced a QC profile in their model which is similar to the "mode" concept proposed by Meisel and Bierwirth (2006). As each vessel required a certain amount of QC hours, then different QC profiles can be created. The profile consists of a number of working shifts required by each vessel and also the number of QCs being assigned at each shift. They proposed a two-level heuristic to deal with 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.

2.4 Optimization Algorithms

BAP is widely known to be NP-hard (Chang *et al.*, 2010; Park and Kim, 2003; Kozan and Preston, 1999), and is difficult and complex to solve, especially in large-scale dimensions. In the early stage, the First come first service was applied in terminals as the optimization methodologies in BAP (Lai and Shih, 1992; Lee and Chen, 2009). Some other optimization methods, such as dynamic programming, branch and bound, are also able to solve the problem. However, as the problem size increases, these approaches may become infeasible. Hence, some heuristics algorithm, and meta-heuristics algorithm such as Genetic Algorithm (GA) (Liang *et al.*, 2011; Imai *et al.*, 2008; Liang *et al.*, 2009; Liang *et al.*, 2012; Nishimura *et al.*, 2001; Kozan and Preston, 1999), Simulated Annealing (SA) (Dai *et al.*, 2008; Kim and Moon, 2003), and Tabu Search (TS) (Cordeau *et al.*, 2005; Eduardo *et al.*, 2012) have been proposed to solve the NP-hard problem. In which GA is well known to be a practical and effective widely used robust heuristic to solve NP-hard problems in short computational time (Holland, 1975).

2.4.1 Exact algorithms

Imai *et al.* (2001) studied BAP with dynamic vessel arrival time. They aimed to minimize the total vessel waiting and vessel handling time by using mixed integer programming (MIP) with Lagrangian relaxation. However, it may not be applicable to most container terminals in many countries because the study is based on a public berth system. Park and Kim (2002) formulated BAP into a MILP model with Lagrangean relaxation model using sub-gradient optimization techniques. As a result, the proposed model can be able to solve by using commercial optimization solving package.

Park and Kim (2003) solved the integrated BAP and QCA in a sequential manner. They adopted the methodology proposed in Park and Kim (2002) again to solve the BAP and used dynamic programming for the quay crane assignment. Monaco and Sammarra (2007) extended the model proposed by Imai *et al.* (2001) into a vessel priorities model and solved by using Lagrangian relaxation. Mauri *et al.* (2008) studied the problem of Cordeau *et al.* (2005) and proposed a hybrid column generation approach. Among which, the sub-problem is solved by using an evolutionary based algorithm named population training algorithm. Experimental results showed that it can deliver a better solution in a shorter runtime than TS. Buhrkal *et al.* (2011) reviewed five different models in the literature for dynamic BAP. In which the Generalized Set Partitioning Problem (GSSP) model has been improved. Experimental results demonstrated that it outperformed all others remarkably.

2.4.2 Approximation algorithms

(i) Genetic Algorithm (GA)

GA is widely adopted for solving scheduling problems. For examples in solving BAP, Nishimura *et al.* (2001) applied GA to solve the problem of Imai *et al.* (1997) with the consideration of multi-water depth configuration. Imai *et al.* (2007b) studied BAP in hybrid berth layout which allows a maximum of two vessels being simultaneously served at the same berth. They formulated the problem as an integer linear programming model, solving by using GA. In the literature, researchers also combine GA with other heuristics for optimization. Imai *et al.* (2007a) proposed to use GA and Lagrangian relaxation with sub-gradient optimization to solve a bi-objective BAP. Imai *et al.* (2008a) also developed a GA-based heuristic to minimize the total service time of vessels at an external terminal.

Moreover, GA has always been applied to solve integrated problems. For examples, Lee and Wang (2010) formulated a mixed integer programming model for integrated BA and QCSP, and proposed GA to solve the problem. Han *et al.* (2010) formulated a non-linear MIP model and proposed GA incorporating with Monte Carlo simulation for generating a robust BA and QC schedule. The BA and QC assignment for each vessel are represented by a chromosome and is evaluated by simulation. Their experimental results demonstrated that the proposed algorithm provides a satisfied performance with uncertainties. Liang *et al.* (2009) studied an integrated BA and QCAP with the aim of minimizing vessel handling time, waiting time, and delay time. They developed a GA with heuristics to determine an approximation solution which is applicable for practical uses.

Moreover, Han *et al.* (2006), Takano and Arai, (2009), Chang *et al.* (2010), Seyedalizadeh Ganji *et al.*, (2010), Liang *et al.* (2011), Yang *et al.* (2012), Fereidoonian and Mirzazadeh (2012) and Golias *et al.* (2014) have also used GA in their papers for solving their problems.

(ii) Simulated Annealing (SA)

Kim and Moon (2003) formulated a MILP model for a continuous BAP. They proposed SA algorithm for solving the problem. Moorthy and Teo (2006) addressed home berth design problems which concern the allocation of berth location preference for each vessel, and proposed a sequential pairing based SA algorithm. The experimental results showed that the proposed SA algorithm is capable of constructing efficient and robust template for terminal operations. Dai *et al.* (2008) modeled static BAP by using rectangle packing approach with release time constraints. They employed sequence pair concept to define the structure of the neighborhood, and proposed a SA algorithm to search through the space of all possible sequence pairs. De Oliveira *et al.* (2012) proposed an alternative which applies Clustering Search (CS) in the SA algorithm for solving the discrete BAP. Zhen *et al.* (2011b) studied the BAP with uncertainties in vessel arrival time and vessel handling time, and proposed SA for solving the large scale problems. Lin and Ting (2013) also proposed a SA approach to solve the dynamic BAP in both the discrete and continuous situations. Results showed that their approach obtain optimal solutions in all the discrete testing instances.

(iii) Tabu Search (TS)

Cordeau *et al.* (2005) formulated a discrete and a continuous dynamic BAP with due dates and proposed TS algorithm to deal with it. The numerical result demonstrated that the proposed TS outperformed FCFS heuristic. However, the problem size being test was relatively small. Eduardo *et al.* (2012) also addressed the discrete BAP with a goal to minimize vessel port staying time and proposed a hybrid algorithm comprised of TS and path re-linking. It was compared with the best mathematical model, GSPP, in the literature, and the TS algorithm proposed by Cordeau *et al.* (2005). Experimental results showed that their proposed hybrid TS algorithm was as good as GSPP in small scale problems and obtained even better solutions than the TS algorithm proposed by Cordeau (2005). Giallombardo *et al.* (2010) studied BA-QCAP at the tactical level. They developed a heuristics algorithm by combining TS and mathematical programming techniques for solving the problem.

(iv) Other heuristics

Some other heuristics can also be found in the literature for solving BAP. For examples, Wang and Lim (2007) proposed a stochastic beam search algorithm, which is a new multi-stage searching method, to solve a multi-stage decision making process in BAP. The proposed algorithm has improved the traditional beam search approach. Hansen *et al.* (2008) introduced a novel model which minimizes the cost in BAP, and proposed heuristic named variable neighborhood search to search for approximate solutions. Lee and Chen (2009) proposed a neighborhood-search heuristics to optimize the BAP. Lee *et al.* (2010) studied BAP in continuous berth layout, and developed a Greedy Randomized Adaptive Search Procedure (GRASP) to solve the problem. They compare their algorithm with stochastic beam search proposed by Wang and Lim (2007) and CPLEX to demonstrate its effectiveness.

2.5 Research Gaps

Four main research gaps have been identified:

(i) Determination of Vessel Sequencing priority

In traditional approach, vessel sequencing priority is usually determined by customer importance or handling volume. However, both factors are important. Customer importance related to customer relationship, while handling volume has immediate impact on to the terminal profit. Therefore, development of a methodology that can simultaneously considering both of them are important.

(ii) Decomposition methodology for integrated BAP and QCAP

In literature, it is known that BAP has strong relationship with QCAP. Many existing papers have already simultaneously solving them together, known as the integrated BAP and QCAP. This integrated problem is very complicated. Therefore, development of an efficient optimization methodology is important. Accordingly, development of an efficient decomposition methodology is important.

(iii) 15-minute based time segment approach in the integrated model of BAP and QCAP

From the literature, hourly based time unit is usually used. However, using hourly based time unit may cause idle of QC and Berth especially in transshipment hubs. In addition, referring to some terminal operations in Hong Kong, nowadays, they are already changing to 30-minute based time planning approach. Therefore, it is important to develop a 15-minute based time segment approach for the integrated BAP and QCAP.

(iv) Multi-continuous berth layout modeling approach

Quay Discontinuities can be found in many existing container terminals. However, the existing discrete and hybrid berth layout modeling approaches may cause low berth space utilization, while the continuous berth layout modeling approach can only handle one single quay layout. Therefore, there is a need to develop a multi-continuous berth layout modeling approach to deal with quay discontinuities in real terminal layouts.

2.6 Summary

BAP has received much attention in the literature. This chapter summarized some important literatures related to BAP and BA-QCAP, and provides fundamental supports for developing BAP models in the research study.

From the literature review, it is noted that customer satisfaction becomes more important nowadays, terminals strive to reduce vessels waiting time, handling time, etc. It is not only because of the improvement on the overall terminal productivity, but because of the improvement on customer satisfaction to rise up competitiveness. However, subjected to resources constraints, it is difficult for a terminal to provide the same service quality to all the incoming vessels. Therefore, assigning priority to vessels is a common practice to improve the satisfactions of some groups of customers. In the literature, few studies concerned about which vessels should deserve higher vessel priority. In fact, this issue is critical, and has great impacts on both the long and short term business gains. Therefore, this research will have a study on this area.

Moreover, it is more common to integrate BAP with QCAP nowadays, in which QCAP is responsible for determining vessel handling time. It can be observed there are two main model types for BA-QCAP, one for considering time invariable quay crane assignment and another for variable-in-time quay crane assignment. In fact, variable-in-time quay crane assignment can provide higher flexibility, while only a few studies considering this type as it is more complex.

Furthermore, discrete and hybrid berth layout models are always suggested for the ease of scheduling, while continuous berth layout model is recognized to be better berth space utilization. In addition, some characteristics in real world container terminals, i.e. quay discontinuity and natural curves, have seldom been addressed in the existing continuous berth layout models found in the literature. To improve the berth space utilization with the consideration of the real world terminal layout settings - quay discontinuity, a multi-continuous berth layout model will be proposed.

Chapter 3 Vessel Service Priority in Berth Allocation Problem

3.1 Introduction

In general, terminals should serve all their customers at their berth. However, since terminals are capital-intensive with huge investment in infrastructure and equipment, they are always subjected to facilities constraints, for example the number of QCs, berth spaces, etc (Wagscha, 1985; Liang *et al.*, 2011). During the peak seasons, providing the same service quality to all the incoming vessels are difficult. Therefore, assigning priority to vessels is a practical approach to improve satisfactions of certain group(s) of customers. In the literature, vessel priority is determined either by: i) customer relationship factor, or ii) handling volume factor. The customer relationship factor concerns the relationship between the customers and the terminal. Lower the priority of the long-term customers may affect the customer loyalty and induce a long-term business loss to the terminal. On the other hand, the handling volume factor concerns the throughput of the terminal, and directly affects the terminal productivity and profitability. In fact, both factors are crucial and should be considered simultaneously as they are closely interrelated. Therefore, one of the focuses in this chapter is to study the characteristics of assigning vessel service priority in the conventional BAP.

Hong Kong is one of the world's busiest regions of container terminals since it is the primary entry point to the Southern China region (Murty *et al.*, 2005). It is also subjected to facilities constraints, and therefore, it is critical for the terminal operators to deal with vessel priority problems. In practice, they may transfer some vessels to their partnered terminals when they cannot serve the incoming vessels within a certain period, such as 2 hours in Hong Kong. However, this practice may induce some drawbacks. If a vessel is transferred, first of all, the containers stored in the original terminal for loading will be required to be transported to the partner terminal where the vessel has been transferred to. Similarly, the unloaded containers will also be required to transport back to the original terminal. All these extra transshipments entail huge monetary consumption, and may also give negative impact to the terminal reputation (Imai *et al.*, 2008a).

In this chapter, a model named Discrete Berth Allocation Problem with Priority considering Customer Relationships and Handling Volume (DBAP-priority-RH) is proposed to extend the conventional BAP model to simultaneously consider customer importance and handling volume in vessel service priority. A new GA based optimization methodology, named GA for BAP (GA-BAP), is proposed to minimize the vessel transfers cost and the total service time.

3.2 Mathematical modeling for Discrete Berth Allocation Problem with priority considering customer relationships and handling volume (DBAP-priority-RH)

The DBAP-priority-RH model is modeled in a discrete berth layout. Fixed arrival time is given to each vessel, and hence, the vessels cannot berth earlier. The vessel handling time is affected by a number of factors, for examples, the available QCs being assigned to the berth, the container travelling distance between the vessel and the storage location, etc. It is found that most of these factors are related to the berthing position. It implies that handling time required for the same number of containers at different berths can be different. Therefore, in the initial phase of the research study, position based vessel handling time is preliminarily studied.

To model the customer importance, the vessels are assumed to be classified into 3 categories, representing the customer relationship with the terminal. The most important customers (with long-term partnerships) are defined as the 3^{rd} level. Frequent customers are defined as 2^{nd} level, and the rest is defined as the 1^{st} level. It is noted that to quantify the customer importance, it can also be based on how long the partnerships has been built (e.g. in unit of month) or how many the accumulated volume handled (e.g in unit of TEU), etc. In fact, it is difficult to assign a specific value to each customer level since different terminals may bear their own point of view. Therefore, determining an exact value for them will not be the focus in this thesis. In this connection, the values are set to be adjustable. In practice, these values can be subjectively decided by the decision makers based on their own company views.

To model the characteristic of the handling volume, number of TEU is applied. Both the customer level (v_j) with the handling volume (h_j) are used for defining the service priority of a vessel. The objective is to maximize the service quality by minimizing the total vessel servicing time required and the total vessel transfers cost induced, as shown in Equation (3.1-3.3).

DBAP-priority-RH model

The notations used in the mathematical model are shown in the following:

Input Data:

B set of berths in terminal, $B = \{1,2..I\}$

V set of vessels, $V = \{1,2..J\}$

v_j value of customer level for vessel j, $v_j = \{v^1, v^2, v^3\}$

e_j expected arrival time of the vessel j

h_j handling volume of vessel j

t_{ij} handling time of vessel j at berth i

a_i the first idle time of berth i in the planning horizon

λ_j coefficient of service time and vessel transfer of vessel j

α weighting of the total service time

β weighting of the total vessel transfer

L maximum waiting time for the incoming vessels

M a sufficient large positive number

In addition, $o(i)$ and $d(i)$ are introduced as the starting node and ending node at berth $i \in B$. $y_{o(i)}$ and $y_{d(i)}$ represent the starting time and ending time of the planning horizon of berth $i \in B$.

Variables:

s_j berthing time of vessel j

p_j service time of vessel j

c_j completion time of vessel j

Decision Variables:

$$x_{ijk} = \begin{cases} 1 & \text{if vessel } k \text{ served after vessel } j \text{ at berth } i \text{ at the orginal terminal} \\ 0 & \text{otherwise} \end{cases}$$

$$r_j = \begin{cases} 1 & \text{if vessel } j \text{ is transferred to the external terminal for serving} \\ 0 & \text{otherwise} \end{cases}$$

Objectives:

$$F_1 = \text{Min} \sum_{j=1}^{J} \lambda_j p_j \quad (3.1)$$

$$F_2 = \text{Min} \sum_{j=1}^{J} \lambda_j r_j [L + max\,\{t_{ij} : i \in B\}] \quad (3.2)$$

$$F_3 = \text{Min}\,\{\alpha F_1,\ \beta F_2\} \quad (3.3)$$

, where

$$p_j = \begin{cases} 0 & \text{, if vessel } j \text{ is transferred} \\ p_j = c_j - e_j & \text{, otherwise} \end{cases}$$

$$\lambda_j = v_j h_j \qquad , \forall j \in V$$

Constraints:

$$r_j + \sum_{i \in B} \sum_{k \in V \cup d(i)} x_{ijk} = 1 \qquad , \forall j \in V \qquad (3.4)$$

$$\sum_{k \in V \cup d(i)} x_{io(i)k} = 1 \qquad , \forall j \in V \qquad (3.5)$$

$$\sum_{j \in V \cup o(i)} x_{ijd(i)} = 1 \qquad , \forall j \in V \qquad (3.6)$$

$$\sum_{j \in V \cup o(i)} \sum_{n \in V \cup d(i)} (x_{ijk} - x_{ikn}) = 0 \qquad , \forall i \in B, \ \forall k \in V \qquad (3.7)$$

$$c_j = s_j + \sum_{i \in B} \sum_{k \in V \cup d(i)} x_{ijk} t_{ij} \qquad , \forall j \in V \qquad (3.8)$$

$$s_k \geq c_j - M \cdot (1 - x_{ijk}) \qquad , \forall i \in B, \forall j \in V \cup o(i), \ \forall k \in V \cup d(i) \qquad (3.9)$$

$$s_j - e_j \geq 0 \qquad , \forall j \in V \qquad (3.10)$$

$$s_k \geq a_i - M \cdot (1 - x_{io(i)k}) \qquad , \forall i \in B, \forall k \in V \cup d(i) \qquad (3.11)$$

$$L \geq (s_i - e_j) - M \cdot (1 - x_{ijk}) \qquad , \forall i \in B, \forall j \in V, \ \forall k \in V \cup d(i) \qquad (3.12)$$

$$x_{ijk} \in \{0,1\} \qquad , \forall i \in B, \forall j \in V \cup o(i), \ \forall k \in V \cup d(i) \qquad (3.13)$$

$$r_j \in \{0,1\} \qquad , \forall j \in V \qquad (3.14)$$

In this model, the scheduling of berth allocation that assigning Vessel k to Berth i after Vessel j is determined by the binary decision variable x_{ijk}. Another binary decision variable r_j is used to define the j^{th} vessel being transferred to another terminal for servicing.

Objective (3.1) aims to minimize the total vessel service time berthed at the original terminal, comprising the vessel waiting time and the vessel handling time, where the service time of vessel j (p_j) is equal to its completion time minus its expected arrival time or equal to zero if Vessel j is transferred. Objective (3.2) minimizes the cost of vessel transfers. To convert the value of the cost to the same attribute of Objective (3.1), it is defined as the summation of its maximum waiting and handling time. Objective (3.3) is a bi-objective function including Objectives (3.1) and (3.2), where λ_j is the coefficient of the service time and vessel transfer, considering the customer priority simultaneously. Constraint (3.4) assures that every vessel must either be served at a berth regardless of service order at the original terminal or transferred. Constraints (3.5) and (3.6) ensure the incoming and outgoing flows to each berth, and Constraint (3.7) ensures the flow conservation for the remaining vessels at the berth. Constraint (3.8) defines the completion time of each vessel served at the terminal. Constraint (3.9) ensure every vessel cannot berth earlier than the finishing time of the previous vessel at the same berth. Constraint (3.10) ensures no vessel can berth earlier than its estimated arrival time. Constraint (3.11) ensures the berthing time of the first served vessel at each berth must be on or after the first idle time of the assigned berth in the planning horizon. Constraint (3.12) ensures that the vessels berthed at a terminal cannot wait longer than the waiting time limit. Constraints (3.13) and (3.14) define x_{ijk} and r_j are binary variables.

3.3 Methodology: Genetic Algorithm for BAP (GA-BAP)

An optimization methodology framework for berth planning and vessel assignment is shown as in Figure 3.1. The framework consists of three main parts, including the Input Data (data gathering), GA (the optimization), and the output. GA-BAP is employed in the optimization part. Moreover, both terminal and vessel information are required for the optimization methodology, for examples, vessel arrival time, vessel handling volume, number of berths in the terminal, etc.

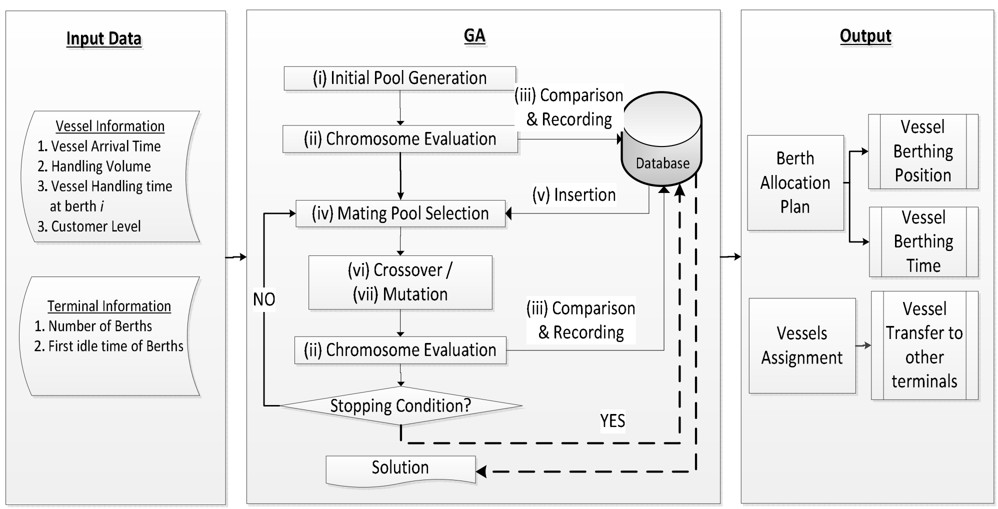

Figure 3.1 A GA-BAP methodology framework

3.3.1 Framework of the proposed algorithm

The proposed GA-BAP consists of 7 parts, (i) Initial Pool Generation, (ii) Chromosome Evaluation, (iii) Comparison and Recording, (iv) Selection, (v) Insertion, (vi) Crossover operation, and (vii) Mutation operation. First of all, a number of initial solutions are generated. Each solution is represented by a chromosome. These chromosomes form an initial pool, and are evaluated based on the objective function. Then, fitness value will be assigned to each chromosome afterwards. The chromosome with the highest fitness value is then compared with the one stored in the database. If the optimality of the chromosome is better than that of the stored chromosome, it will replace the one stored in the database. After that, the selection procedure is conducted to select a new set of chromosomes from the solution pool, to form a mating pool. The chromosome stored in the database is inserted into the mating pool by replacing the weakest chromosome. Genetic operations, either crossover or mutation, are then carried out. The iteration will stop until the pre-defined stopping condition. Finally, the best solution obtained will be the final solution.

3.3.2 Generation of Initial Pool and Chromosome Representation

A number of chromosomes (Q_1) will be randomly generated to form the initial solution pool. Figure 3.2 demonstrates the encoding and decoding of a chromosome by using a numerical example. It consists of (J+I) number of genes, and is divided into I segments separated by a character "0" to represent I berths. The position of each gene represents the vessel service order in the assigned berth, increasing from the left to the right. The example shows 5 vessels being allocated to 3 berths, in which Vessels 3 and 1 are being assigned to Berth 1, Vessel 2 is assigned to Berth 2 and so on. At Berth 3, Vessel 4 is served and is followed by Vessel 5.

		Chromosome							
Encoding:		3	1	0	2	0	4	5	0
Decoding:	Berth	1	1		2		3	3	
	Service Order	1	2		1		1	2	
	Vessels assigned to berths	3	1		2		4	5	

Figure 3.2 Encoding and decoding of the chromosome

In the case if a vessel is expected to wait longer than the waiting time limit, it will be immediately transferred to another terminal rather than waiting for 2 or more hours. For the example in Figure 3.2, Vessel 1 is being served at Berth 1. After calculation, if it is determined that the Vessel 1 will have to wait longer than 2 hours. Then, it will be transferred to the partner terminal for service.

3.3.3 Fitness Evaluation

The fitness values of the chromosome x is calculated by equation (3.15).

$$f(x) = 1 - [F_3(x) / \sum_{q=1}^{Q} F_3(q)] \quad (3.15)$$

, where $F_3(x)$ is the objective value of the chromosome x, and Q is the solution pool size of the GA-BAP.

The individual chromosome is evaluated by calculating its fitness value. The smaller the objective value, the higher the fitness can be.

3.3.4 Selection and Elitist Strategy

The selection methodology applied is the commonly used Roulette Wheel Selection approach. A probability is given to each chromosome according to its fitness value. The higher the fitness, the higher the probability is for the chromosome to be selected. It is similar to the concept of survival of the fittest. However, it is not a deterministic choice, and remains a probability. Therefore, a solution with a comparatively low fitness may still be chosen.

Elitist strategy is applied to avoid the loss of the best chromosome, which is recorded every time and inserted back into the mating pool to replace the weakest chromosome during the evolution.

3.3.5 Genetic Operations: Crossover

Uniform crossover with ratio *(3/(I+J))* is applied. Figure 3.3 shows an example in which the 2^{nd}, 3^{rd} and 4^{th} genes are randomly selected for crossover. After crossover, Chromosome (a), Vessel 2 has been assigned to berth more than once, while Vessel 4 is missing. In Chromosome (b), Vessel 4 has been assigned twice, while Vessel 2 is missing. Therefore, validation should be carried out by replacing the missing vessel(s) with the duplicated vessel(s).

Parents:	Chromosome (a)	5	1	4	0	3	0	2	0
	Chromosome (b)	3	2	0	1	0	4	5	0
After crossover									
Offspring:	Chromosome (a)	5	2	0	1	3	0	2	0
	Chromosome (b)	3	1	4	0	0	4	5	0
After validation									
Offspring:	Chromosome (a)	5	2	0	1	3	0	4	0
	Chromosome (b)	3	1	4	0	0	2	5	0

Figure 3.3 An example of crossover operations

3.3.6 Genetic Operations: Mutation

In order to avoid random searching, a low mutation ratio ($1/(J+1)$) is applied. A gene will be randomly selected and mutated to other values within [1-J]. Note that the separator "0" will not be selected for mutation. Figure 3.4 shows an example in which the 6th gene is randomly selected and mutated to a value of 2. However, after that, it becomes invalid. Therefore, the validation process will be carried out similar to the previous process in crossover.

Parents:	Chromosome	1	2	0	4	0	3	5	0
After mutation									
Offspring:	Chromosome	1	2	0	4	0	2	5	0
After validation									
Offspring:	Chromosome	1	3	0	4	0	2	5	0

Figure 3.4 An example of mutation operations

3.4 Numerical Experiments

This section aims to demonstrate the solution quality of the proposed GA-BAP and the significance of considering the proposed DBAP-priority-RH model. The proposed GA-BAP is programmed in JAVA language and run on a PC with a CPU of 1.33GHz and 4GB RAM.

3.4.1 Testing the optimization quality of the proposed algorithm: GA-BAP

First of all, the optimization performance of the proposed GA-BAP algorithm is verified by benchmarking with a similar model by Liang *et al.* in 2012, in which they consider direct transshipments between vessels as well. They proposed a hybrid multistage operation-based GA, and aimed at minimizing the total vessel service time and the total delay time. The testing model consists of 11 vessels being allocated to 4 berths with 7 QCs in total. The vessel information given by Liang *et al.* (2012) is shown in Table 3-1. A fixed numbers of QCs are assigned to berths, i.e. 3 QCs are assigned to Berth 1, 2 QCs are assigned to Berth 2, 1 QC is assigned to Berth 3, and 1 QC is assigned to Berth 4. The proposed GA-BAP algorithm is compared with them to test the solution quality. The GA is set as follows: the number of evolutions is set as 500, the crossover rate and mutation rate are as mentioned before.

The total service time(s) found by the proposed algorithm and by Liang *et al.* (2012) are 2772 minutes and 2837 minutes respectively. Both approaches have zero delay time. Figure 3.5 shows the Gantt chart of the solution found by the Liang *et al.* (2012) and by the proposed algorithm. Comparing the results, the proposed algorithm has around 2.3% reduction in total service time. It demonstrates that the proposed algorithm is capable of determining a better solution.

Table 3-1 Vessel information provided by Liang *et al.* (2012)

Vessel number	Arrival time	Depart time	Total number of handling volume (TEU)	Transshipment	
				Vessel number	Volume (TEU)
1	9:00	20:00	428		
2	9:00	21:00	455	8	150
3	0:30	13:00	259	5	200
4	21:00	23:50	172		
5	0:00	23:50	684	3	200
6	8:30	21:00	356		
7	7:00	20:30	435		
8	11:30	23:50	350	2	150
9	21:30	23:50	150		
10	22:00	23:50	150		
11	9:00	23:50	333		

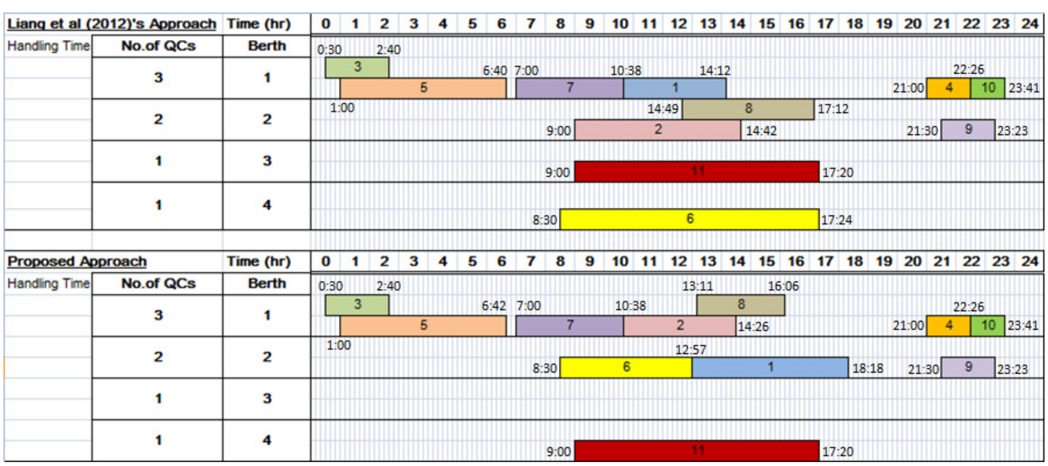

Figure 3.5 The Gantt charts of the solutions found by Liang *et al.* (2012) approach and the proposed GA-BAP approach

3.4.2 Significance of the proposed BAP-priority-RH model

The experiment here is to demonstrate the significance of the proposed BAP-priority-RH modeling approach which simultaneously considers customer importance and handling volume in determine the vessel service priority, towards the service quality of the terminal.

To have a detailed comparison of different possible scenarios in real terminal environments, a total of 75 sets of test data are generated by the parameters used in Tables 3-2, 3-3 and 3-4. A test problem size T = 20 is used. The number of berths (I) = 3. Each test data set is further divided according to the vessel arrival intervals (σ_1) and the customer types (σ_2). σ_1 represents the patterns of the vessel arrival intervals, where the test data sets will be randomly generated according to the patterns shown in Table 3-2. Each pattern has 25 sets of test data generated from loose to tight. σ_2 represents different compositions of customer types. Similarly, the test data sets are randomly generated according to the compositions shown in Table 3-3. Each composition has 15 sets of test data generated. The handling volume of each vessel is generated according to the percentages shown in Table 3-4. The maximum waiting time (L) at the terminal is still 2 hours.

Instead of selecting the non-dominating solutions, the objective here is to maximize the utilization of the terminals by minimizing the vessel transfer cost, while minimize the service time of vessels. Thus, the weighting of the service time and the vessel transfer are set as $\alpha = 0.1$ and $\beta = 0.9$ respectively. The solution pool size (Q_1) for GA-BAP is 10. The number of evolutions is 800, which is tested to be long enough to obtain a steady solution.

Table 3-2 Vessel arrival intervals

σ_1	Scenario	Vessel Arrival Interval (%)	Data Sets
1	Loose	($0 \leq V \leq 100$) min: 30 ($101 \leq V \leq 300$) min: 60 ($301 \leq V \leq 600$) min: 10	1-5, 16-20, 31-35, 46-50, 61-65
2	Normal	($0 \leq V \leq 100$) min: 60 ($101 \leq V \leq 300$) min: 30 ($301 \leq V \leq 600$) min: 10	6-10, 21-25, 36-40, 51-55, 66-70
3	Tight	($0 \leq V \leq 100$) min: 80 ($101 \leq V \leq 300$) min: 10 ($301 \leq V \leq 600$) min: 10	11-15, 26-30, 41-45, 56-60, 71-75

Table 3-3 Distribution of customer types

σ_2	Customer Types Distribution in %			Data Sets
	Level 1	Level 2	Level 3	
1 (Extreme)	80	10	10	1-15
2 (Extreme)	10	80	10	16-30
3 (Extreme)	10	10	80	31-45
4 (Normal)	30	40	30	46-60
5 (Normal)	40	20	40	61-75

Table 3-4 Handling volume percentage in data sets

Handling Volume	Percentage (%) of the Vessel
100 – 500 TEUs	30
501 – 2000 TEUs	40
2001 – 5000 TEUs	30

In this experiment, three more approaches are created for benchmarking. The first approach simulates one stream found in the literature which considers only customer relationships in determining vessel priority, named as Discrete Berth

Allocation Problem with Priority considering Customer Relationships (DBAP-priority-R). Similarly, the second approach simulates another stream which considers only handling volume in determining vessel priority, named as Discrete Berth Allocation Problem with Priority considering Handling Volume (DBAP-priority-H). The last approach is Discrete Berth Allocation Problem with First-Come-First-Served principle (DBAP-FCFS) that is a commonly applied approach in terminals in their daily operations, as mentioned by Imai et al. (2003) and Liang et al. (2009). For comparison, these three concerned performances are evaluated and analyzed including, (i) Customer Importance Fulfillment Index (CIFI), (ii) Average Service Time (AST), and (iii) Handling Volume (HV).

CIFI is proposed to indicate the percentage of important customers being served. This thesis proposes to define important customers as those with the upper customer level and with a large handling volume. Accordingly, each vessel will be given a priority value, which is calculated by its customer level (v_j) multiplied by its handling volume (h_j). CIFI is the total summation of the vessels being serviced. The weighting of the customer level is subjective and can be decided by the terminal operator. In this experiment, the weighting of the customer in Level 1 (v^1) = 1, in Level 2 (v^2) = 3, and in Level 3 (v^3) = 10. For AST, it is known to be an important measure for the efficiency of a terminal, and in addition, it can be used to measure the service quality provided to customers since it consists of waiting time and handling time. Short service time means the vessels can leave earlier and enhance their turnover ability. In addition, the terminal turnaround time can also be improved. AST at the home terminal is calculated by the sum of the service time for each vessel divided by the total number of containers handled. Therefore, the shorter the service time required per a container, the better the service quality it is. As mentioned, although servicing high level customers is important, it is known that the number of containers handled is also critical because it determines the terminal profitability. Figure 3.6 shows the trend of the results comparing among the four approaches in various scenarios, and Table 3-5 summarizes their average percentage changes of each performance.

(i) Customer Importance Fulfillment Index (CIFI)

Generally, the results show the percentage of fulfillment decreases when the interval gets tighter in all approaches. It means that more vessels cannot be served in the terminal and they have to be transferred. Among these, the proposed approach considering DBAP-priority-RH model outperforms the other three approaches in achieving higher fulfillment, while the DBAP-FCFS approach is the worst. It indicates that more important customers can be served by considering our proposed approach.

(ii) Average Service Time (AST)

Figure 3.6 shows that the DBAP-FCFS approach results in the shortest AST in many cases. However, the number of containers handled is much fewer than the other 3 approaches by 40-60%. It is also observed that AST of the other 3 approaches are similar. From Table 3-5, the maximum difference is only about 4%. Therefore, the efficiencies of the proposed approach considering the DBAP-priority-RH, DBAP-priority-R and DBAP-priority-H models are similar.

(iii) Handled Volume (HV)

As expected, the DBAP-FCFS approach performs the worst in HV. It can handle only half the volume handled by the other approaches. Since the DBAP-priority-H modeling focuses on maximizing the volume to be handled, it is not surprising that it can perform better in this attribute. However, the proposed DBAP-priority-RH modeling is found to be reliable in various situations. From Figure 3.6, in the extreme cases ($\sigma_2 = 1, 2, 3$), if one customer type is dominant, the proposed DBAP-priority-RH modeling will be able to achieve the performance of the DBAP-priority-H modeling. However, the DBAP-priority-R modeling will perform very poorly if low level customers dominate. In the normal cases ($\sigma_2 = 4, 5$), the performance of the proposed DBAP-priority-RH modeling is still as good as the DBAP-priority-R modeling and DBAP-priority-H modeling.

Overall, the DBAP-priority-H modeling concerns only the handling volume, representing good profitability. However, from Table 3-5, its CIFI is 4-8% lower than the proposed DBAP-priority-RH modeling. This means that DBAP-priority-H approach cannot service as many as important customers. For the DBAP-priority-R modeling, it only concerns the customer level, so is not sensitive to the volume. The handling volume is about 5-12% lower than the proposed DBAP-priority-RH modeling. Therefore, the DBAP-priority-R modeling will obtain solutions with low profitability. Although, AST of the proposed DBAP-priority-RH modeling is 1-4% longer than the DBAP-priority-R modeling, it can handle more containers, and can be applied in different situations. Moreover, the proposed DBAP-priority-RH modeling can serve more important customers (around 4-8%) than the DBAP-priority-H modeling, while providing the same efficiency, even when considering an extra factor.

Table 3-5 Average percentage changes of the three performances

Data Set	Average % change of CIFI				Average % change of AST				Average % change of HV			
	AP1	AP2	AP3	AP4	AP1	AP2	AP3	AP4	AP1	AP2	AP3	AP4
1-15	0	-5.92433	-8.00758	-46.1406	0	-1.16643	2.66114	31.30738	0	-12.7936	3.425443	-49.4133
16-30	0	-7.40967	-7.16292	-59.0134	0	-2.65336	-0.09811	29.77614	0	-9.51018	2.056721	-58.5433
31-45	0	-8.67612	-4.78421	-58.4719	0	-4.13495	-2.16904	26.72554	0	-7.97496	4.981227	-55.5579
46-60	0	-3.29712	-8.1958	-65.1753	0	-2.10223	0.24937	31.51102	0	-5.74468	4.401515	-51.9876
61-75	0	-3.42186	-8.01347	-62.0681	0	-2.47468	1.888356	33.83112	0	-9.35316	4.679873	-60.5889

****AP1 - [DBAP-priority-RH], AP2 - [DBAP-priority-R], AP3 - [DBAP-priority-H], AP4 - [DBAP-priority-FCFS]**

3.5 Summary

Scheduling of BAP is known to be difficult and critical to terminal operations because it determines terminals' productivity and profitability. In addition, it determines the service quality provided to the customers. In the literature, researchers give priority to vessels based on either of the two factors i) customer relationships with the terminal, and ii) vessel handling volume. In this chapter, a DBAP-priority-RH model was proposed to consider both factors simultaneously. For optimization, an algorithm GABAP was proposed. The optimization performance of the proposed algorithm has been verified by comparing the results with the existing test data found in the literature. Another 75 sets of test data have also been created in the numerical experiments to test the significance of considering both factors in determining vessel priority. Three additional approaches have been created for comparisons with the proposed approach, including the DBAP-priority-R modeling for considering only customer levels in vessel priority, the DBAP-priority-H modeling for considering only handling volume in vessel priority, and the commonly used first-come-first-served approach (DBAP-FCFS). The results demonstrated that if either the customer level or its handling volume only is considered, the other will be affected significantly. The proposed approach is able to make a trade-off between them. The results also indicated that the proposed approach as efficiency as the DBAP-priority-R modeling and the DBAP-priority-H modeling. Meanwhile, it could serve more important customers than the other approaches. The proposed DBAP-priority-RH modeling is sensitive to various situations, so that it can make good adjustments in improving handling capacity, providing good customer service quality, and maintaining good profitability.

In this chapter, position based vessel handling time was assumed in our approach for the ease of modeling. In fact, vessel handling time mainly depends on the number of QCs assigned to a vessel. In this connection, vessel handling time in BAP will be studied with the consideration of another resource planning problem – QCAP in the next chapter.

**AP1 - [DBAP-priority-RH], AP2 - [DBAP-priority-R], AP3 - [DBAP-priority-H], AP4 - [DBAP-priority-FCFS]

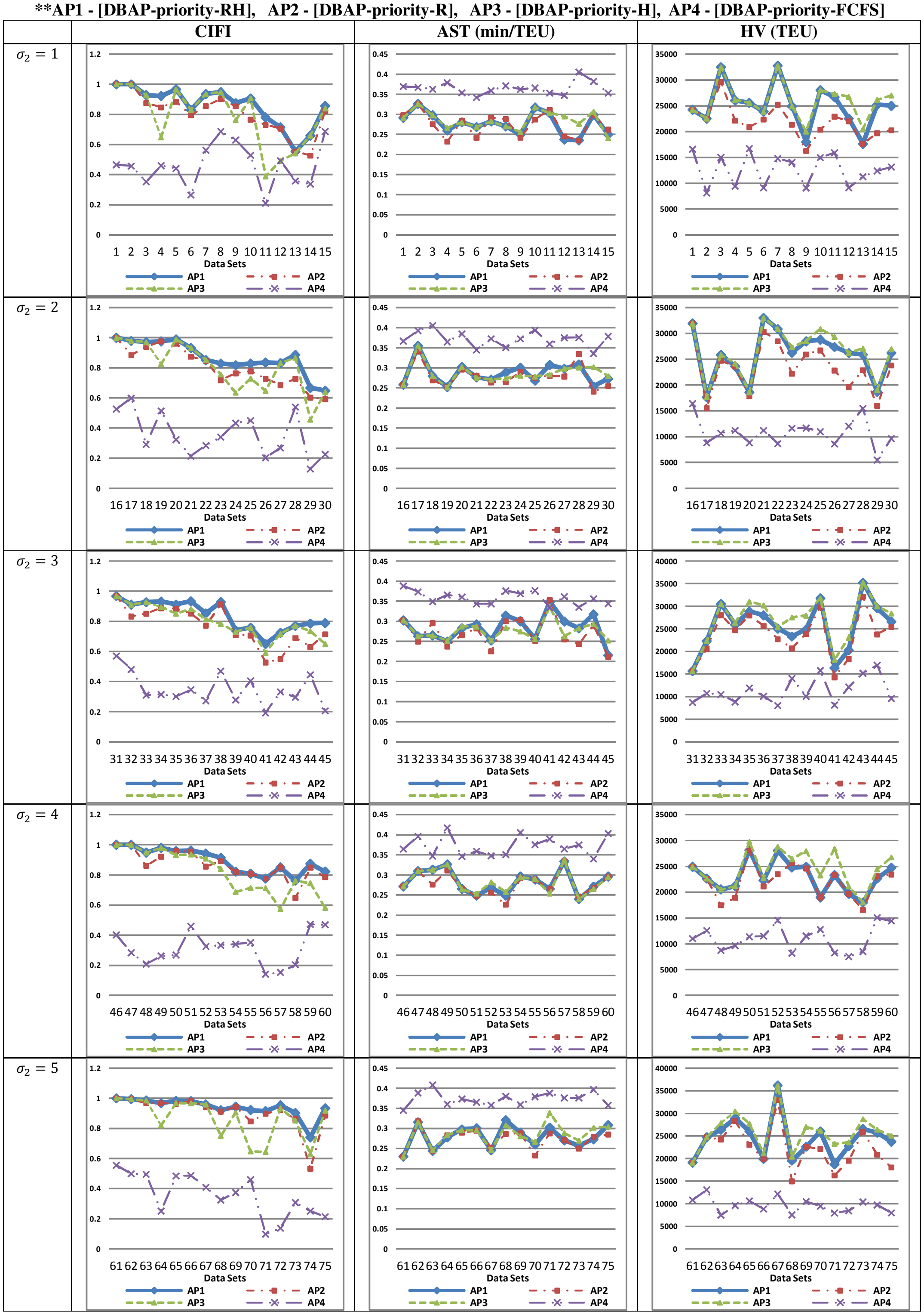

Figure 3.6 Optimization results of the 75 test data sets

Chapter 4 Integrated Berth Allocation with Quay Crane Assignment Problem

4.1 Introduction

Traditionally, vessel handling time in BAP is always assumed to be constant or depends on the berthing position like the model mentioned in the previous chapter. Recently, more attention has been attracted by researchers on the integrated Berth Allocation and QCAP named BA-QCAP here. BAP and QCAP in fact are highly interrelated. QCAP refers to the problem of assigning a number of QCs to a vessel for handling containers. In more specific, the QCAP determines vessel handling time in the BAP, while the BAP provides essential information to the QCAP.

Many methodologies have been proposed to deal with this integrated problem (Chang *et al.*, 2010, Liang *et al.*, 2009, Raa *et al.*, 2011, Yang *et al.*, 2012, Zhang *et al.*, 2010). Among them, Liang *et al.* (2009) developed a hybrid evolutionary algorithm for solving a real case in one of the Shanghai container terminals in China. They proposed a methodology that can be used in practical situations, and provided a complete set of data for comparisons. It is common in the literature to deal with this integrated problem by a single GA approach. However, it may be too complicated to obtain a good solution by such approach. In addition, the number of evolutions required to obtain a steady solution may be very long.

In this connection, a new algorithm named Two-Level Genetic Algorithm (TLGA) is proposed to deal with it. It aims to minimize the total waiting time, the total handling time and the total delay time. Comparing to the existing algorithms found in the literature, the proposed TLGA decomposes the integrated problem into a master quay crane assignment problem and a vessel scheduling sub-problem, and solved them by two interrelated GAs. This approach can greatly improve the searching ability to enhance the optimization result, and reduce computational time by reducing the problem complexity. The data set and the computational results provided by Liang *et al.* (2009) have been used for comparison in one of the experiments to test the solution quality of the proposed TLGA. The traditionally used Single Genetic Algorithm (SGA) has also been used as a second comparison in the experiments. The experimental results demonstrate that the proposed TLGA is more efficient in solving the integrated problem. It obtains a better solution in a shorter period of time. The total vessel handling time, waiting time and delay time are reduced. In addition, the utilization of each berth is improved, which enhances the competitiveness of the terminal.

4.2 Mathematical modeling for Discrete Berth Allocation Problem and Quay Crane Assignment (DBAP-QCA)

This section presents a mathematical DBAP-QCA model. In which, the terminal is in discrete berth layout. Only one vessel is allowed to be served in each berth at a time. A fixed arrival time is given to each vessel. Hence, vessels cannot be berthed before the expected arrival time.

DBAP-QCA model

Notations used in the model are shown as follows:

Input Data:

B set of berths in terminal, $B = \{1,2..I\}$

V set of vessels, $V = \{1,2..J\}$

R set of QCs in terminal, $R = \{1,2..Q\}$

e_j expected arrival time of the vessel j

h_j handling volume of vessel j

E QC productivity (volume / QC/ min)

D_j due departure time of vessel j

$Maxq$ maximum number of QCs that can be assigned to each vessel

Q total number of QCs in terminal

In addition, $o(i)$ and $d(i)$ are introduced as the starting node and ending node at berth $i \in B$. $s_{o(i)}$ and $s_{d(i)}$ represent the starting time and ending time of the planning horizon of berth $i \in B$.

Decision variables:

s_j berthing time of vessel j

c_j completion time of vessel j

w_j waiting time of vessel j

y_i number of QCs assigned to berth i

p_{jq} handling time of vessel j served with q number of QCs

x_{ijk} set to 1 if vessel k is served after vessel j at berth i, and 0 otherwise

QB_{iq} set to 1 if q number of QCs are assigned to berth i, and 0 otherwise

QV_{ijq} set to 1 if q number of QCs are assigned to vessel j at berth i, and 0 otherwise

$$\text{Min } z = \sum_{j \in V}\left(\sum_{i \in B}\sum_{z \in R} QV_{ijz}\, p_{jz} + w_j + \max\{0, (c_j - D_j)\}\right) \quad (4.1)$$

,where

$$w_j = s_j - e_j$$

$$p_{jq} = h_j / E \cdot y_i$$

$$\sum_{i \in B}\sum_{k \in V \cup d(i)} x_{ijk} = 1, \qquad \forall j \in V \quad (4.2)$$

$$\sum_{k \in V \cup d(i)} x_{io(i)k} = 1, \qquad \forall i \in B \quad (4.3)$$

$$\sum_{j \in V \cup o(i)} x_{ijd(i)} = 1, \qquad \forall i \in B \quad (4.4)$$

$$\sum_{j \in V \cup o(i)}\sum_{n \in V \cup d(i)} (x_{ijk} - x_{ikn}) = 0, \qquad \forall i \in B, \forall k \in V \quad (4.5)$$

$$c_j = s_j + \sum_{i \in B}\sum_{q \in R} QV_{ijq}\, p_{jq}, \qquad \forall j \in V \quad (4.6)$$

$$s_j - e_j \geq 0, \qquad \forall j \in V \qquad (4.7)$$

$$s_k \geq c_j - N \cdot (1 - x_{ijk}), \qquad \forall i \in B, \forall j \in V \cup o(i), \ \forall k \in V \cup d(i) \qquad (4.8)$$

$$y_i \leq Maxq, \qquad \forall i \in B \qquad (4.9)$$

$$\sum_{i \in B} y_i \leq Q, \qquad (4.10)$$

$$\sum_{q \in R} q \cdot QB_{iq} = y_i, \qquad \forall i \in B \qquad (4.11)$$

$$\sum_{q \in R} QV_{ijq} = \sum_{k \in V \cup d(i)} x_{ijk}, \qquad \forall i \in B, \forall j \in V \qquad (4.12)$$

$$(1 - \sum_{k \in V \cup e(i)} x_{ijk})N + QV_{ijq} \geq QB_{iq}, \qquad \forall i \in B, \forall j \in V, \forall q \in R \qquad (4.13)$$

$$\sum_{i \in B} \sum_{q \in R} QV_{ijq} = 1, \qquad \forall j \in V \qquad (4.14)$$

The scheduling of berth allocation that assigning Vessel k to Berth i after Vessel j is determined by the binary decision variable x_{ijk}. The number of QCs assigned to Berth i is decided by decision variable y_i.

Objective (4.1) minimizes the sum of the handling time, waiting time, and the delay time for each vessel. Constraint (4.2) ensures each vessel must be served once at the berth and each berth serves up to one vessel at any time. Constraints (4.3) and (4.4) ensure the incoming and outgoing flows to each berth, and Constraint (4.5) ensures the flow conservation for the remaining vessels at the berth. Constraint (4.6) defines the calculation of the completion time of each vessel, while Constraints (4.7) and (4.8) ensure no vessel will berth before its arrival time and the completion time of the previous vessel. Constraint (4.9) ensures the number of QCs assigned to each berth will not exceed the maximum number of QCs that can be assigned to each vessel. Constraint (4.10) ensures the total number of QCs assigned to the berths cannot exceed the total number of QCs available in the terminal. Constraints (4.11 – 4.13) ensure the consistency of the variables. Constraint (4.14) ensures a number of QCs is assigned to each vessel.

4.3 Methodology: Two-Level Genetic Algorithm (TLGA)

The integrated planning problem mainly consists of two parts, i) BAP and ii) QCAP. BAP is a kind of two-dimensional stock-cutting problem (Park and Kim, 2003), which is an NP-hard problem (see references for detail), and the GA is widely used as an effective heuristic for solving this kind of problem (Chang *et al.*, 2010; Kozan and Preston, 1999; Park and Kim, 2003; Tavakkoli *et al.*, 2009). Thus, a genetic based algorithm called TLGA is designed to decompose this integrated problem into BAP and QCA problems, and to solve them in an iterative approach. The framework of the proposed method is presented in Figure 4.1.

The TLGA algorithm consists of two levels. The first level determines the number of QCs assigned to each berth by a GA, hereafter called Quay Crane Assignment Genetic Algorithm (QCAGA). It is the master problem since it directly confines the container handling capability for each berth. The QCA-chromosome will store the information of the QC assignments. The second level, hereafter called Vessel Scheduling Genetic Algorithm (VSGA), is used for vessel schedule and allocation solution by another GA. This will be the sub-problem and the solution determined will feedback into the master problem for further process. The following describes the procedure of the TLGA algorithm:

Step 1: To start with, a pool of initial solutions for the QCAGA will be formed (mechanism presented in section 4.3.1). A number of QCA-chromosomes will be randomly generated according to a pre-defined solution pool size.

Step 2: Each QCA-chromosome, acting as input data, will be individually passed to the VSGA.

Step 3: In the VSGA, a number of VS-chromosomes will be randomly generated to form an initial solution pool (details in section 4.3.1). Then, Steps 3a – 3c will be carried out until the stopping condition is reached, and the best VS-chromosome found during the evolutions will be recorded.

Step 3a: Fitness value evaluation for the VS-chromosomes with the corresponding QCA-chromosome (details in section 4.3.2).

Step 3b: Formation of the mating pool by using the conventional roulette wheel selection approach. To avoid the loss of the best chromosome, elitist strategy is also applied. Elitist strategy is to record the best chromosome and insert back into the mating pool to replace the weakest chromosome in the next evolution.

Step 3c: Genetic Operations – Uniform crossover and mutation for the VS chromosome (details in section 4.3.3).

Step 4: The best obtained VS chromosome from Step 3 will be fed into the QCAGA.

Step 5: The fitness of the QCA-chromosomes can then evaluated (details in section 4.3.2).

Step 6: The mating pool for the QCAGA will be formed by randomly selecting a number of QCA-chromosomes by using the traditional roulette wheel selection approach with elitist strategy.

Step 7: Genetic Operation – Uniform crossover and mutation for the QCAGA chromosome (details in section 4.3.3).

Step 8: Check if the stopping condition is reached. If not, repeat Steps 2 – 7. Otherwise, record the best solution of the QC assignment with the vessel schedule.

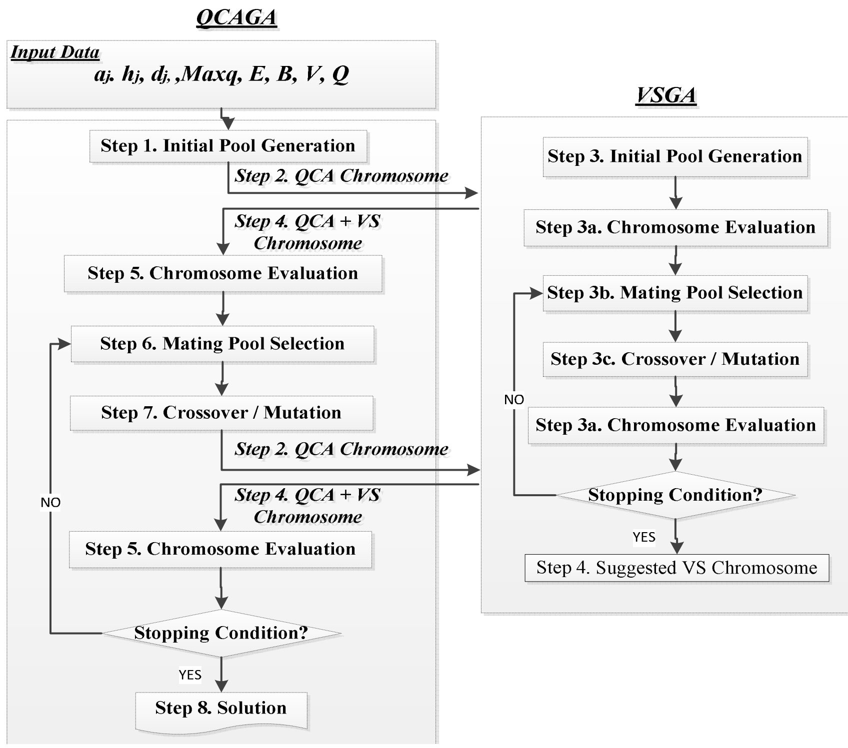

Figure 4.1 The framework of TLGA

For example, Figure 4.2 show the assignment of 5 vessels into 3 berths with a total of maximum 8 QCs (with productivity rate = 0.5 TEU/min). First of all, in QCAGA part, assuming the solution pool size is 4. Therefore, 4 QCA-chromosomes will be randomly generated to form the initial pool, such as 3-2-3, 4-3-2, 2-3-3, and 1-3-4. Then each of these chromosomes will pass to the VSGA to determine an optimal vessel scheduling. Assuming the solution pool size is also 4. Then, 4 VS-chromosomes will be randomly generated, such as 1-2-0-3-4-0-5, 4-0-2-3-5-0-1-0, 0-0-1-2-4-5-3-0, and 1-5-3-0-4-0-2-0. For example with the QCA information of the first QCA-chromosome (3-2-3), the fitness value of each VS-chromosome can be calculated. Then, formation of mating pool, crossover, and mutation can be carried out until the stopping condition is met. After that, the best vessel sequencing solution (VS-chromosome e.g. 1-2-5-0-4-0-3-0) can be found corresponding to the QCA-chromosome (3-2-3). After that, the second QCA-chromosome (4-3-2) will pass into the VSGA, and the aforementioned steps will be carried out again. The rest of the QCA-chromosome will be passed into VSGA one by one until all are passed.

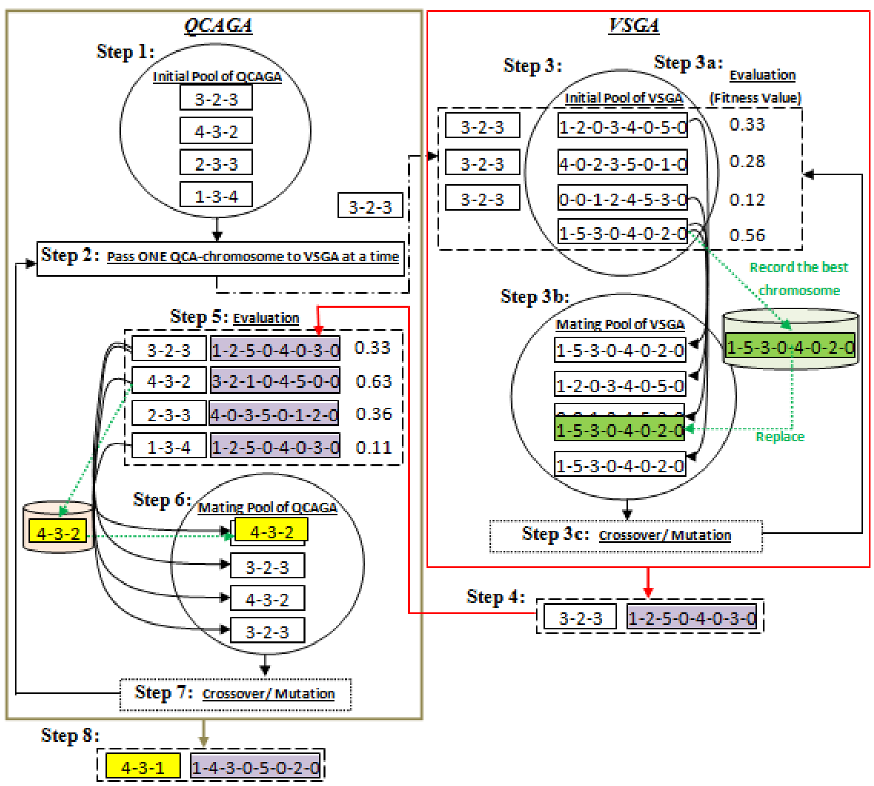

Figure 4.2 Examples of the execution process of TLGA

4.3.1 Generation of Initial Pool and Chromosome Representation

In the QCAGA, QCA-chromosomes are represented by character strings as shown in Figure 4.3. It consists of *I* genes. The position of each gene represents the berth number (Berth *i*), increasing from the left to the right. The value of the gene represents the number of QCs being assigned to that berth. The example demonstrates the encoding of 18 QCs being assigned to 3 berths, i.e. 6 QCs are assigned to Berth 1, 8 QCs to Berth 2, and 4 QCs to Berth 3.

Encoding	QCA-Chromosome	6-8-4
	Berth *i*	1-2-3

Figure 4.3 Encoding of a chromosome in QCAGA

In the VSGA, VS-chromosomes are represented by character strings as shown in Figure 4.4. It is used to represent the Vessel-Berth assignment and the service order of each vessel in the assigned berth. It consists of (*I*+*J*) number of genes and is divided into *I* segments separated by a character "0" to represent *I* berths. The value of the gene represents the vessel number. In Berth 1, Vessel 1 is the first vessel being assigned. The service order is defined from the left to the right. The latter vessel has to wait unit the previous vessel was completed its job.

Encoding	VA-Chromosome	1-3-4-8-0-9-5-7-0-2-6-10-0
	Berth *i*	1-1-1-1-0-2-2-2-0-3-3-3 -0
	Service Order *k*	1-2-3-4-0-1-2-3-0-1-2-3 -0

Figure 4.4 Encoding of a chromosome in VSGA

4.3.2 Fitness Evaluation

Each chromosome is evaluated by a fitness value which is calculated by fitness function (4.15). This function is an inverse function of the objective function. Hence, the smaller the objective value, the higher the fitness value can be. The fitness value represents the relative strength of the chromosome to the others in the same solution pool.

$$f(x) = 1 - \left(\frac{z(x)}{\sum_{n=1}^{N} z(n)}\right) \tag{4.15}$$

, where $z(x)$ is the objective value of the chromosome x, and N is the initial solution pool size of GA.

4.3.3 Genetic Operations: Crossover

Uniform crossover is applied in both the QCAGA and the VSGA. In the QCAGA, two values (α and β) are involved. The first value (α) represents the number of genes involved in crossover, which depends on the crossover rate of the QCAGA and should be smaller than I. The second value (β) represents the position of the gene for starting crossover. It is randomly generated within [1 to $(I - \alpha + 1)$]. Figure 4.5 shows an example for crossover in the QCAGA, in which $\alpha = 2$ and $\beta = 2$, so the 2nd and 3rd genes are selected for crossover between Chromosome (A) and Chromosome (B). After crossover, the number of QCs assigned to berths in Chromosome (A) changes to 6-6-8, and Chromosome (B) changes to 4-8-4. Since the total number of QCs is not equal to 18, a validation for

QCAGA will be carried out to ensure the total number of QCs is the same as the original value. In the validation, the adjustment will start from the last gene of the chromosome. Therefore, the value of the third gene will be changed from 8 to 6 in Chromosome (A), and will be changed from 4 to 6 in the one in Chromosome (B) accordingly.

In the VSGA, α and β are also involved, in which α depends on the crossover rate of the VSGA and should be smaller than $(I + J)$, while β is randomly generated within [1 to $(I + J - \alpha + 1)$]. Figure 4.6 shows an example for the crossover in the VSGA, in which $\alpha = 3$ and $\beta = 3$, so the 3rd , 4th and 5th genes are selected for crossover between Chromosome (C) and Chromosome (D). After crossover, Chromosome (C) represents three vessels assigned to the Berth 1 in the order of Vessels 1, 3 and 4. In Chromosome (D), 4 vessels are assigned to the Berth 1 in the order of Vessels 1, 2, 4 and 8. A validation for VSGA will then be conducted in these chromosomes to ensure all the vessels must be assigned only once. In Chromosome (C), the Vessel 3 is assigned more than once whereas Vessel 8 has not been assigned. Therefore, the duplicated Vessel 3 in Berth 1 will be replaced by the missing Vessel 8. Similarly, the duplicated Vessel 8 in Berth 3 will be replaced by the missing Vessel 3 in Chromosome (D).

Before crossover:

QCA-Chromosome (A)	6-**8-4**
QCA-Chromosome (B)	4-**6-8**

After crossover:

QCA-Chromosome (A)	6-**6-8**
QCA-Chromosome (B)	4-**8-4**

After validation:

QCA-Chromosome (A)	6-6-**6**
QCA-Chromosome (B)	4-8-**6**

Figure 4.5 An example of crossover in QCAGA

Before crossover:

VS-Chromosome (C)	1-3-**4-8-0**-9-5-7-0-2-6-10-0
VS-Chromosome (D)	1-2-**4-0-3**-5-9-7-0-6-8-10-0

After crossover:

VS-Chromosome (C)	1-3-**4-0-3**-9-5-7-0-2-6-10-0
VS-Chromosome (D)	1-2-**4-8-0**-5-9-7-0-6-8-10-0

After validation:

VS-Chromosome (C)	1-**8**-4-0-3-9-5-7-0-2-6-10-0
VS-Chromosome (D)	1-2-4-8-0-5-9-7-0-6-**3**-10-0

Figure 4.6 An example of crossover in VSGA

4.3.4 Genetic Operations: Mutation

Mutation is another genetic operation in both the QCAGA and the VSGA, in which only a single chromosome is involved. In QCAGA, a number of genes are selected for mutation based on the mutation rate of QCAGA, and the positions of the genes are randomly decided. The value stored inside these genes will then be randomly changed to a value within [1 – Q]. For example in Figure 4.7, the 2nd gene is randomly selected for mutation. A random number (e.g. 7) is generated to replace the value originally stored in the second gene. After mutation, if the total number of QCs assigned is not equal to 18, the chromosome becomes invalid. Then validation will be carried out as in the crossover. Thus in the example, the number of QCs assigned to Berth 3 will change from 8 to 5.

Before mutation:

QCA-Chromosome	6-**4**-8

After mutation:

QCA-Chromosome	6-**7**-8

After validation:

QCA-Chromosome	6-7-**5**

Figure 4.7 An example of mutation in QCAGA

In VSGA, a number of genes are selected for mutation based on the mutation rate of VSGA, and the positions of these genes are randomly decided, but do not include the genes with character "0". The value stored inside the gene will then be randomly changed to a value within [1 – *J*]. For example in Figure 4.8, the sixth gene is randomly being selected for mutation, and a random number (e.g. 3) is generated to replace the original value. After mutation, the chromosome becomes invalid because Vessel 3 has been assigned twice, and Vessel 5 has not been assigned. Therefore, validation will be carried out to change another Vessel 3 to the missing Vessel 5.

Before mutation:

VS-Chromosome	1-2-4-8-0-**5**-9-7-0-6-3-10-0

After mutation:

VS-Chromosome	1-2-4-8-0-**3**-9-7-0-6-3-10-0

After validation:

VS-Chromosome	1-2-4-8-0-3-9-7-0-6-**5**-10-0

Figure 4.8 An example of mutation in VSGA

4.4 Numerical Experiments

The main objective of the numerical experiments is to test the optimization performance of the proposed TLGA algorithm. First of all, the solution quality will be verified by comparing with CPLEX and the traditional SGA. Then, the TLGA algorithm will be applied in a case study and compared with three existing approaches found in the literature, including i) the traditional SGA, ii) the approach by Liang and Gen (2006), iii) the approach by Liang *et al.* (2009). The TLGA, SGA and the approach by Liang and Gen (2006) is assigning QCs to berths, while the approach by Liang *et al.* (2009) is assigning QCs to vessels.

The proposed TLGA is programmed in JAVA language and run on a PC with CPU 1.33GHz and 4GB RAM. The solution pool sizes for QCAGA and VSGA are both 10. The crossover and mutation rates QCAGA and VSGA are set as 0.3 and 0.1 respectively. A low crossover rate is applied in order to avoid random searching. This is especially important for QCAGA since it is the master problem and is controlling the global search of the algorithm.

4.4.1 Testing the optimization quality of the proposed algorithm: TLGA

To provide a comprehensive analysis, 27 data sets representing small (T = 10), medium (T =20), and large (T = 50) problem scales are systematically generated. The problems have two characteristics in terms of the vessel arrival pattern and the vessel handling volume, reflecting different situations in a terminal. Each of the characteristics is further divided into 3 levels. For the arrival pattern: loose, normal, and tight. For the handling volume: light, normal, and heavy. To define the levels of the arrival pattern, the maximum arrival interval is defined. It is equal to:

$$\text{Maximum arrival interval} = \frac{\text{the duration of the planning horizon} \times \text{the total number of berths}}{\text{the total number of the vessels}} \tag{4.16}$$

For example, in a 24 hours planning horizon for 10 vessels in 4 berths, the maximum arrival interval = 24 hours / 10 vessels × 4 berths = 9.6 hours. After determining the maximum arrival interval, vessels are assigned to 4 berths. In each berth, the arrival interval between two vessels is (90±10)% of the maximum arrival interval and is classified as loose, (70±10)% of that as normal, and (50±10)% of that as tight. To define the levels of the handling volume, the maximum handling capacity in a planning horizon is first determined.

Maximum handling capacity = (the total QC productivity per time unit × the duration of the planning horizon). (4.17)

For example, in a 24 hours planning horizon, a terminal with 8 QCs and the QC productivity (E) is assumed to be 0.667×60 = 40.2 TEU/hour. The maximum handling capacity is = 8 QCs × 40.2 TEU/hour × 24 hours = 7683.84 TEU. In this experiment, the data relating to the configuration of the terminal are decided according to the real case provided by Liang *et al.*, (2009), i.e. the number of berths and QCs involved in the planning and the QC productivity. It is assumed that the terminal will not handle more than its maximum handling capacity. Hence, the maximum handling volume per each vessel can be estimated by the maximum handling capacity (7683.84 TEU) over the total number of vessels (e.g. 10) = 768.3 TEU/vessel. A vessel with (90±10)% of the maximum handling capacity is regarded as having a heavy volume, (70±10)% as normal volume, and (50±10)% as light volume. A set of combinations of these characteristics are shown in Table 4-1 to represent different scenarios, and the data sets of the combinations are generated for each problem scale.

In this experiment, both the proposed TLGA and the traditional SGA are tested and compared with the optimal solution obtained by CPLEX. The results are summarized in Table 4-2. For small scale problems (J=10), all three approaches can obtain the same solutions. Both TLGA and SGA are able to obtain the optimal solution faster than CPLEX, and TLGA obtains it slightly faster than SGA in all scenarios. From the results, it is also observed that the problem complexity is greatly increased with the increasing of handling volume, and the computational time used by CPLEX varies from 3.06 sec to 1196.2 sec, while there are no increment occurred in the GA based approaches. For the medium scale problems, CPLEX can only find the optimal solutions in Scenarios 1 (loose-light) and 4 (normal-light). For the remaining scenarios, no optimal solution can be found within 15 hours. For Scenarios 1 and 4, the computational time required by CPLEX in solving the medium scale problem is around 4000 to 5000 times more than that in solving the small scale problems. Although the total handling volume does not change much, as it is limited by the maximum handling capacity, the problem complexity still can be enormously increased when the number of vessels is increased. This increment also affects the performance of TLGA algorithm and SGA algorithm, but the effect is relatively small.

Compared to the small scale problems, both TLGA and SGA in the medium scale problems (J=20) require more evolutions to achieve a steady solution state, and their computational times are increased by 3 and 5 times respectively. From the results, TLGA and SGA are able to obtain optimal solution in Scenarios 1 and 4, and TLGA is 2.44 times faster than SGA on average. However, for Scenarios 3, 5, 8 and 9, SGA cannot find solutions as well as TLGA.

For the large scale problems (J=30), clearly it is the most complicated problem set, and CPLEX is not able to find a solution. It is also more difficult for the SGA to achieve its steady solution state, and therefore the computational time increases exponentially. The results show that TLGA outperforms SGA in both the computational time and solution quality by 2-6% and 94-97 %, respectively.

Generally speaking, these experiments demonstrate that the proposed TLGA outperforms the traditional SGA in all scenarios in terms of computational time and solution quality.

Table 4-1 The performance of TLGA and SGA

(*T*)	Data Set	(S)	CPLEX		SGA		TLGA			
			Z (min)	time (s)	Z (min)	time (s)	Z (min)	time (s)	(% change) comparing to SGA: Z	(% change) comparing to SGA: time (s)
(10) Vessels = Small size	**1**	**1**	1644.25	4.31	1644.25	3.72	1644.25	2.12	0.00	-43.01
	2	**2**	2615.02	4.43	2615.02	3.54	2615.02	2.28	0.00	-35.59
	3	**3**	3619.16	63.41	3619.16	3.57	3619.16	2.31	0.00	-35.29
	4	**4**	1512.95	3.06	1512.95	3.42	1512.95	2.08	0.00	-39.18
	5	**5**	2364.99	5.69	2364.99	3.59	2364.99	2.27	0.00	-36.77
	6	**6**	3523.17	56.96	3523.17	4.01	3523.17	2.34	0.00	-41.65
	7	**7**	1669.50	14.58	1669.50	3.51	1669.50	2.23	0.00	-36.47
	8	**8**	2798.31	185.28	2798.31	3.53	2798.31	2.30	0.00	-34.84
	9	**9**	4462.33	1196.23	4462.33	3.56	4462.33	2.28	0.00	-35.96
(20) Vessels = Medium size	**10**	**1**	1825.59	18617.14	1825.59	18.87	1825.59	7.93	0.00	-57.98
	11	**2**	---	---	3075.22	17.98	3075.22	7.84	0.00	-56.40
	12	**3**	---	---	3913.89	18.91	**3845.30**	7.25	-1.75	-61.66
	13	**4**	1786.36	17595.32	1786.36	18.23	1786.36	7.23	0.00	-60.34
	14	**5**	---	---	3337.89	18.18	**3328.46**	7.8	-0.28	-57.10
	15	**6**	---	---	8272.20	18.81	8272.20	7.67	0.00	-59.22
	16	**7**	---	---	2003.35	18.39	2003.35	7.24	0.00	-60.63
	17	**8**	---	---	6506.99	18.43	**6492.48**	7.23	-0.22	-60.77
	18	**9**	---	---	12067.13	18.51	**12018.57**	7.29	-0.40	-60.62
(50) Vessels = Large size	**19**	**1**	---	---	8094.47	1082.70	**7827.47**	42.45	-3.30	-96.08
	20	**2**	---	---	11387.25	1090.32	**11010.16**	43.84	-3.31	-95.98
	21	**3**	---	---	17389.96	1076.52	**16429.28**	40.10	-5.52	-96.28
	22	**4**	---	---	8290.043	1075.08	**8050.12**	42.62	-2.89	-96.04
	23	**5**	---	---	13604.51	1093.98	**13114.38**	43.02	-3.60	-96.07
	24	**6**	---	---	22948.72	1086.66	**22060.28**	43.60	-3.87	-95.99
	25	**7**	---	---	9477.28	1080.18	**9161.86**	42.28	-3.33	-96.09
	26	**8**	---	---	18340.12	1099.50	**17641.07**	42.17	-3.81	-96.16
	27	**9**	---	---	32619.81	1090.74	**30671.30**	43.88	-5.97	-95.98

Table 4-2 Different scenarios of terminal situation

Scenario (*S*)	Arrival pattern	Handling volume
1	Loose	Light
2	Loose	Normal
3	Loose	Heavy
4	Normal	Light
5	Normal	Normal
6	Normal	Heavy
7	Tight	Light
8	Tight	Normal
9	Tight	Heavy

4.4.2 Case study on a Shanghai container terminal (Liang *et al.*, 2009)

In this experiment, the benchmarking data set provided by the Shanghai container terminal in China is used, consisting of 11 vessels as summarized in Table 4-3 (Liang *et al.*, 2009). There are 4 discrete berths and 7 QCs, and it is regarded as a small scale problem. The QC productivity (E) is 0.667 TEU/min. For this problem scale, 10 evolutions for QCAGA and 30 evolutions for VSGA are sufficient to obtain a steady solution, and the computational time is around 3 seconds.

Figure 4.9 and Table 4-4 show the optimization results obtained by different approaches. Figure 4.9 shows that the proposed TLGA reaches its steady state at around 80 evolutions, while the traditional SGA reaches its steady state at around 240 evolutions. In this example, our proposed approach can obtain a solution around 3 times faster than SGA.

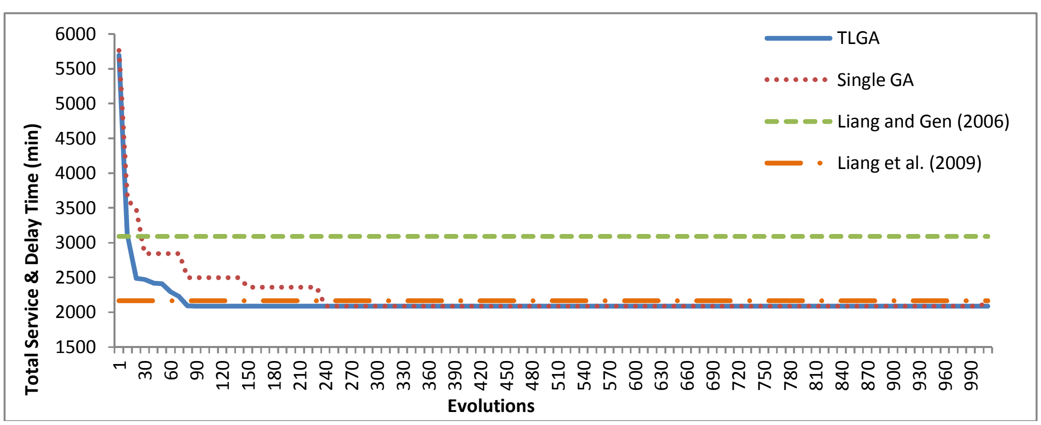

Figure 4.9 The optimization performance of different approaches

Table 4-3 Vessels Information provided by Liang *et al.*, (2009)

	Vessel name	Expected Arrival time	Due Departure time	Total number of loading / unloading containers (TEU)
1	MSG	9:00	20:00	428
2	NTD	9:00	21:00	455
3	CG	0:30	13:00	259
4	NT	21:00	23:50	172
5	LZ	0:30	23:50	684
6	XY	8:30	21:00	356
7	LZI	7:00	20:30	435
8	GC	11:30	23:50	350
9	LP	21:30	23:50	150
10	LYQ	22:00	23:50	150
11	CCG	9:00	23:50	333

Table 4-4 shows that the proposed TLGA and the traditional SGA can obtain a new best solution with the shortest total waiting time and handling time. The TLGA outperforms the approach by Liang and Gen (2006) and Liang *et al.* (2009) by 32% and 3 % respectively.

The solutions obtained by the Liang *et al.* (2009) approach and TLGA are plotted as in Figures 4.10 and 4.11 respectively. The Liang *et al.* (2009) approach finished the tasks at 23:02 hours, and the proposed TLGA finished at 23:01 hours. Although the completion times for both approaches are close, the assignment of vessels by the Liang *et al.* (2009) approach occupies four berths. However, for the proposed TLGA, only two berths are required (Berths 1 and 3), and other two berths (Berths 2 and 4) can be reserved for other usage. Therefore, the solution obtained by the proposed TLGA approach shows good utilization of the berths.

Table 4-4 Result Comparisons

	TLGA (QCs assigned to Berths)	**SGA** (QCs assigned to Berths)	**Liang and Gen (2006)** (QCs assigned to Berths)	**Liang *et al.* (2009)** (QCs assigned to Vessels)
Total service time (min)	2088	2088	3080	2165
Total handling time (min)	1570	1570	2794	1555
Total waiting time (min)	518	518	286	610
Total delay time (min)	0	0	0	0

In the literature, some researchers applied the assigning QCs to vessel approach because they believed that such approach can increase the flexibility of the schedule, and potentially improve the performance of the schedule. However, in this experiment, the proposed TLGA adopts the approach of assigning QCs to berths, but still can achieve good performance and an even better solution than the one proposed by Liang *et al.* (2009). Moreover, assigning QCs to vessels instead of berths, QCs may have to move from one berth to another berth after completion of a job. The movements consume energy and cause increasing operation cost.

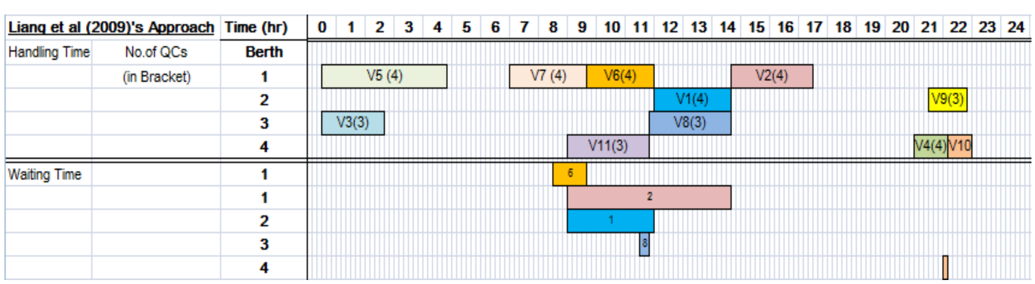

Figure 4.10 The solution obtained by Liang *et al.* (2009)'s approach

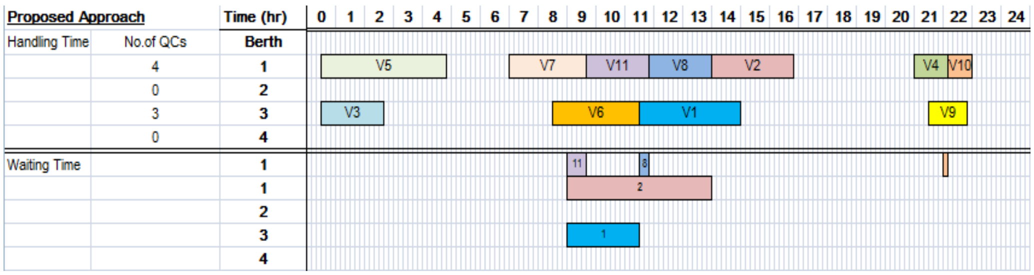

Figure 4.11 The solution obtained by TLGA

4.5 Summary

In general, BAP determines the berthing position and the berthing time for each incoming vessel, while QCAP determines the suitable number of QCs to a vessel for handling containers. In many traditional approaches, BAP and QCAP are planned separately, and vessel handling time is always assumed to be constant. Vessel handling time can also be determined by the number of QCs assigned to the vessels. With this relationship, integrated planning of berth allocation and quay crane assignment becomes more important.

In this chapter, BA-QCAP is studied, and it was noted that researchers and terminal practitioners need a good solution for the integrated planning. Therefore, this thesis proposes TLGA algorithm to minimize the total vessel waiting time, handling time and delay time by simultaneously adjusting QC assignment with berth allocation. The proposed TLGA is composed of two genetic based algorithms, QCAGA and VSGA. The first one is designed to determine the quay crane assignment and the latter one is designed to determine the corresponding vessel schedule. Since these decisions are interrelated, the two genetic algorithms interact iteratively to determine the final solution. The optimization reliability of the proposed approach is tested in numerical experiments based on a set of real data obtained from the literature and the optimal results found by CPLEX. The results show that the proposed TLGA is an effective approach which generates a solution with good quality in a fast time, and this computation time is affordable for practical use. It is also represented that the problem decomposition mechanism employed in TLGA works well in the integrated problem. With good quality of the results, the total vessel service time can be reduced and the berth utilization can be improved.

The DBAP-QCA model is one of the ideas of the integrated berth allocation and quay crane assignment model, which assumes QCs are assigned to berth. In more specific, quay crane assignment can be assigning QCs to vessels. From the literature, QCs can be assigned to vessels by two ways: (i) time invariable quay crane assignment which assigns a constant number of QCs to vessels over the whole service period, and (ii) Variable-In-Time Quay Crane Assignment (VITQCA) which allows the number of QCs being assigned to vessels varying along the whole service period. Due to great complexity, only a few research studies considered the latter one, though it can provide better QC utilization. In the next chapter, the focus will be on BA-QCAP with VITQCA, and the application of the existing modeling approaches from the literature to improve QC utilization.

Chapter 5 Integrated Berth Allocation with Variable-in-time Quay Crane Assignment Problem

5.1 Introduction

In this chapter, an integrated Berth Allocation and Variable-In-Time Quay Crane Assignment Problem (BA-VITQCAP) in transshipment hub is studied. Transshipment hub is one of the most popular terminal business models because of the changes in supply chain model. Examples can be found in Hong Kong, Singapore, and Southeast Asia, etc (Zhen *et al.*, 2011a; Lee *et al.*, 2012; Liang *et al.*, 2012). Transshipment hub mainly deals with transshipment activities. The vessels turnover is usually fast. Vessel arrival rate is relatively more frequency 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 unloading and loading operations. While in traditional gateway terminal, vessels are usually with a larger handling volume and a longer staying time (can be over 1 day).

Because of the business nature of the traditional gateway terminal, most studies applied hourly based approach because the QC idling time induced by this approach is relatively small and acceptable (Meisel and Bierwirth, 2009;

Giallombardo *et al.*, 2010). For example, vessel handling time can be 40 hours for a large vessel with 5,000 containers (Queensland Government, 2014), thus the QC idling time within an hour may become less significant. Therefore, based on this practice, many sophisticated optimization methodologies have been developed and solved the problems nicely. However, in transshipment hub, the business nature is changed. Adoption of hourly based modeling approach may not be desirable as the QC idling time for an hour becomes significant. In this connection, nowadays, some terminals (example those in Hong Kong) are already changing to 30-minute based planning approach. Therefore, there is a need to develop a finer time based approach for the transshipment hubs so that the QC idling time can be reduced. The efficiency of transshipment hubs can be increased. However, some small adjustment in time may be involved in reality, for example the movement of QCs from one position to another position, waiting time for being service after berth, etc. Too fine detail (e.g. minutely based), however, may not be necessary in practice. To take in the account of this, a 15-minute based approach suggested by some terminal operators is proposed as an appropriated finer time based approach.

To solve the 15-minute based model, traditional approaches (such as integer programming) may not be practical as the computational time will be too long. In addition, it is known that solving BA-VITQCAP is much more complicated than dealing with BAP and VITQCAP separately. Problem decomposition seems to be a promising way to do the optimization of the integrated problem (Buhrkal *et al.*, 2011). It is known that GA is widely used to be a robust and effective metaheuristic for handling NP-hard problems (Damodaran *et al.*, 2009), and because of the successfulness of the proposed TLGA approach in the previous chapter. Therefore, a 3-Level Genetic Algorithm (3LGA) is proposed. It decomposes the problem into three sub-problems: i) berth assignment, ii) quay crane assignment, and iii) vessels service sequence. To consider VITQCA, which is to allow idled QC to service another vessel, a QC shifting heuristics is also proposed to combine with 3LGA for fine local searching. The new approach aims to improve the operation efficiency of the transshipment hubs by minimizing the total vessel waiting time and vessel handling time.

5.2 Mathematical modeling for the integrated Discrete Berth Allocation Problem and Variable-In-Time Quay Crane Assignment (DBAP-VITQCA)

In this section, a mathematical model for the 15 minutes based integrated Discrete Berth Allocation and Variable-In-Time Quay Crane Assignment (DBAP-VITQCA) is presented. The model structure modified based on the models presented by Meisel and Bierwirth (2009) and Gialombardo *et al.* (2010). In this model, the terminal is in discrete berth layout, and dynamic vessel arrivals are considered. Hence, vessel cannot berth earlier than its arrival times. The vessel handling time of the vessel varies depending on quay crane assignment. In traditional models of VITQCA, a set of vessels is always assigned into a planning horizon which is divided into hourly based time segments. In this model, it is modified into minutely based, referred as a 15-minute based time segment. Since most QC interferences is only considered in quay crane scheduling problem in detail (Chung and Chan, 2013), and the schedule of the QCs is not going to be investigated, a constant QC productivity is used, and the interference among the QCs is assumed to be insignificant. The objective function (5.1) aims to improve the operation efficiency of terminal by minimizing the total vessel waiting time and vessel handling time.

DBAP-VITQCA model

The notations used for the parameters in the mathematical model are shown in the following:

Input data:

B set of berths in terminal, $B=\{1,2..I\}$

V set of vessels, $V=\{1,2..J\}$

U set of 15-minute time steps, $U=\{1,2..T\}$

e_j expected arrival time of the vessel j

h_j handling volume of vessel j

q_j^{max} maximum number of QCs can be assigned to vessel j

q_j^{min} minimum number of QCs can be assigned to vessel j

R_j range of the assignable number of QCs for vessel j, where $R_j = [q_j^{min}, q_j^{max}]$

E QC productivity, volume (TEU) / a QC/ a time step

Q total number of QCs in terminal

M a sufficiently large positive constant number

In addition, $o(i)$ and $d(i)$ are introduced as the starting node and ending node at berth $i \in B$. $s_{o(i)}$ and $s_{d(i)}$ represent the starting time and ending time of the planning horizon of berth $i \in B$.

Decision variables:

s_j berthing time of vessel j

c_j completion time of vessel j

$y_{jtq} \in \{0, 1\}$, set to 1 if q number of QCs are being assigned to vessel j at time step t, and 0 otherwise;

$y_{jt} \in \{0, 1\}$, set to 1 if at least one QC is being assigned to vessel j at time step t, and 0 otherwise;

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

$x_j^i \in \{0, 1\}$, set to 1 if vessel j is assigned to berth i, and 0 otherwise;

Objective:

$$Z_1 = Min \sum_{j \in V} (c_j - e_j) \tag{5.1}$$

Constraints:

$$\sum_{i\in B} x_j^i = 1, \qquad \forall j \in V \qquad (5.2)$$

$$\sum_{j\in\{V\cup d(i)\}} x_{jk}^i = x_j^i, \qquad \forall j \in V, \forall i \in B \qquad (5.3)$$

$$\sum_{k\in\{V\cup d(i)\}} x_{o(i)k}^i = 1, \qquad \forall i \in B \qquad (5.4)$$

$$\sum_{j\in\{V\cup o(i)\}} x_{jd(i)}^i = 1, \qquad \forall i \in B \qquad (5.5)$$

$$\sum_{k\in\{V\cup d(i)\}} x_{jk}^i - \sum_{j\in\{V\cup o(i)\}} x_{kj}^i = 0, \qquad \forall j \in V, \forall i \in B \qquad (5.6)$$

$$\sum_{i\in B} x_{jd(i)}^i \cdot (s_{d(i)} - c_j) \geq 0, \qquad \forall j \in V \qquad (5.7)$$

$$\sum_{i\in B} x_{o(i)k}^i \cdot (s_k - s_{o(i)}) \geq 0, \qquad \forall k \in V \qquad (5.8)$$

$$s_j - e_j \geq 0, \qquad \forall j \in V \qquad (5.9)$$

$$\sum_{k\in\{V\cup d(i)\}} s_k + M \cdot (1 - x_{jk}^i) \geq c_j\,, \qquad \forall j \in V, \forall i \in B \qquad (5.10)$$

$$\sum_{j\in V} \sum_{q\in R_j} (q \cdot y_{jtq}) \leq Q, \qquad \forall t \in U \qquad (5.11)$$

$$\sum_{q\in R_j} y_{jtq} = y_{jt}\,, \qquad \forall j \in V, \forall t \in U \qquad (5.12)$$

$$\sum_{t\in U} \sum_{q\in R_j} E \cdot y_{jtq} \geq h_j, \qquad \forall j \in V \qquad (5.13)$$

$$\sum_{t\in U} y_{jt} = c_j - s_j, \qquad \forall i \in V \qquad (5.14)$$

$$(t+1) \cdot y_{jt} \leq c_j, \qquad \forall j \in V, \forall t \in U \qquad (5.15)$$

$$t \cdot y_{jt} + M \cdot (1 - y_{jt}) \geq s_j, \qquad \forall j \in V, \forall t \in U \qquad (5.16)$$

$$y_{jtq},\ y_{jt},\ x_{jk}^i,\ x_j^i \in \{0,1\}, \qquad \forall j \in V,\ t \in U,\ i \in B \qquad (5.17)$$

Constraint (5.2) ensures that every vessel has been served at one of the berths. Constraint (5.3) sets the relationship between the two variables. Constraints (5.4) and (5.5) define the starting and the ending of the flow of the served vessels at each berth, while Constraint (5.6) ensures the flow conservation for the remaining vessels at a berth. Constraints (5.7) and (5.8) ensure the vessels will be served within the planning horizon. Constraints (5.9) and (5.10) ensure no vessel should berth before its arrivals or the completion of the pervious vessel. Constraint (5.11) ensures the total number of assigned QCs at each time step must not exceed the total number of QCs in the terminal. Constraint (5.12) ensures the consistency of the variables. Constraint (5.13) ensures every vessel receives sufficient QC capacity for servicing. Constraints (5.14) – (5.16) set the berthing time and completing time of the vessel without preemption.

5.3 Methodology: 3-Level Genetic Algorithm (3LGA)

The 3LGA algorithm is developed as the optimization methodology for the mentioned model. The methodology framework is shown in Figure 5.1. It consists of three levels, hereafter called the 1st level GA, the 2nd level GA and the 3rd level GA. The 1st level GA is designed to allocate vessels to berths, while the 2nd level GA and 3rd level GA are designed to determine the service sequence of vessels and the quay crane assignment respectively. A total of 4 databases, Database A (DA), Database B (DB), Database C (DC) and Database D (DD), are involved to record the chromosome determined every time and the best chromosome obtained in each level. If an individual Berth Allocation chromosome (BA-chromosome) is newly generated in the 1st level GA, the 2nd and 3rd level GA will be carried out, and after that, DA will records 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 Figure 5.1.

When the same 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 (details in section 5.3.3). A QC shifting heuristics is proposed and implemented into the 3rd level GA to determine the complete VITQCA. The interaction among different levels of 3LGA, and the procedures are described as follows:

Procedures of 3LGA:

Start: Both the container terminal and the vessel information are required as the input data for 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 (details in section 5.3.1).

Step 2: If an individual BA-chromosome generated is new, 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 accordingly (details in section 5.3.1). 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 (details in section 5.3.1).

Step 2a (ii): They will go through the QC shifting heuristic (details in section 5.3.6) to obtain the complete QCA.

Step 2a (iii): Fitness evaluation for the QCA-chromosome with its completed QCA (details in section 5.3.2). 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 (details in section 5.3.3).

Step 2a (vi): Genetics Operations – Uniform mutation (details in section 5.3.5). Go back to **Step 2a (ii)**.

Step 2b: Fitness evaluation for the VS-chromosome with its best QCA-chromosome (details in section 5.3.2). 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 1^{st} 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 (details in section 5.3.3).

Step 2e: Genetics Operations – Uniform crossover and mutation (details in section 5.3.4 and 5.3.5). Go back to **Step 2a (i)**.

Step 3: Fitness evaluation of the BA-chromosome together with its best VS-chromosome & QCA-chromosome (details in section 5.3.2). 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 randomly selected to form the mating pool by using the traditional roulette wheel selection approach, and elitist strategy is applied (details in section 5.3.3).

Step 6: Genetics Operation – Uniform crossover and mutation (details in section 5.3.4 and 5.3.5). 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.

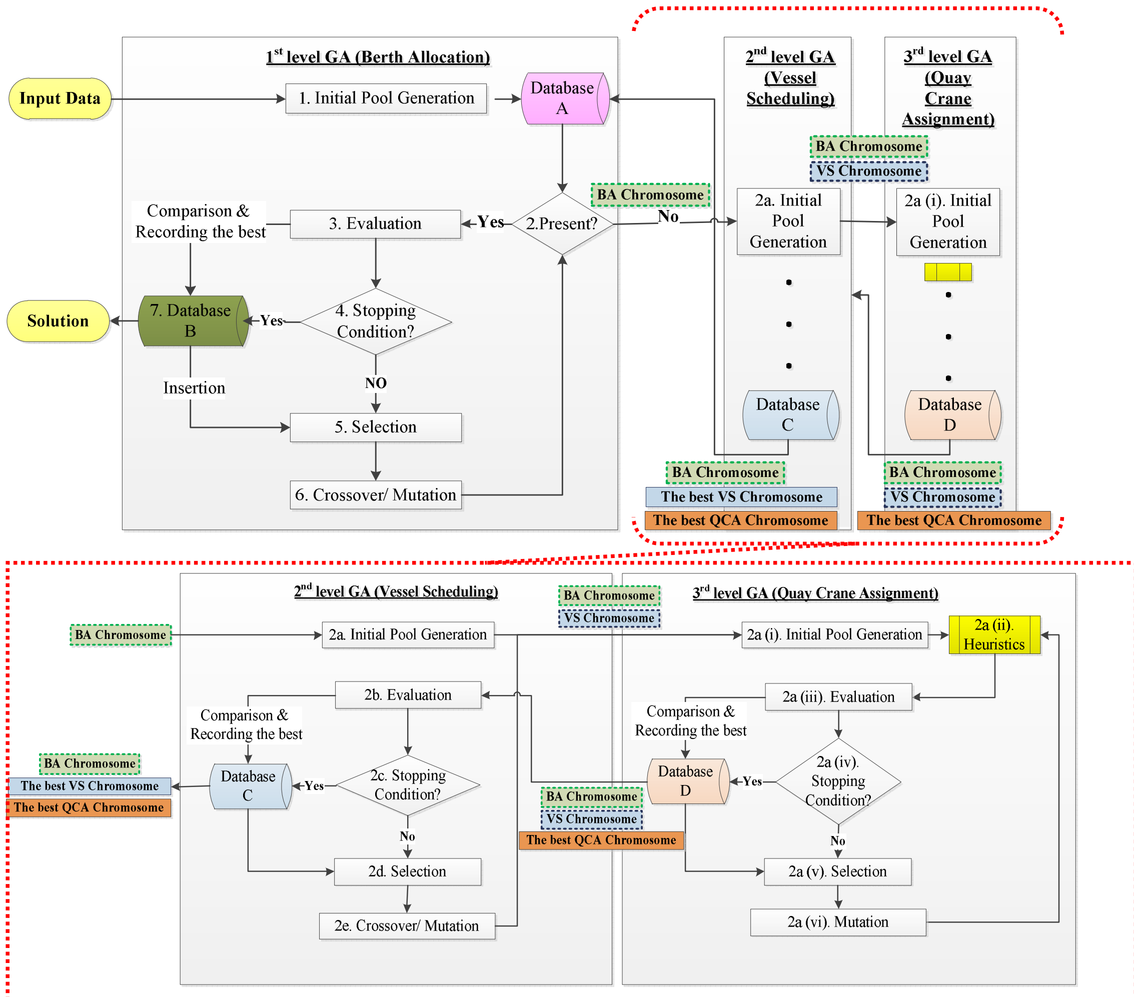

Figure 5.1 A 3LGA optimization methodology framework

5.3.1 Generation of initial pool and Chromosome Representation

To form the initial pool of the 1st level GA, a number of BA-chromosomes are randomly generated. Figure 5.2 shows an example of a BA-chromosome, which consists of *J* number of genes. Each gene corresponds to the vessel number indicated by its position, increasing from the left to the right. The gene value 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 an initial pool of the 2nd level GA. It consists of J number of genes. The position of each gene corresponds to the 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 as in Figure 5.3.

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

Figure 5.2 A chromosome of the 1st level GA

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

Figure 5.3 A chromosome of the 2nd level GA

By combining the BA-chromosome with the VS-chromosome, the vessel schedule can be obtained. Figure 5.4 shows an example of a vessel schedule formed by the BA-chromosome in Figure 5.2 with the VS-chromosome in Figure 5.3. To obtain the schedule, starting from the vessel with θ = 1 which is Vessel 4, it will be served as the first vessel (o = 1) at Berth 3. Then, for θ = 2, Vessel 1 will be served as the first vessel (o = 1) at berth 1. For θ = 3, Vessel 5 will be served as the second vessel (o = 2) at Berth 1, and so on.

Vessel schedule (v_{io})			
	Service order at a berth (o)		
Berth (i)	1	2	3
1	1	5	2
2	7	3	---
3	4	6	8

Figure 5.4 An example of the vessel schedule

For the 3rd level GA, QCA-chromosomes cannot be generated randomly as infeasible solutions may result easily. This will reduce the optimization efficiency of the algorithm a lot. Therefore, to generate a QCA-chromosome with a feasible solution, the determined vessel schedule and the following QCA-chromosome Generating Procedures are followed:

i. Check the berthing time (s_j) = max {berth available time, vessel arrival time (e_j)} of the vessel j being served at each Berth $i \in B$ with o =1. Since all vessels arrive after starting time of planning horizon, it starts by the Vessel j with the earliest arrival time.

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

iii. Randomly assign a number of QCs (q) for the vessel j range in $[q_j^{min}, q_j^{max}]$ at s_j without violate the constraint (5.11).

iv. Calculate c_j of the vessel j by the eq. (5.18).

$$c_j = s_j + \frac{v_j}{E \times q} \tag{5.18}$$

v. If c_j is not a multiplication of 15, c_j could increase to the nearest of the multiplication of 15 to get the actual value of c_j. Update $y_{jtq} = 1$ from $t = s_j$ to $t = c_j$, and the berth available time to $c_j + 1$.

vi. Check the next vessel with the earliest berthing time among Berth $i \in B$ 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.

Given an example, followed by the vessel schedule in Figure 5.4. Assuming that Vessel 1 has the earliest arrival time among the vessels with o = 1, including Vessel 1, 7 and 4. Hence, Vessel 1 will operate the task 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 randomly generated within the range [1 - 4], for example 2 QCs. By using eq. (5.18) with $v_j = 300$ TEU and $E = 0.5$, 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. After completed the assignment procedures, a feasible QCA-chromosome is formed which is shown in Figure 5.5. The QCA-chromosome consists of J number of genes. Each gene corresponds to the vessel number indicated by its position in the chromosome, increasing from the left to the right. The gene value represents the number of QCs being assigned to that vessel. Similarly, the initial pool of the 3rd level GA is then generated.

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

Figure 5.5 A chromosome of the 3rd level GA

5.3.2 Fitness 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. (5.19).

$$f(x) = 1 - \left(\frac{Z_3(x)}{\sum_{p=1}^{P} Z_3(p)}\right) \quad (5.19)$$

, 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.

5.3.3 Selection and Elitist Strategy

The selection methodology applied is the commonly used Roulette Wheel Selection approach. It gives to each chromosome a probability value, which is directly proportional according to its fitness value. The higher the fitness value 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.

5.3.4 Genetic Operations: Crossover

Uniform crossover with ratio (1/*J*) is applied in both the 1st level and 2nd level GA. Since a slight modification will cause dramatic changes to the 2nd level GA and to the 3rd level GA, a slow graduate evolution approach is applied in order to prevent random searching as adopted in TLGA algorithm before. A pair of BA-chromosomes is required for the crossover operation. Figure 5.6 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.

$j =$	1	2	3	4	5	6	7	8
parent (1):	1	1	2	3	1	3	2	3
parent (2):	2	1	3	1	1	1	3	2

offspring (1):	1	1	2	1	1	3	2	3
offspring (2):	2	1	3	3	1	1	3	2

Figure 5.6 Crossover operation of 1st level GA

For the 2nd 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, validation will be processed to ensure each vessel will be assigned to a θ once and only one. Figure 5.7 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 $\theta = 8$.

Given the BA-chromosome as the one shown in Figure 5.3, the vessel schedules formed the BA-chromosome with the VS-chromosomes (1) before crossover and after crossover are shown as in Figure 5.8. In this case, the service order o at Berth 2 of Vessels 3 and 7 are swapped.

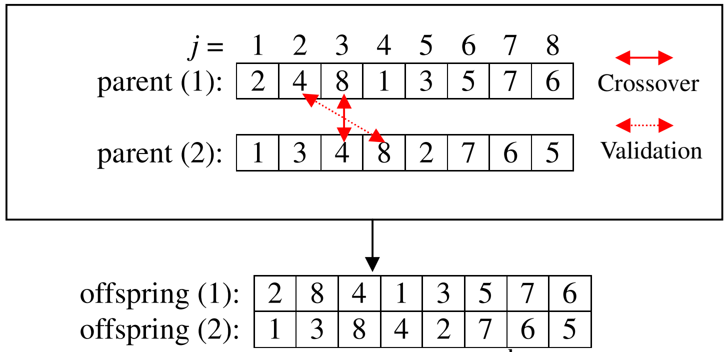

Figure 5.7 Crossover operation of the 2nd level GA

Before crossover

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

After crossover

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

Figure 5.8 The vessel schedule after crossover

For the 3rd level GA, the range of the assignable number of QCs (R_j) for each vessel are different. Crossover operation may produce many infeasible solutions and reduce computational efficiency. Therefore, it will not be used.

5.3.5 Genetic Operations: Mutation operation

To avoid random searching, mutation with ratio (1/*J*) is applied in both the 1st level GA, the 2nd level GA and the 3rd level GA (Chung et al., 2010, Chung and Chan, 2012). Only one chromosome is required for the mutation operation. For the 1st level GA, a value is randomly generated within the set *B* to replace another randomly selected gene from a BA-chromosome. In an example shown in Figure 5.9, the berth allocated to Vessel 2 is change from Berth 1 to the mutated value Berth 2.

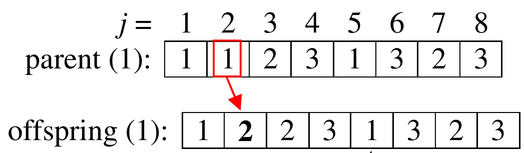

Figure 5.9 Mutation of the 1st level GA

In the 2nd level GA, two genes of a VS-chromosome will be randomly selected and swap with each other. Figure 5.10 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.

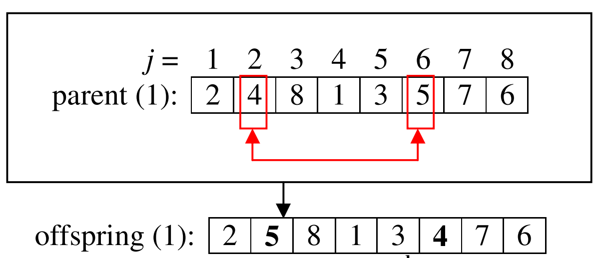

Figure 5.10 Mutation of the 2nd level GA

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 and becomes $(\hat{q})$. It means that one more QC is assigned to the corresponding vessel. Sometimes, the change may cause infeasible chromosome. Therefore, validation processes are needed as shown below, and it will be started from the Vessel m with the mutated gene.

Validation Processes:

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 reduced by 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 $y_{mt\hat{q}} = 1$ from $t = s_j$ to $t = \widehat{c_m}$.

V3. Check the next vessel with the earliest berthing time among Berth $i \in B$, 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 being assigned to vessels 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.

Figure 5.11 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.

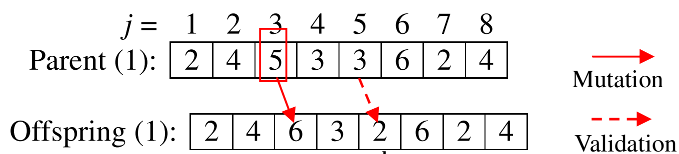

Figure 5.11 Mutation of the 3rd level GA

5.3.6 Heuristics for VITQCA

By the QCA-chromosome Generating Procedures of the 3rd level GA, a fixed number of QCs is assigned to serve a vessel through the entire service period. This QCA is called time-invariable assignment. Under this assignment mechanism, when a vessel is under operation, other idled QCs are not allowed to join in. It may reduce the utilization of QCs. To improve the utilization, a QC shifting heuristics is proposed and implemented, which changes the QCA to time-variable assignment. It allows the idled QCs to serve other vessels this time. However, it is known that QC are not suggested to move too frequently (Giallombardo et al., 2010) as it may induce interruptions. Therefore, QCs in this heuristics can only shift among the berths without crossing the other working vessels, and a maximum two shifts is considered for a vessel. Therefore, two situations for QC shifting are designed in the proposed heuristics as outlined in Figure 5.12.

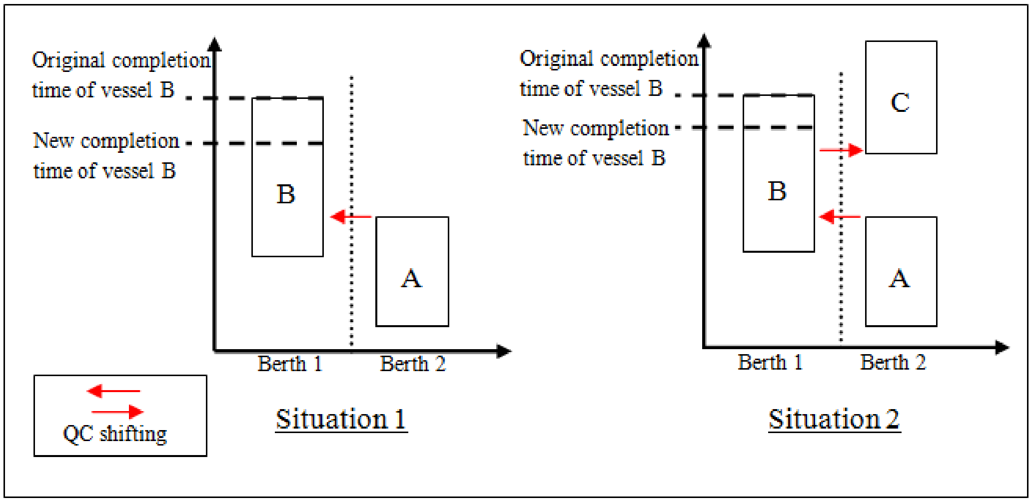

Figure 5.12 2 Situations of QCs shifting

If the time of QCs released after the completion of Vessel A is within the service period of Vessel B, and there are no vessel will be served at Berth 2 before the completion time of Vessel B, the situation is regarded as Situation 1. In this situation, the QCs released at completion time of Vessel A will move to serve Vessel B until the completion of Vessel B. The number of QCs involved in the shifting depends on the remaining QC capacity of the Vessel B. If the time of QCs released after the completion of Vessel A is within the service period of Vessel B, and there is another Vessel C will be served afterward at Berth 2 before the completion time of Vessel B, this situation is regarded as Situation 2. In this situation, the QCs released at completion time of Vessel A will move to serve Vessel B, and then move back to serve Vessel C at the berthing time of Vessel C.

5.4 Numerical Experiments

In this section, numerical experiments are conducted to test the performance of the proposed 3LGA algorithm and the significance of the proposed 15-minute based DBAP-VITQCA modeling approach. The generation of the test instances and the parameters setting are included in Section 5.4.1. To testify the solution quality of the proposed 3LGA algorithm, it is compared with two other approaches: i) SGA, and ii) 2-level GA (with the idea similar to the previously proposed TLGA algorithm). To illustrate the significance of using the proposed 15-minute based time segment model, and to demonstrate the developed approach is capable of considering that, a detail analysis will be given in section 5.4.3.

5.4.1 Generation of test instances

In these experiments, the quay of the terminal is partitioned into 3 berths (I = 3) with a total of 8 QCs (Q = 8). There are 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 summarized in Table 5-1. Each instance will randomly generate 3 set of data, with a total of 27 set of test data being generated. The handling volume of each vessel is randomly generated within the range 100-3000 (TEUs), as shown in Table 5-2. It is assumed that no QC breakdown may occur and the productivity of each QC is constant, handling 0.5 TEU containers in one minute. The minimum assignable number of QCs is from 1 to 3, while the maximum assignable number of QCs is from 4 to 6. SGA, 2-level GA, and the proposed 3LGA are programmed in JAVA language and run on a PC with a CPU of 1.33GHz and 4GB RAM. The parameters setting for 3LGA are shown in Table 5-3.

Table 5-1 Proportions of vessel arrival intervals

Type	Proportions of the vessel arrival intervals (min)	%
Tight (A)	$0 \leq V \leq 100$ $101 \leq V \leq 300$ $301 \leq V \leq 600$	80 10 10
Normal (B)	$0 \leq V \leq 100$ $101 \leq V \leq 300$ $301 \leq V \leq 600$	60 30 10
Loose (C)	$0 \leq V \leq 100$ $101 \leq V \leq 300$ $301 \leq V \leq 600$	30 60 10

Table 5-2 Proportions of the handling volume of vessels

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

Table 5-3 Parameters settings in 3LGA

	3LGA								
	1st level GA			2nd level GA			3rd level GA		
Number of Vessels	10	20	50	10	20	50	10	20	50
Population size	10	10	10	4	4	4	4	4	4
Number of evaluations	100	200	500	10	10	10	10	10	10
Crossover rate	0.1	0.05	0.02	0.1	0.05	0.02	0.1	0.05	0.02
Mutation rate	0.1	0.05	0.02	0.1	0.05	0.02	0.1	0.05	0.02

5.4.2 Testing the optimization quality of the proposed algorithm: 3LGA

In the literature, GA is widely used for solving the BAP without decomposing the problem, meaning that the whole problem is represented by a single chromosome. To simulate such problem practice, SGA is created. For BA-QCAP, some studies, including the one mentioned in the previous chapter, decomposed it into 2 sub-problems and solved them sequentially or iteratively. To simulate such problem decomposition practice, 2-level GA is also created. To compare the performance of these approaches, the total number of evolutions used and population size are set to be the same. Each test data is solved 10 times individually by the three algorithms. The averages of the solution values obtained by these three approaches are summarized in Table 5-4.

The results show that the proposed 3LGA algorithm obtains the same or a better solution than SGA and 2-level GA. For the small size problems (V=10), about 0 to 2.5% improvement can be achieved by 3LGA. 0% change 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 SGA and 2-level GA in solving large problems faster and better.

Table 5-4 Experiment results of SGA, TLGA and 3LGA

	Instance	(1) 1-level GA	Time (s)	(2) 2-level GA	Time (s)	Proposed 3LGA	Time (s)	Compare to (1) % change	Compare to (2) % change
V=10	**10A-1**	3180	4.13	3105	4.13	3098	4.26	-2.57	-0.22
	10A-2	4180	5.04	4172	4.22	4120	4.86	-1.36	-1.24
	10A-3	3535	4.73	3529	4.87	3519	4.32	-0.4	-0.28
	10B-4	3962	4.1	3962	4.86	3971	5.01	-1.29	-1.29
	10B-5	3892	4.51	3845	4.11	3825	4.36	-1.72	-0.52
	10B-6	2370	4.61	2348	4.71	2348	4.7	-1.1	0
	10C-7	3279	4.24	3275	4.15	3275	4.56	-0.18	0
	10C-8	3724	4.28	3722	4.19	3722	4.27	-0.11	0
	10C-9	3572	4.3	3572	4.29	3572	4.29	0	0
V=20	**20A-1**	12040	10.22	11842	10.62	11644	10.42	-3.29	-1.69
	20A-2	11190	10.68	10945	10.76	10842	10.15	-3.1	-0.94
	20A-3	12328	10.62	12139	10.81	11979	10.77	-2.83	-1.31
	20B-4	13741	10.71	13499	10.53	13269	10.21	-3.43	-1.7
	20B-5	12522	10.92	12261	10.26	12061	10.92	-3.68	-1.63
	20B-6	14329	10.34	14100	11.1	13762	11.04	-3.96	-2.4
	20C-7	11060	10.43	10910	10.21	10783	10.37	-2.5	-1.11
	20C-8	11240	10.23	10931	10.3	10812	10.38	-3.8	-1.08
	20C-9	9645	10.48	9401	10.25	9305	10.26	-3.53	-1.02
V=50	**50A-1**	44985	68.18	43712	68.22	40527	67.12	-9.91	-7.29
	50A-2	40759	65.74	39040	68.1	37116	68.42	-8.94	-4.93
	50A-3	33170	65.55	32605	64.63	31536	65.21	-4.93	-3.28
	50B-4	38261	67.25	37451	65.93	34328	66.13	-10.28	-8.34
	50B-5	51105	66.17	49013	66.13	46603	65.63	-8.81	-4.92
	50B-6	38197	65.52	37406	65.88	35397	65.1	-7.33	-5.37
	50C-7	59982	65.18	58544	65.27	55886	66.21	-6.83	-4.54
	50C-8	65989	65.64	62786	65.19	58468	65.35	-11.40	-6.88
	50C-9	40636	65.66	39882	65.23	38133	65.86	-6.16	-4.39

5.4.3 Significance of the proposed 3LGA with 15-minute based time segments

Hourly based time segment is always used for quay crane assignment in the literature. They were incidentally assumed that each QC can serve only one vessel at each time segment, and the berthing time of vessels can only in hours. However, this limitation and assumption may affect the QC utilization. Therefore, a 15-minute based modeling approach is proposed. To study the significance of using the 15-minute based time segments, another experiment is conducted. The 27 test data set are used again. Two different time-unit configurations are used in the proposed 3LGA: 1) hourly based time segment (Conf-H) is used to simulate the traditional practice in the literature, and 2) the proposed 15-minute based time segment (Conf-15) which is suggested by operators in some transshipment hubs in Hong Kong.

A small size problem (the set 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 Figures 5.13 and 5.14. In the diagrams, a rectangular block represents a vessel, and the height of the block represents the maximum vessel QC capacity. 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 vessel waiting time, and the shadowed area shows the idled time of QCs occupied by a time segment.

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, the proposed 3LGA algorithm with the configuration of the proposed Conf-15 shows even better performance than that with Conf-H in terms of both the 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.

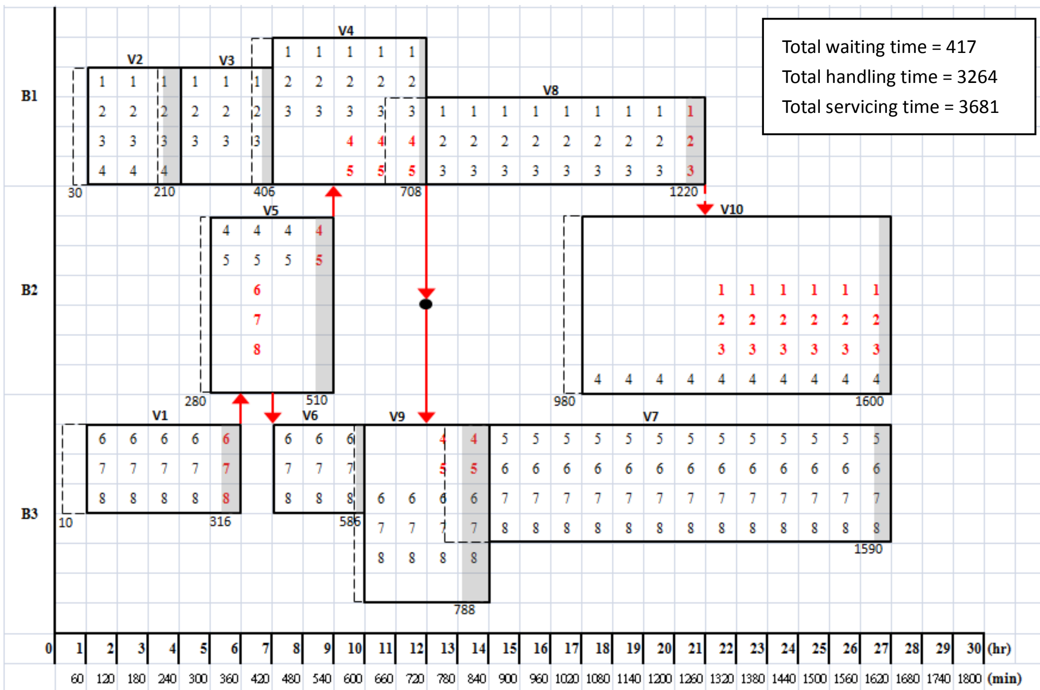

Figure 5.13 The space-time diagram of the result from 3LGA with traditional Conf-H

With Conf-H, it is observed that many idled QCs are occupied in a time segment (Figure 5.13). 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 (Figure 5.14). 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.

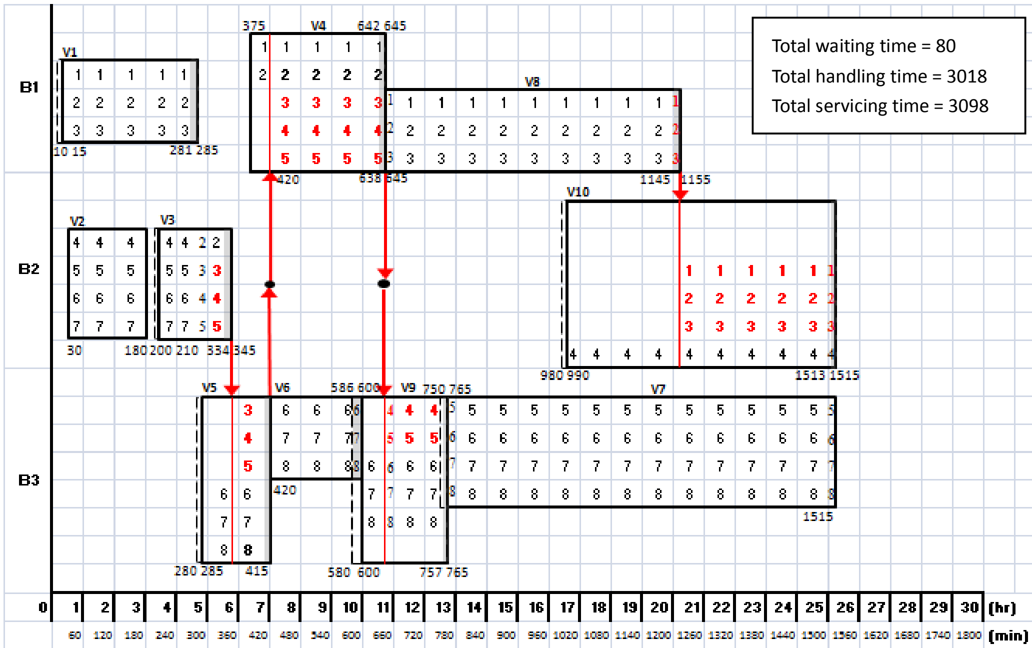

Figure 5.14 The space-time diagram of the results from 3LGA with proposed Conf-15

The proposed 3LGA algorithm 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 5-5. Results show that Conf-15 performs better than Conf-H in all instances. The percentage of the improvement is shown in Figure 5.15. Up to 20% improvement can be achieved by using Conf-15. The variation may depend on the vessel arrival time, 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 can be observed from Fig. 5.15.

Table 5-5 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

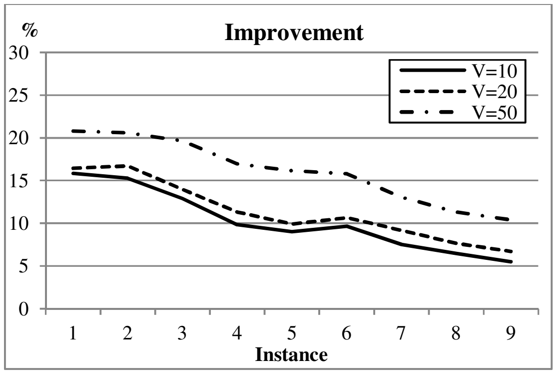

Figure 5.15 Improvement percentage (conf-15)

5.5 Summary

Operation efficiency and fully utilization of resources are crucial to terminal industries as it directly affects the profitability. In traditional modeling approach, BAP and QCAP are usually modeled in hourly based. However, this limitation and assumption reduce the utilization of the quay cranes significantly and induce 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 QC resources by VITQCA, the proposed 3LGA algorithm is embedded with a QC shifting heuristics for fine local searching. 3LGA decomposes the problem into berth allocation, vessel scheduling, and quay crane assignment. The solution quality of the proposed algorithm and the significance of using 15-minute based time segments are tested and demonstrated by a number of numerical experiments. For testing the solution quality, two additional approaches are created, named SGA and 2-level GA. The results demonstrate that the proposed 3LGA outperforms the other two by obtaining better solutions. To demonstrate the significance of using 15-minute based time segments, another experiment is conducted. The results demonstrate a significant improvement on waiting time and handling time obtained by using the 15-minute based time segments comparing with the traditional hourly based segments. It is concluded that the proposed 3LGA algorithm with 15 minute based time segments approach can improve the performance of the terminal operations, and provide better QCs utilization significantly.

In the next chapter, the improvement of the utilization of the terminal resources will be continuing. The existing berth layout models will be studied, and a new model will be proposed which can maximize the berth space utilization and can be applicable to real-world container terminals.

Chapter 6 A new Multi-continuous Berth Layout Model

6.1 Introduction

In BAP, a continuous berth layout model allows vessels to berth on any position within the boundaries of the quay. It is always suggested for better berth space utilization and also provides a highly flexible berth allocation plan to the terminals, especially to those busy transshipment hubs, where various sizes of vessels call (Imai *et al.*, 2005). In the literature, various linear programming formulations can be found for the conventional continuous berth layout model (Park and Kim, 2002; Imai *et al.*, 2005; Lee *et al.*, 2010; Ganji *et al.*, 2010). However, most of them cannot be directly applied in real-world container terminals that comprise a number of quay sections, which are separated geographically. For examples, the Medcenter Container Terminal and the BLG Italia terminal located at the Port of Gioia Tauro (Cordeau *et al.*, 2005; 2007; 2011), the Brani Terminal at the Port of Singapore (Lee *et al.*, 2012), the Port of Izmir Alsancak Container Terminal (Esmer *et al.*, 2013), etc.

6.2 Problem of quay discontinuity in BAP

Due to the natural geographic layout of the harbor or artificial layout design of the terminal, sharp curves (Figure 6.1 a) or disconnections (Figure 6.1 b) can be commonly be found on the quay of many real-world container terminals. In these cases, the quay is divided into a number of sections. This layout problem is named as quay discontinuity.

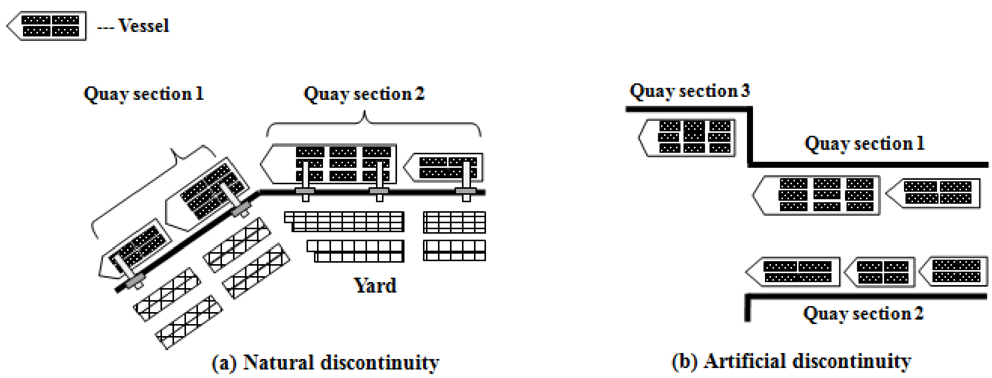

Figure 6.1 Typical forms of the continuous berth layout with discontinuity

To obtain a better berth space utilization in single berth, many papers study continuous berth layout. Figure 6.2 shows a typical form of the conventional continuous berth layout model described in the literature. In this model, the quay is presented in a linear continuous form which allows vessel to berth at anywhere. However, the common layout characteristic – quay discontinuity was seldom addressed. If this model directly applied to the terminal with quay discontinuity, it may results in infeasible solutions (Figure 6.3).

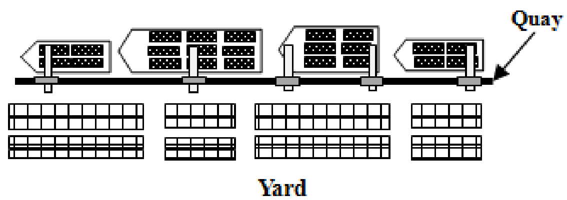

Figure 6.2 A conventional continuous berth layout model

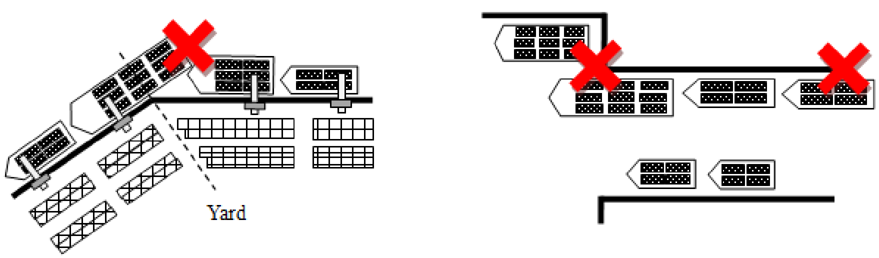

Figure 6.3 Infeasible solutions obtained by using conventional continuous berth layout model in a layout with discontinuity

6.3 Existing models to deal with quay discontinuities

Real world container terminals always have the problem of natural discontinuity or sharp curves on their quay as addressed in some papers (Cordeau *et al.*, 2005; Cheong *et al.*, 2010; Moorthy and Teo, 2006).

To deal with such cases, it is common to consider the berth layout as a discrete berth layout model or a hybrid berth layout model. These models either divide the quay space into a number of berths or small segments. According to the definition given by (Bierwirth and Meisel, 2010), in the discrete model, one berth can only service one vessel, while in the hybrid model, one vessel can occupy more than one berth or one berth can be shared by more than one vessel. There are also some papers (Cordeau *et al.*, 2005; Turkogullari *et al.*, 2014) classify the model, which divides the quay space into small segments, as a type of continuous model that, however, the papers are regarded as a hybrid model here. The discrete model takes an advantage of ease of scheduling, but leads to low space utilization. The hybrid model makes some improvement on this, but yields another decision in determining the length of the berth segments.

Another practical way is to assign the incoming vessel to one of the quay sections at first, and consider each section as the conventional continuous berth layout model in optimizing the quay space utilization. However, this approach may greatly increase the problem complexity, especially in integrated problems.

6.4 Mathematical modeling

To provide a high space utilization model while considering quay discontinuity, multi-continuous berth layout is studied. It is found that the quay discontinuity problem can be tackled by adding virtual berth partitions into the conventional continuous berth layout model (Figure 6.4). Therefore, the multi-continuous berth layout model is developed based on the framework of an existing conventional continuous berth layout model. Some new constraints for the virtual berth partitions are also proposed.

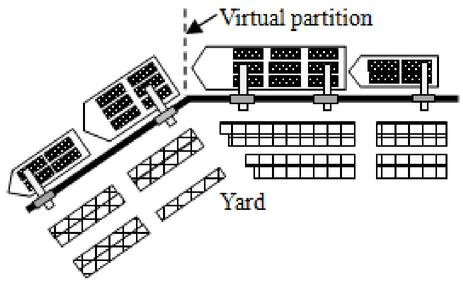

Figure 6.4 A multi-continuous berth layout model

6.4.1 The integrated Continuous Berth Allocation Problem and Variable-In-Time Quay Crane Assignment (CBAP-VITQCA) model proposed by Zhen *et al.* (2011a)

There are a number of integrated berth allocation and quay crane assignment in continuous berth layout models existing in the literature, while only a few of them considering VITQCA. The one proposed by Zhen *et al.*, (2011) is selected as it is a CBAP-VITQCA model, embedded with a concept of QC-profile to simplify the formulations of the VITQCA part.

In the model, a set of vessels (V) is to be berthed in a conventional continuous quay with length (L) within a planning horizon of (H) time step. To determine the handling time of Vessel j, the idea of QC-profile proposed by Giallombardo *et al.*, (2010) is employed. For each vessel $j \in V$, a set of possible feasible QC-profiles (P_j) are generated for selection. The selected QC-profile involves the number of time steps required for handling, including the vessel handling time, and the number of QCs being assigned throughout each time step. The QC-profile allows the number of QCs varying along the servicing period, and takes into the account of the maximum and the minimum number of QCs guaranteed for each vessel. The mathematical model CBAP-VITQCA is shown as below:

CBAP-VITQCA model

Input Data:

B	set of berth segments, $B = \{1,2\ldots I\}$
V	set of vessels, $V = \{1,2\ldots J\}$
P_j	set of the QC-profiles for Vessel j
h_{jp}	handling time (time steps) of Vessel j by using QC-profile p
H	number of time steps involved along the planning horizon
E	maximum handling time allowed for all vessels, $E = max_{\forall j \in V}\{h_{jp} \mid p \in P_j\}$
U	set of time steps currently being consideration, $U = \{1, 2\ldots H + E\}$
$[a_j^M, b_j^M]$	feasible turnaround time interval for Vessel j
$[a_j^e, b_j^e]$	expected turnaround time interval for Vessel j
L	length of the quay measuring in meter
m	length of the berth segment measuring in meter
u_j	length of Vessel j
Q_t	number of QCs available at time step t
q_{jpm}	number of QCs utilized at time step m^{th} if QC-profile p is selected by Vessel j.

M	a sufficiently large positive constant number
w_j^{Be}, w_j^{Bt}	weighting of the earliness and tardiness deviated to the expected turnaround time interval for Vessel j.

Variables:

δ_{jk}^{T}	$\in [0, 1]$	set to 1 if the finishing time of handling Vessel j is earlier than the starting time handling Vessel k , and 0 otherwise
δ_{jk}^{B}	$\in [0, 1]$	set to 1 if Vessel j is berthed right below Vessel k in the berth axis and 0 otherwise
η_{jpt}	$\in [0, 1]$	set to 1 if QC-profile p is selected by Vessel j and starts handling at time step t, and 0 otherwise
ζ_{jb}	$\in [0, 1]$	set to 1 if Berth segment b is being occupied by Vessel j and 0 otherwise. In addition, two auxiliary variables, ζ_{jb}^{U}, $\zeta_{jb}^{L} \in [0, 1]$, are defined for ζ_{jb}, such that if $\zeta_{jb}^{U} = \zeta_{jb}^{L} = 1$, then $\zeta_{jb} = 1$
s_j	$\in \{1, \ldots H\}$	the berthing time step of Vessel j for handling
c_j	$\in U$	the ending time step of Vessel j for handling
ρ_t	≥ 0	the number of QCs used at time step t
o_b, d_b	$\in U$	start and end time steps for Berth segment b

Decision variables:

β_j ∈ [0, L] defined as continuous variable, representing the berthing position of Vessel *j* according to its middle point

π_{jt} ∈ [0, 1] set to 1 if Vessel *j* starts the handling at time step *t*, and 0 otherwise

γ_{jp} ∈ [0, 1] set to 1 if QC-profile *p* is selected by Vessel *j* and zero otherwise

Objective function:

Min $Z_1 = \sum_{j \in V} \omega_j^{Be} \cdot \left(a_j^e - \varepsilon_j\right)^+ + \omega_j^{Bt} \cdot \left(\sigma_j - b_j^e\right)^+$

(6.1)

Min $Z_2 = \sum_{j \in V} \omega_j^{Be} \cdot \tau_j^{a+} + \omega_j^{Be} \cdot \tau_j^{a-} + \omega_j^{Bt} \cdot \tau_j^{b+} + \omega_j^{Bt} \cdot \tau_j^{b-}$

(6.2)

Objective function (6.1) aims at minimizing the vessel service cost induced by the deviation of expected turnaround time intervals for vessels. The nonlinear objective function (6.1) was linearized to a linear objective function (6.2) by adding four positive integer variables $\tau_j^{a+}, \tau_j^{a-}, \tau_j^{b+}, \tau_j^{b-}$, and Constraints (6.3) – (6.5):

$$a_j^e + \varepsilon_j = \tau_j^{a+} - \tau_j^{a-} \quad , \forall j \in V \qquad (6.3)$$

$$\sigma_j - b_j^e = \tau_j^{b+} - \tau_j^{b-} \quad , \forall j \in V \qquad (6.4)$$

$$\tau_j^{a+}, \tau_j^{a-}, \tau_j^{b+}, \tau_j^{b-} \geq 0 \qquad , \forall j \in V \tag{6.5}$$

Constraints:

a. Non-overlapping constraints:

$$s_j + \sum_{p \in P_j} \gamma_{jp} \cdot h_{jp} \leq s_k + (1 - \delta_{jk}^T) \cdot M \qquad \forall j, k \in V, j \neq k \tag{6.6}$$

$$\beta_j + (\mu_j + \mu_k)/2 \leq \beta_k + (1 - \delta_{jk}^B) \cdot M \qquad \forall j, k \in V, j \neq k \tag{6.7}$$

$$\delta_{jk}^T + \delta_{jk}^T + \delta_{jk}^B + \delta_{jk}^B \geq 1 \qquad \forall j, k \in V, j \neq k \tag{6.8}$$

Constraint (6.6) ensures $\delta_{j,k}^T$ is set to 1 if Vessel *k* starts after the completion of Vessel *j*. Constraint (6.7) ensures $\delta_{j,k}^B$ is set to 1 if Vessel *j* berth completely on the right side of Vessel *k* along the quay. Constraint (6.8) guarantees at least one of the above relationships is valid among Vessels *j* and *k*.

b. Berthing position constraint:

$$\frac{u_j}{2} \leq \beta_j \leq L - \frac{u_j}{2} \qquad \forall j \in V \tag{6.9}$$

Constraint (6.9) ensures all the vessels must be berthed within the quay length.

c. QC constraints:

$$\sum_{p \in P_j} \gamma_{jp} = 1 \qquad \forall j \in V \tag{6.10}$$

$$\eta_{jpt} \geq \gamma_{jp} + \pi_{jt} - 1 \qquad \forall j \in V, \forall p \in P_j, \forall t \in U \tag{6.11}$$

$$\rho_t = \qquad \forall t \in U \tag{6.12}$$

$$\sum_{j\in V}\sum_{p\in P_j}\sum_{h=max\,(1;\,t-h_{jp}-1)}^{t} q_{jp(t-h+1)}\cdot\eta_{jpt}$$

$$\rho_t \leq Q_t \qquad \forall t\in\{1,2,\dots H\} \qquad (6.13)$$

$$\rho_t+\rho_{(t+H)} \leq Q_t \qquad \forall t\in\{1,2,\dots E\} \qquad (6.14)$$

Constraint (6.10) ensures each vessel can only select one QC-profile. Constraint (6.11) connects γ_{jp} and π_{jt} by using η_{jpt}. Constraint (6.12) sums up the number of QCs used in each time step, while Constraints (6.13) and (6.14) ensure the total number of QCs used will not exceed the QC capacity available at each time step.

d. Time constraints:

$$\sum_{t\in u}\pi_{jt} = 1 \qquad \forall j\in V \qquad (6.15)$$

$$s_j = \sum_{t\epsilon U}\pi_{jt}\cdot t \qquad \forall j\in V \qquad (6.16)$$

$$s_j+\sum_{p\in P_j}\gamma_{jp}\cdot h_{jp}-1 = c_j \qquad \forall j\in V \qquad (6.17)$$

$$s_j \geq a_j^M \qquad \forall j\in V \qquad (6.18)$$

$$c_j \leq b_j^M \qquad \forall j\in V \qquad (6.19)$$

Constraint (6.15) defines the starting time step of each vessel, and Constraint (6.16) sets the relationship between the variables s_i and $\pi_{j,t}$. Constraint (6.17) calculates the ending time of each vessel. Constraints (6.18) and (6.19) guarantees the starting and the ending time are within the feasible turnaround time interval of the vessel.

e. Other constraints:

$$\beta_j + \frac{u_j}{2} - m \cdot (b-1) \leq \zeta_{jb}^U \cdot M \qquad \forall b \in B, \forall j \in V \qquad (6.20)$$

$$m \cdot b - \beta_j + \frac{u_j}{2} \leq \zeta_{jb}^L \cdot M \qquad \forall b \in B, \forall j \in V \qquad (6.21)$$

$$\zeta_{jb} \geq \zeta_{jb}^U + \zeta_{jb}^L - 1 \qquad \forall b \in B, \forall j \in V \qquad (6.22)$$

$$o_b \leq s_j + (1 - \zeta_{jb}) \cdot M \qquad \forall b \in B, \forall j \in V \qquad (6.23)$$

$$d_b \geq c_j + (\zeta_{jb} - 1) \cdot M \qquad \forall b \in B, \forall j \in V \qquad (6.24)$$

$$d_b - o_b \leq H - 1 \qquad \forall b \in B \qquad (6.25)$$

$$\delta_{jk}^T, \delta_{jk}^B \in \{0,1\} \qquad \forall j, k \in V, j \neq k \qquad (6.26)$$

$$\eta_{jpt}, \gamma_{jp}, \pi_{jt} \in \{0,1\} \qquad \forall j \in V \quad , \quad \forall p \in P_j \quad , \quad \forall t \in U \qquad (6.27)$$

$$\zeta_{jb}, \zeta_{jb}^U, \zeta_{jb}^L \in \{0,1\} \qquad \forall b \in B, \forall j \in V \qquad (6.28)$$

Constraints (6.20) – (6.25) are set up for consideration of re-planning based on the periodicity of the vessel schedule. Constraints (6.20) – (6.22) define the berth segment b that is occupied by Vessel j. Constraints (6.23) – (6.25) ensure the difference between o_b and d_b is within the planning horizon. Constraints (6.26) – (6.28) define the variables.

6.4.2 A mathematical model for the integrated Multi-continuous Berth Allocation Problem and Variable-In-Time Quay Crane Assignment (MBAP-VITQCA)

In order to model the MBAP-VITQCA model, the CBAP-VITQCA mode described in the previous section will be modified.

MBAP-VITQCA model

The objective function (6.2) and Constraints (6.3) – (6.8), (6.10), (6.15) – (6.28) will be the same.

Additional Input Data:

C	set of quay sections, $C = \{1,2\ldots C\}$
SL_c	starting point of quay section c
EL_c	ending point of quay section c

Decision variables:

y_{jc}	$\in [0, 1]$	set to 1 if vessel j is assigned to quay section c , and 0 otherwise
η_{jptc}	$\in [0, 1]$	set to 1 if QC-profile p is selected by vessel j and starts its handling at time step t at the quay section c, and 0 otherwise
ρ_{tc}	≥ 0	the number of QCs used at time step t at quay section c

Virtual Partitions constraint:

To introduce the concept of virtual partitions, the entire quay is divided into a set of quay sections C where no discontinuity or curve existing in each section $c \in C$, and a decision variable $y_{jc} \in [0, 1]$, where $j \in V, c \in C$, is also added. Constraint (6.29) ensures each Vessel $j \in V$ can be assigned to one quay section. Constraint (6.30) defines the variable.

$$\sum_{j \in V} \sum_{c \in C} y_{jc} = 1 \qquad \forall j \in V, \forall c \in C \qquad (6.29)$$

$$y_{jc} \in [0, 1] \qquad \forall j \in V, \forall c \in C \qquad (6.30)$$

Quay length constraint:

Since the quay is divided into a set of quay sections C, SL_c and EL_c are introduced to represent the starting point and ending point of section $c \in C$, and the length is calculated by $(EL_c - SL_c)$. Constraint (6.9) is no longer valid. Constraint (6.31) is introduced to consider the quay section length instead of the whole quay length (L) considered in Constraint (6.9) to ensure the feasibility of berthing position β_j for $j \in V$.

$$SL_c + u_j/2 - (1 - y_{jc})M \leq \beta_j \leq EL_c + (1 - y_{jc})M - u_j/2, \qquad \forall j \in V, \forall c \in C \qquad (6.31)$$

QC constraints:

Moreover, QCs usually cannot be transferred from one section to another section due to the discontinuities or curves on the quay. Therefore, the number of QCs available for service is also affected, and it should be counted individually in each section. Variable η_{jpt} is replaced by η_{jptc}, and Constraint (6.11) becomes invalid. Constraint (6.32) is then introduced to additionally recognize the section assigned to the vessel. Constraint (6.33) defines the variable.

$$\eta_{jptc} \geq \gamma_{jp} + \pi_{jt} + y_{jc} - 2 \qquad \forall j \in V, \forall p \in P_j, \forall t \in T, \forall c \in C \qquad (6.32)$$

$$\eta_{jptc} \in [0, 1] \qquad \forall j \in V, \forall p \in P_j, \forall t \in T, \forall c \in C \qquad (6.33)$$

Since η_{jpt} is replaced by η_{jptc}, Constraint (6.12) becomes invalid. Constraint (6.34) is introduced accordingly. Variable ρ_t is replaced by ρ_{tc}, and the number of QCs used at each time step t in each section is recorded by ρ_{tc}, where $t \in T$ and $c \in C$. Constraints (6.13) and (6.14) again become invalid. Constraints (6.35) and (6.36) are introduced respectively to ensure the number of QCs used at each time step will not exceed the available number of maximum QCs available in that section.

$$\rho_{tc} = \sum_{j \in V} \sum_{p \in P_i} \sum_{h=max\,(1;\, t-h_{jp}-1)}^{t} q_{jp(t-h+1)} \cdot \eta_{j,p,h,c} \qquad \forall t \in T, \forall c \in C \qquad (6.34)$$

$$\rho_{tc} \leq Q_{tc} \qquad \forall t \in \{1, 2, \dots H\}, \forall c \in C \qquad (6.35)$$

$$\rho_{tc} + \rho_{(t+H)c} \leq Q_{tc} \qquad \forall t \in \{1, 2, \dots E\}, \forall c \in C \qquad (6.36)$$

6.5 Summary

In this chapter, because of the existing of quay discontinuity in reality, multi-continuous berth layout model is studied to achieve better berth space utilization. Even though quay discontinuity exists in many real-world terminals, it has not been studied in the literature. However, the neglect of the quay discontinuity problem may result in infeasible berth allocation plan solutions in which vessels have been assigned to the positions presenting of sharp curves or disconnection. Although the problem has been mentioned by some papers, most of the existing models deal it by using discrete or hybrid model which may greatly reduce the utilization of the berth space. In this connection, a new MBAP-VITQCA model is proposed. It is noted that the quay discontinuity problem can be tackled by adding virtual berth partitions to the conventional continuous berth layout model. An existing CBAP-VITQCA model developed by Zhen *et al*., (2010), is selected for modification. The model embeds the QC-profile concept which simplifies the formulations of the VITQCA part. A multi-continuous berth layout MBAP-VITQCA model is developed based on the framework of the existing continuous berth layout model by introducing the concept of virtual berth partitions approach.

In the next chapter, the proposed model will be used for a tactical integrated operational planning. Numerical experiments will also be carried out to demonstrate the feasibility and the significance of the proposed model.

Chapter 7 An Integrated Model for Berth and Yard Planning With Multi-continuous Berth layout

7.1 Introduction

In this chapter, the feasibility and the significance of the proposed MBAP-VITQCAP model is tested. Meanwhile, the integrated berth allocation and quay crane assignment study is extended to consider the Storage Space Assignment (SSA) as well. Vessel berthing position is not only being a concern of BAP, but also plays an important role of SSA, especially in transshipment hubs. It is because vessel berthing position in BAP has strong impact on determining the total travelling time for transporting the unloading container from the vessel berthing position to its storage location, and the loading container from its storage location to the vessel berthing position. Therefore, to be more comprehensive, SSA should also be involved in the study of BAP.

Zhen *et al.* (2011a) recently developed a MIP model which covers berth and yard planning. In Chapter 6, a new MBAP-VITQCA model is proposed to consider the problem of quay discontinuity in the real-world terminal. In this chapter, MBAP-VITQCA model will be integrated with the yard model by using a local refinement approach proposed by Zhen *et al.* (2011a). Finally, a new Guided

Neighborhood Search (GNS) will be proposed to improve the solution quality and reduces the computational time of the vessel sequencing priority by replacing the critical-shaking neighborhood search (CSNS) used by Zhen *et al.* (2011a).

7.2 Mathematical modeling

In this section, the SSA model proposed by Zhen *et al.* (2011a) will be used. In that model, the transshipment hub utilizes the consignment strategy, which dedicates certain sub-blocks to each vessel. For all the transshipment containers and export containers requiring to be loaded onto the same vessel, they will be stored into the same group of dedicated sub-blocks. This approach can simplify the number of re-handling operations of containers inside the yard.

7.2.1 SSA model proposed by Zhen *et al.* (2011a)

In SSA model, the yard template decision (φ_{js}) deal with the assignment of Vessels j to sub-blocks s. The transshipment hub utilizes the consignment strategy, transshipping a number of containers from Vessels j to k (σ_{jk}). The yard related operation cost is the quantity of container to be transshipped from Vessel j to k times the summation of the unloading routes (λ_{jk}^{U}) and the loading routes(λ_{k}^{L}). Unloading routes (λ_{jk}^{U}) are the average distance between the sub-blocks s dedicated to Vessel k and the berthing position of Vessel j for each unloading container. Loading routes (λ_{k}^{L}) are the average distance between the berthing position of Vessel k and the sub-blocks s dedicated to Vessel k for each loading container. Moreover, Zhen *et al.* (2011a) also considered traffic congestion in the loading activity, i.e. it is not allowed that two or more sub-blocks, which share the same truck path or belong to the same block, operate loading activities at the same time step.

SSA model

Input Data:

B	set of berth segments, $B = \{1,2\ldots I\}$
V	set of vessels, $V = \{1,2\ldots J\}$
K	set of sub-blocks available, $K = \{1,2\ldots K\}$
N	set of pairs of sub-blocks that are neighbor, $N = \{1, 2\ldots N\}$
G	set of the groups of five sub-blocks that belong to the same block, $G = \{1,2\ldots G\}$
r_j	number of sub-blocks reserved for vessel j
ε_{jk}	number of transshipment containers from vessel j to vessel k
D^U_{sb}	unloading route travelling distance from berth segment b to sub-block k
D^L_{kb}	loading route travelling distance from sub-block k to berth segment b
w^Y	weighting of travelling distance of containers in yard
$l_{jpm} \in [0, 1]$	set to 1 if vessel j has to perform loading operation at time step m^{th} by QC-profile p, and set to 0 otherwise

ω_{jb} $\in[0, 1]$ set to 1 if vessel *j* is at berthing segment *b*, and 0 otherwise

θ_{jt} $\in[0, 1]$ set to 1 if vessel *j* has loading operation at time step *t*, and 0 otherwise

Variables:

ξ_{jts} $\in [0, 1]$ set to 1 if vessel *j* has loading operation at time step *t* and reserves sub-block *s* for storage, and 0 otherwise

φ_{ksjb} $\in[0, 1]$ set to 1 if vessel *k* reserves sub-block *s* and vessel *j* is berthing at segment *b*, and 0 otherwise

φ_{ksb} $\in[0, 1]$ set to 1 if vessel *k* reserves sub-block *s* and berthing at segment *b*, and 0 otherwise

λ_{jk}^{U} ≥ 0 the average unloading route travelling distance between the berthing position of vessel *j* and all the sub-blocks for vessel *k*

λ_{k}^{L} ≥ 0 the average loading route traveling distance between the berthing position of vessel *k* and all the sub-blocks for vessel *k*

Decision variables:

φ_{js} $\in [0, 1]$ set to 1 if vessel *j* reserves sub-block *s*, and 0 otherwise,

Objective function:

$$\text{Min } Z_3 = \omega^{Y} \sum_{j \epsilon V} \sum_{k \epsilon V, k \neq j} \varepsilon_{jk} \cdot (\lambda_{jk}^{U} + \lambda_{k}^{L}) \quad (7.1)$$

Constraints:

$\sum_{j \in V} \varphi_{js} \leq 1$	$\forall s \in K$	(7.2)
$\sum_{s \in K} \varphi_{js} = r_j$	$\forall j \in V$	(7.3)
$\xi_{jts} \geq \varphi_{js} + \theta_{jt} - 1$	$\forall j \in V, \forall t \in U, \forall s \in K$	(7.4)
$\sum_{s \in n} \sum_{j \in V} \xi_{jts} \leq 1$	$\forall t \in \{E+1, \dots H\}, \forall n \in N$	(7.5)
$\sum_{s \in g} \sum_{j \in V} \xi_{jts} \leq 1$	$\forall t \in \{E+1, \dots H\}, \forall g \in G$	(7.6)
$\sum_{s \in n} \sum_{j \in V} \xi_{jts} + \sum_{s \in n} \sum_{j \in V} \xi_{j(t+H)s} \leq 1$	$\forall t \in \{1, \dots E\}, \forall n \in N$	(7.7)
$\sum_{s \in g} \sum_{j \in V} \xi_{jts} + \sum_{s \in n} \sum_{j \in V} \xi_{j(t+H)s} \leq 1$	$\forall t \in \{1, \dots E\}, \forall g \in G$	(7.8)
$\lambda_{jk}^{U} = (\sum_{s \in K} \sum_{b \in B} \varphi_{ksjb} \cdot D_{sb}^{U})/r_k$	$\forall j, k \in V, j \neq k$	(7.9)
$\lambda_{k}^{L} = (\sum_{s \in K} \sum_{b \in B} \varphi_{ksb} \cdot D_{sb}^{L})/r_k$	$\forall k \in V$	(7.10)
$\varphi_{ksjb} \geq \varphi_{ks} + \omega_{jb} - 1$	$\forall j, k \in V, j \neq k, \forall s \in K, \forall b \in B$	(7.11)
$\varphi_{ksb} \geq \varphi_{ks} + \omega_{kb} - 1$	$\forall k \in V, \forall s \in K, \forall b \in B$	(7.12)
$\varphi_{ksjb}, \varphi_{ksb} \in \{0,1\}$	$\forall i, j \in V, i \neq j, \forall k \in K, \forall b \in B$	(7.13)
$\varphi_{js}, \xi_{jts}, \in \{0,1\}$	$\forall i \in V, \forall t \in T, \forall k \in K$	(7.14)
$\lambda_{i,j}^{U}, \lambda_{j}^{L} \geq 0$	$\forall i, j \in V, i \neq j$	(7.15)

Constraint (7.2) ensures each sub-block can at most be reserved by only one vessel. Constraint (7.3) ensures a sufficient number of sub-blocks to be available to all incoming vessel. Constraint (7.4) links variables φ_{js} and θ_{jt} by ξ_{jts}. Constraints (7.5) and (7.6) ensure two sub-blocks, which share the same truck path or belong to the same block, cannot have a simultaneously loading process throughout the planning horizon at every time step. Constraints (7.7) and (7.8) consider periodicity. Constraint (7.9) calculates the average travelling distance for the loading route between the berthing position of Vessel j and all the sub-blocks reserved for Vessel j. Constraint (7.10) calculates the average travelling distance for the loading route between the berth position of Vessel j and all the sub-blocks reserved for Vessel j. Constraint (7.11) links variables φ_{ks} and ω_{jb} by φ_{ksjb}, while Constraint (7.12) links variables φ_{ks} and ω_{jb} by φ_{ksb}. Constraints (7.13) – (7.15) define the variables.

7.2.2 Mathematical model for the integrated Multi-continuous Berth Allocation Problem, Variable-In-Time Quay Crane Assignment and Storage Space Assignment (MBAP-VITQCA-SSA)

In this sub-section, the MBAP-VITQCA model proposed in Chapter 6 will be combined with the above SSA model with the same notations to form an integrated MBAP-VITQCAP-SSA model. The objective function (7.16), which combines the objective functions (6.2) and (7.1), aims at minimizing the total vessel servicing cost induced by the deviation of expected turnaround time for vessels, and the total operation cost induced by the transshipment of the containers from the quay space to the yard storage sub-block. After that, a local refinement procedure and an iterative heuristic algorithm proposed by Zhen *et al.*

(2011a) are presented to show how these two models are linked up.

MBAP-VITQCA-SSA model

Objective function:

Min $Z_4 = \sum_{j \in V}(\omega_j^{Be} \cdot (a_j^e - s_j)^+ + \omega_j^{Bt} \cdot (c_j - b_j^e)^+) + \omega^Y \sum_{j \epsilon V} \sum_{k \epsilon V, j \neq k} \varepsilon_{jk} \cdot$

$(\lambda jkU + \lambda kL)$

(7.16)

Subject to:

Constraints (6.3) – (6.8); (6.10); (6.15-36); (7.2) – (7.15);

Local Refinement

The idea of Local Refinement is to link up the two models, MBAP-VITQCA and SSA, with a feedback loop to improve the solution quality, e.g. further minimize the service cost and operation cost, by adjusting berth and yard related decision variables. First of all, the MBAP-VITQCA model is solved, and β_j obtained by solving the MBAP-VITQCA model will be converted to ω_{jb}. Similarly, θ_{jt} will be derived by the two variables (η_{jpt} and l_{jpm}) obtained by the MBAP-VITQCA model. Then, the variables ω_{jb} and θ_{jt} will input to the SSA model. After the SSA model is solved, the yard related decision (φ_{js}) is temporary determined. Local refinement then refines the solutions obtained from the MBAP-VITQCA-SSA model by fixing the yar

d-related decision (φ_{js}), then reverses the direction, and fixes the improved berth-related decisions (ω_{jb} and θ_{jt}) to optimize the yard-related decision. It reverses the directions iteratively until no improvement can be obtained. For large scale problems, to solve the MBAP-VITQCA-SSA model, a proportion α of the δ_{jk}^{T} and δ_{jk}^{B} parameters is suggested to be fixed, and an Iterative Heuristics Algorithm proposed by Zhen *et al.* (2011a) is used. The procedure is shown as follows:

<u>Algorithm 1: Iterative Heuristic Algorithm</u>

Without considering the SSA model, solving the MBAP-VITQCA model for large scale problem is already difficult as it combines berth allocation with quay crane assignment. Thus, given an initial priority sequence of vessels generated by priority rules, Zhen *et al.* (2011a) propose a sequence method to search for a feasible solution with a reasonable computational time. The priority rules and the mechanism of the sequence method are discussed in section 7.3.

1: Input: Vessel Priority Sequence (σ)
2: *bool* = True;
3: For n = 1 to *N-DS* // *N* is the number of vessels, while depth of search (*DS*) = 10 is suggested by Zhen *et al.* (2011a)
4: Solve the MBAP-VITQCA model;
5: Do{
6: Input variables: ω_{jb} and θ_{jt}
7: Solve the SSA model;
8: Fixed variable: φ_{js} and α of δ_{jk}^{T} and δ_{jk}^{B}
9: Solve the α-MBAP-VITQCA-SSA model; //Local Refinement, set *bool* = False if no improvement achieved
10: }While (*bool*)

7.3 Methodology

7.3.1 Discussion on sequential method and CSNS heuristic for large scale problem

Zhen *et al.* (2011a) mentioned that for large number of vessels, it is intractable to solve the integrated BA and QCAP even without considering the yard storage sub-block assignment. Thus, in order to obtain a good feasible solution within a reasonable computational time, they proposed a sequential method to solve the problem. A priority sequence of N vessels, and a parameter called Depth of Search (DS) are used to define the number of iterations ($N-DS$) conducted and the number of vessels ($DS+1$) involved in the iteration. Figure 7.1 shows an example of the procedures. Given N = 10 and DS = 5, in the 1st iteration (i = 1), the first six vessels (5+1 = 6) are solved. In the 2nd iteration (i = 2), the decision variables of the first vessel is fixed, and the second six vessels are solved and so on. Hence, Vessel 7 will never be considered with Vessel 4 in the same iteration, similar as Vessel 9 with Vessels 4 and 3, and so on. Therefore, the priority sequence of vessels becomes more critical as it determines not only the service priority, but also the groups of vessels being considered together.

To generate the initial priority sequence of the vessels, Zhen *et al.* (2011a) proposed two priority rules to generate an initial vessel service sequence (the priority is in descending order): (1) by the weighting of ω_j^{Be} or ω_j^{Bt}, and (2) by the ratio of $\frac{min_{p\in P_j} h_{jp}}{b_j^M - a_j^M + 1}$, $j \in V$, which is the minimum handling time required divided by the maximum turnaround time interval of the vessel. In such a ratio, a large value implies the slack time for the vessel is less. Thus those vessels with higher ratio should be ranked with a higher priority. To further improve the quality of solution, CSNS is adopted to change the priority sequence of the vessels. Critical elements will be identified and randomly changed their priority. Any vessel can be regarded as critical as long as they have a high objective value. The procedure of CSNS is shown as follows (Algorithm 2).

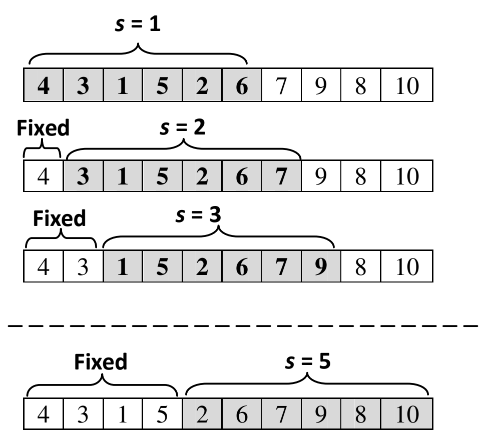

Figure 7.1 Sequential method proposed by Zhen *et al.* (2011a)

Algorithm 2: Critical-shaking neighborhood search (CSNS)

1: Generate initial sequence σ_0 for the N vessels according to the priority rule
2: Let σ and the optimal sequence σ_{opt} be σ_0;
3: Let L be the maximum check ($L_{max} = 5$);
4: Do{
5: Input: σ
6: *Algorithm 1: Iterative Heuristic algorithm*;
7: Select a number of NC critical elements, which have the highest cost value V_i from σ;
8: Randomly shake the critical elements priority to generate a new σ′.
9: If σ′ has already been generated before, a new σ′ will be randomly generated;
10: Input: σ′
11: *Algorithm 1: Iterative Heuristic algorithm*;
12: If (σ′ is better than σ_{opt})
13: then{
14: $\sigma_{opt} \leftarrow \sigma'$;
15: $L \leftarrow L_{max}$;
16: $\sigma \leftarrow \sigma'$;}
17: else{
18: $L = L-1$;}
19: } While ($L > 0$)

However, it is noted that the random movement maybe ineffective, and may result in a very long and unstable computational time. Therefore, a new guided neighborhood search is proposed to change the sequence effectively.

7.3.2 The proposed GNS heuristics

In this section, GNS is introduced to change the vessel priority sequence. Given i) the priority sequence of vessels, and ii) the objective cost of each vessel (V_j), the critical level ℓ as a portion ∂ of the highest vessel objective cost are defined by experiments (Lim and Xu, 2006). The vessels, whose objective cost above ℓ, are identified as the critical elements for changing the priority. Since some of the vessels with the highest V_j may have no further room for improvement, especially for those who already have had high priority, the critical elements search will start from the vessel with priority (DS+2), because the first (DS+1) vessels have already been solved simultaneously in the 1st iteration. Before changing the priority of the critical elements, two-way movement is suggested, including forward movement and backward movement. Forward movement promotes the priority of the critical element, while backward movement lightens its priority. It is noted that the critical elements are used to compete the resources, such as berthing location, berthing time, yard storage space, etc., with some other vessels. Therefore, it is suggested the critical elements to be moved or inserted into a new position in the vessel priority sequence in order to be considered with its potential competitor in the same iteration. For example in Figure 7.2, if DS = 4, for the Case 1, Vessel 8 with the priority x is selected as the one of the critical elements. Vessel 2 with the priority j, which is higher than x, is the potential competitor. In this case, forward movement is suggested for Vessel 8 for higher priority, and it is randomly inserted into the priority between (j-1) and (j+DS+1) in order to involve both vessels in the same iteration. Similarly, for Case 2, if backward movement is suggested, Vessel 1 with priority x should be inserted randomly between the priorities (j+1) and (j-DS+1).

To decide which type of movement should be used for the critical element, the reason accounting for the high cost will be check first. Since the objective cost is comprised of: i) the berth part, and ii) the yard part, the costs caused by each part will be compared and determined which part induces the most. If it is from the berth part, it will check whether the cost is related to the deviation caused by earliness or tardiness. Backward movement is suggested if the deviation involves only earliness, otherwise a forward movement is suggested. If it is from the yard part, forward movement is suggested.

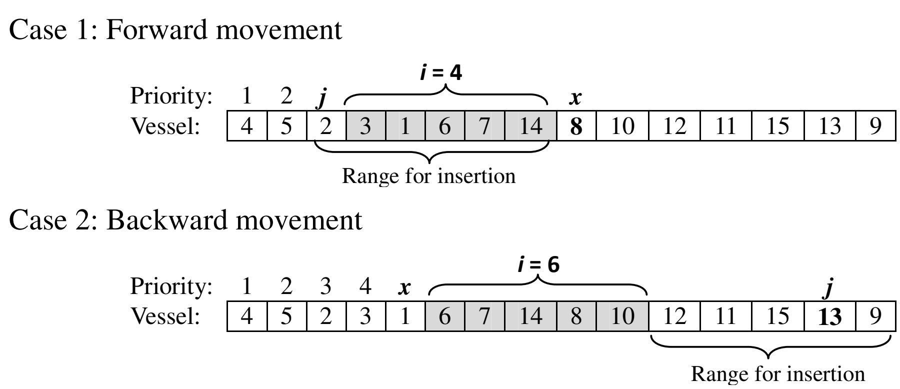

Figure 7.2 Forward and backward movement of the vessel priority

To identify the position for the insertion of critical element, the corresponding potential competitors should be firstly identified. The planning horizon is divided into a number of time intervals based on the average vessel handling time, i.e. 4

time steps as a time interval. Vessels are then assigned to the interval when they berth. Since it is critical to allocate resources (i.e. berth space, QCs, etc.) to the vessels within the same or the adjacent time intervals, these critical vessels should be considered in the same iteration because they most likely are competing with each other. For those whose high cost is mainly come from the berth part, if the deviation involves only earliness, or both earliness and tardiness, it means the vessel may not berth at its desired berthing time. Those vessels working at the same or the adjacent time intervals will be regarded as potential competitors. If the deviation involves only tardiness, it may be because of insufficient QC resources assigned to the vessel. Similarly, the vessels working at the same or adjacent time intervals can be regarded as potential competitors as they compete with each other for the QC resource. It may also be because of the assigned quay section does not have sufficient QC resources. In this case, the potential competitors should be those assigned to the section with sufficient QC resources while working at the same or the adjacent time intervals. For those whose high cost mainly comes from the yard part, it is affected mainly by the transshipment volume and transportation distance. Those vessels berthed in the same locations compete the nearest yard storage sub-block with each other. Moreover, the transshipment volume has not been considered in the priority rules. Therefore, the vessels with higher priority berthing at the same location with fewer transportation volumes can be regarded as potential competitors. Moreover, the vessels should also be considered with their transshipment partners in the same iteration. The overall procedures of GNS are shown as follows (Algorithm 3):

Algorithm 3: Guided neighborhood search (GNS)

Generate initial sequence σ_0 for the N vessels according to the priority rule
Let σ and the optimal sequence σ_{opt} be σ_0;
Let L be the maximum check ($L_{max} = 3$);
Do{
    Input: σ
    Algorithm 1: Iterative Heuristic algorithm;
        Select a number of NC critical elements whose $V_j \geq \ell$;
        for ($n = 1$ to $n = NC$) {
        Forward movement || backward movement;
        Identify the potential competitor for each critical element;
        Change the priority of the critical elements within the suggested range ;}
    A new σ' generated. If σ' has already been generated before, generates a new one;
    Input: σ'
    Algorithm 1: Iterative Heuristic algorithm;
    If (σ' is better than σ_{opt})
    then{
        $\sigma_{opt} \leftarrow \sigma'$;
        $L \leftarrow L_{max}$;
        $\sigma \leftarrow \sigma'$;}
    else{
        $L = L - 1$;}
} While ($L > 0$)

7.4 Numerical Experiments

In this section, the generation of the test instances and parameter settings is described. Moreover, numerical experiments are provided to verify the solution quality of the proposed GNS and to demonstrate the significance of multi-continuous berth layout model. The proposed approach was programmed in JAVA language with a 64-bit version of CPLEX, and ran on a PC with a CPU of 1.33GHz and 8GB RAM.

7.4.1 Generation of test instances

Test instances is generated based on the framework provided by Zhen *et al.* (2011a), and then it is extended into multi-continuous berth layout. In this study, every day is divided into 6 time steps, and a planning horizon covers one week (7 days) with a total of 42 time steps. The test instances are classified into six problem scales as shown in Table 7.1. Since the study considers quay discontinuities, the quay was divided into 2 quay sections in problem scales with 15 to 30 vessels, and 3 quay sections in problem scales with 40 to 60 vessels. QC capacity in each section is also given in Table 7-1. The vessels served by the terminal can be classified into three groups: (i) Feeder, (ii) Medium, and (iii) Jumbo, according to the technical specifications shown in Table 7-2. This information is also used for generating the QC-profiles. It is also assumed the QC productivity is about 30 containers per hour. This assumption meets the common requirement of terminals. Vessels can arrive randomly along the planning horizon.

The feasible time windows [a_j^M, b_j^M], and the expected time window [a_j^e, b_j^e] can be the same or at a maximum five times its average handling time. It is assumed that the average loading and unloading container tasks are set to be half and half ratio for each vessel, and all containers are of 40-ft size (equal to two TEUs). The number of containers transshipped from Vessel j to Vessel k (ε_{jk}), can be randomly generated without violating the total number of loading and unloading containers of the vessel. The number of sub-blocks required for Vessel j (r_j) is generated according to its container volume. Moreover, some assumptions on yard configuration are also made, as in other yard studies. It is assumed that each block consists of 5 sub-blocks, and each sub-block is a basic unit for yard template planning. The capacity and the length of a sub-block are about 240 TEUs and 50m. Every passing lane is set to be 30m in width. To ensure the same order of magnitude in costs related to berth and yard, ω^Y is set as 5×10^{-6}.

Table 7-1 Test instances classes

Number of Vessels	Number of subblocks	Total quay length (m)	No of quay sections	Quay section length (m) [Number of QCs available in each section]		
				Section 1	Section 2	Section 3
15	80	500	1	500 [5QCs]	--	--
20	120	700	2	300 [4QCs]	400 [3QCs]	--
30	160	1100	2	500 [6QCs]	600 [5QCs]	--
40	240	1500	3	500 [6QCs]	600 [5QCs]	400 [4QCs]
50	300	1800	3	500 [6QCs]	800 [5QCs]	500 [7QCs]
60	360	2000	3	500 [6QCs]	800 [6QCs]	700 [8QCs]

Table 7-2 Test instances classes

Class	Vessel length (m)	QC Capacity	Handling time (time steps)	Average handling time (time steps)	workload (QC × time step)	Earliness and Tardiness Weightings (ω_i^{Be}& ω_i^{Bt})	Total number of unloading and loading containers (TEU)	The number of subblocks reserved for vessel
Feeder	100-200	1-3	2-4	3	2-5	2-6	240-600	2-3
Medium	200-300	2-4	3-5	4	6-14	6-10	720-1680	2-4
Jumbo	300-400	3-6	4-6	5	15-20	10-14	1800-2400	8-10

7.4.2 Testing the optimization quality of the proposed algorithm: GNS

To verify the solution quality of the proposed GNS approach, CSNS approach proposed by Zhen *et al.* (2011a) is used as the benchmarking approach. As suggested by Zhen *et al.* (2011a), *DS* is set as 10 for all instances, and for the large scale instances, the parameter α is applied and set as 0.2 for 40 vessels, 0.3 for 50 vessels, and 0.4 for 60 vessels in both the CSNS and GNS approaches. The results obtained from the experiment are presented in Table 7-3.

For the small scale problems, no obvious improvement in objective value can be seen from the results. However, for large scale problems, as the difficulty increases with the problem scale, the searching ability of the algorithm becomes more significant to the solution quality. By improving the procedure of changing the vessel priority sequence, the proposed GNS approach can achieve a maximum improvement of 7% in the objective value. Moreover, a maximum of 45%

reduction in computational time can be achieved. The results show that the proposed GNS can obtain better results more effectively in large scale problems. It is also noted that the enhanced searching mechanism in the GNS approach can reduce the number of checking trials from 5 to 3 times. Since the computational time for each trial is very long, such reduction can significantly reduce the computational time in both small and large scale problems.

Table 7-3 Results of comparing GNS with CSNS

Small Scale Problem							Large Scale Problem						
Instances	CSNS		The proposed GNS				Instances	CSNS		The proposed GNS			
	Obj	Time (min)	Obj	Improvement (%)	Time (min)	Improvement (%)		Obj	Time (min)	Obj	Improvement (%)	Time (min)	Improvement (%)
15-1	368	18	368	0.00	12	33.33	**40-1**	715	116	699	2.30	87	25.00
15-2	326	7	326	0.00	5	28.57	**40-2**	723	147	709	1.89	67	54.42
15-3	360	16	360	0.00	10	37.50	**40-3**	712	183	694	2.46	146	20.22
15-4	355	14	355	0.00	10	28.57	**40-4**	809	212	798	1.37	141	33.49
15-5	393	26	393	0.00	18	30.77	**40-5**	726	134	713	1.84	96	28.36
15-6	342	13	342	0.00	8	38.46	**40-6**	776	129	749	3.45	90	30.23
15-7	328	11	328	0.00	7	36.36	**40-7**	723	102	705	2.55	74	27.45
15-8	395	17	395	0.00	11	35.29	**40-8**	814	155	800	1.74	121	21.94
15-9	367	15	367	0.00	10	33.33	**40-9**	745	134	727	2.48	101	24.63
15-10	369	16	369	0.00	12	25.00	**40-10**	787	162	763	3.1	135	16.67
20-1	454	45	454	0.00	32	28.89	**50-1**	1076	289	937	4.12	224	22.49
20-2	437	28	437	0.00	17	39.29	**50-2**	1119	224	1060	5.31	162	27.68
20-3	474	62	471	0.63	34	45.16	**50-3**	1247	279	919	4.26	186	33.33
20-4	420	69	420	0.00	51	26.09	**50-4**	903	191	875	3.05	114	40.31
20-5	416	55	414	0.48	34	38.18	**50-5**	947	164	902	4.71	91	44.51
20-6	482	66	482	0.00	44	33.33	**50-6**	1238	266	968	5.08	193	27.44
20-7	451	48	448	0.67	28	41.67	**50-7**	1110	272	1074	3.21	197	27.57
20-8	422	34	420	0.47	21	38.24	**50-8**	946	161	901	4.79	120	25.47
20-9	451	57	446	1.11	38	33.33	**50-9**	1043	187	1010	3.21	149	20.32
20-10	417	54	414	0.72	42	22.22	**50-10**	951	195	907	4.67	106	45.64
30-1	658	159	652	0.91	119	25.16	**60-1**	1364	285	1263	7.4	200	29.82
30-2	593	124	589	0.67	83	33.06	**60-2**	1527	294	1431	6.3	229	22.11
30-3	646	204	631	2.32	130	36.27	**60-3**	1308	371	1228	6.12	216	41.78
30-4	600	140	599	0.17	86	38.57	**60-4**	1342	344	1240	7.57	258	25.00
30-5	627	93	624	0.48	56	39.78	**60-5**	1460	410	1369	6.22	261	36.34
30-6	635	172	628	1.10	109	36.63	**60-6**	1453	267	1371	5.61	205	23.22
30-7	580	89	573	1.21	60	32.58	**60-7**	1517	397	1420	6.37	265	33.25
30-8	661	167	660	0.15	106	36.53	**60-8**	1336	210	1253	6.22	134	36.19
30-9	604	108	594	1.66	72	33.33	**60-9**	1305	322	1212	7.11	193	40.06
30-10	628	169	620	1.27	127	24.85	**60-10**	1387	277	1312	5.43	215	22.38

7.4.3 Significance of the multi-continuous berth layout model

This thesis addresses a very realistic berth layout characteristic - quay discontinuity, and proposes using a multi-continuous berth layout model to deal with it. To demonstrate the significance of the proposed model, conventional continuous berth layout model will be used for comparison. However, as conventional continuous berth layout model cannot be directly applied in a terminal with quay discontinuity, a practical simple heuristic approach is applied for vessel-to-berth allocation first of all. Vessels will be assigned according to the ascending order of their arrival time. After that, optimization on each quay section by using the conventional continuous berth layout model can be carried out.

Experimental results are summarized as in Table 7-4. Both the practical heuristic approach and the proposed multi-continuous approach can obtain feasible solutions. However, the results show that the difference in computational time(s) required by these two approaches is quite large with a maximum of 450%. It is because vessels have already been assigned to the quay section, and the problem scales of each section become much smaller and easier. Since these approaches are for the decision making at the tactical level, the computational time required is acceptable in practice as said by terminal operators. However, it is significant that the proposed GNS approach can improve the performance in small scale problem by about 8 to 12 %, and even up to 44 % in large scale problems. These improvements are remarkable and can prove the significance of the proposed multi-continuous berth layout model.

Table 7-4 Results of comparing GNS with the practical approach

Instances	Practical Approach		The proposed GNS approach			
	Obj	Time (min)	Obj	Improvement (%)	Time (min)	Time Gap (%)
20-1	498	11	454	8.84	32.00	190.91
20-2	461	6	437	5.21	17.00	183.33
20-3	510	8	471	7.60	34.00	325.00
20-4	451	20	420	6.79	51.00	155.00
20-5	435	7	414	4.91	34.00	385.71
20-6	522	8	482	7.59	44.00	450.00
20-7	477	13	448	6.08	28.00	115.38
20-8	453	11	420	7.24	21.00	90.91
20-9	473	14	446	5.77	38.00	171.43
20-10	444	18	414	6.83	42.00	133.33
30-1	705	40	652	7.52	119.00	197.50
30-2	633	31	589	6.95	83.00	167.74
30-3	706	36	631	10.62	130.00	261.11
30-4	659	27	599	9.10	86.00	218.52
30-5	681	24	624	8.37	56.00	133.33
30-6	702	40	628	10.54	109.00	172.50
30-7	647	22	573	11.44	60.00	172.73
30-8	731	38	660	9.71	106.00	178.95
30-9	646	31	594	8.05	72.00	132.26
30-10	708	48	620	12.43	127.00	164.58
40-1	855	54	699	18.25	87.00	61.11
40-2	964	33	709	26.45	66.82	102.48
40-3	894	42	694	22.37	146.40	248.57
40-4	995	39	798	19.80	141.33	262.39
40-5	872	47	713	18.23	95.71	103.65
40-6	950	45	749	21.16	90.30	100.67
40-7	890	30	705	20.79	74.18	147.27
40-8	1078	59	800	25.79	120.56	104.33
40-9	924	49	727	21.32	100.50	105.10
40-10	1001	67	763	23.78	135.00	101.49
50-1	1316	84	937	28.80	224.00	166.67
50-2	1528	102	1060	30.64	162.00	58.82
50-3	1365	68	919	32.67	186.00	173.53
50-4	1206	72	875	27.44	114.00	58.33
50-5	1352	88	902	33.28	91.00	3.41
50-6	1433	76	968	32.45	193.00	153.95
50-7	1496	84	1074	28.21	197.00	134.52
50-8	1303	86	901	30.84	120.00	39.53
50-9	1415	97	1010	28.64	149.00	53.61
50-10	1257	64	907	27.82	106.00	65.63
60-1	2112	122	1263	40.20	199.50	63.52
60-2	2332	96	1431	38.64	228.67	138.19
60-3	1955	88	1228	37.19	216.42	145.93
60-4	1959	132	1240	36.70	258.00	95.45
60-5	2353	103	1369	41.82	260.91	153.31
60-6	2104	126	1371	34.84	205.38	63.00
60-7	2561	163	1420	44.55	264.67	62.37
60-8	1750	84	1253	28.40	133.64	59.09
60-9	1736	87	1212	30.18	193.20	122.07
60-10	2109	141	1312	37.79	215.44	52.80

Time Gap % = (Time(GNS) – Time(practical))/ Time(practical)

7.5 Summary

This chapter combines the proposed mixed integer linear programming model of MBAP-VITQCA with the SSA model based upon the existing integrated berth and yard template model proposed by Zhen *et al.* (2011a). The proposed model can be applied in real-world container terminals with quay discontinuities, while enhancing the utilization of each quay section. The objective of the integrated model aims at minimizing the total vessel service cost caused by the deviation of the expected turnaround time, and the total operating cost caused by the transshipment of the containers from the quay space to the yard storage location. Moreover, GNS is proposed for a more effective search of the vessel priority sequence. A set of numerical experiments are conducted, and the results showing that the proposed GNS obtains a better solution comparing to the existing CSNS approach in terms of solution quality and computational time. To demonstrate the significance of the proposed multi-continuous berth layout model, a practical heuristic approach is applied for comparison. Although the computational time required by the proposed approach is longer than that of the practical heuristic approach, it is acceptable in tactical planning. However, the experimental results show a remarkable improvement in the objective value obtained by using the proposed multi-continuous approach.

Chapter 8 Conclusions and Suggestions for Future Research

8.1 Conclusions

This research study embarks on studying a scheduling problem related to berth allocation with an ultimate objective to maximize the efficiency of terminal operations in order to improve resource utilizations in container terminals. BAP determines when and where the incoming vessels should berth. It has been recognized as the leading problem among various planning problems at container terminals as it is the first services provided right before others such as quay cranes, trucks, yard, etc. BAP determines the overall terminal productivity and profitability. This conclusion summarizes the achievements of the thesis study.

In Chapter 1, an introduction is presented, including the problem background, scope, objectives, and the expected deliverables. In Chapter 2, a detail literature review is carried out and discussed on BAP, BA-QCAP, and the related optimization algorithms in the field.

In Chapter 3, vessel service priority is studied. BAP has huge impact on customer service quality because it determines the vessel waiting time, etc. To guarantee good service quality, it is a common practice for a terminal to partner with their nearby terminals to provide services. They will transfer vessels to their partner terminal to carry out the unloading and loading operations if they cannot provide service within a certain period, such as the common practice 2 hours in Hong Kong. However, transfers induce various drawbacks, such as extra transshipments cost. In addition, although vessels can be immediate service by transferred, it may induce negative impact to its reputation. Therefore, a detail studied is carried out with the objective to minimize the total vessel servicing time, the total transfer cost, and the transferring of important customers. In the literature, vessel priority always depends on either one of the two main factors: i) customer relationship with the terminal, and ii) vessel handling volume. In fact, both factors are important as one represents the long term relationship while the other represents immediate profit. In this connection, DBAP-priority-RH modeling is proposed to holistically consider both factors to improve the services of more important customer meanwhile handling more containers. In addition, BAP is well known to be NP-hard, therefore a meta-heuristics algorithm named GA-BAP is designed to deal with it. To verify the optimization performance of GA-BAP, numerical experiments are carried out to compare it with the one proposed by Liang *et al.* (2012). The results demonstrate that about 2.3% improvement is obtained by the proposed GA-BAP. This shows that the proposed algorithm can obtain better solution quality. To test the significance of considering both factors simultaneously, another experiment is conducted. In which, a total of 75 sets test instances is created. The three other existing algorithms for vessel service priority are used for comparison, including (i) considering only customer relationship with the terminal (DBAP-priority-R), (ii) considering only vessel handling volume (DBAP-priority-H), and (iii) First-come-first-served approach (DBAP-FCFS).

The results demonstrate that if only either the customer relationship or vessel handling volume is considered, the other one will be sacrificed significantly. The proposed DBAP-priority-RH modeling is able to make a trade-off between them, so that it makes good adjustments in serving more important customers while maximizing the handling volume.

However, in this chapter, the developed DBAP-priority-RH is modeled in a discrete berth layout. In which, the entire quayside is partitioned into several berths and only one vessel can be assigned to a berth at a particular time. Moreover, deterministic vessel handling time is also assumed and depended on the berthing position and the pre-assigned number of QCs. However, as there are strong inter-relationship between BAP and QCAP, they should be planned simultaneously and becomes the focus of the next chapter.

In Chapter 4, an integrated BAP and QCA is studied, aiming at minimizing the total vessel waiting time, vessel handling time, and delay departure time. It consists of the additional variables and constraints for quay crane assignment. To deal with it, a MIP-DBAP-QCA model is developed. For small scale problems, the model can be solved mathematically. However, for medium to large scale problems, the model cannot be solved in 15 hours. In this connection, a new decomposition approach - TLGA is proposed. It is composed of two genetic based algorithms: QCAGA and VSGA. The first one is designed to determine the quay crane assignment and the latter one is designed to determine the corresponding vessel schedule. Since these decisions are interrelated, the two algorithms interact iteratively to determine the final solution. Numerical experiments are carried out to testify the optimization reliability of the proposed TLGA. The solutions obtained by TLGA are compared to those determined by the existing algorithm proposed in the literature, and the optimal results obtained by CPLEX. The comparisons indicate that the proposed TLGA is an effective approach which can find a good solution in a shorter computational time acceptable for practical use. It also demonstrates that the problem decomposition mechanism employed in TLGA works properly in the integrated problem. By using TLGA, the total vessel service time can be reduced and the berth utilization can be improved.

Although in this chapter the DBAP-QCA model presents one of the practical ideas in integrated berth allocation and quay crane assignment modeling, QCs-to-berth assignment is assumed. In literature, QCs-to-vessels is also being suggested, which can be classified into: (i) time invariable quay crane assignment which assigns a constant number of QCs to vessels over the whole service period, and (ii) variable-in-time QCA which allows the number of QCs being assigned to vessels varying along the whole service period. In this connection, the variable-in-time quay crane assignment modeling is further studied in the next chapter.

In Chapter 5, BA-VITQCAP is studied. The benefits of time varying quay crane assignment in terms of utilization are the focus. It is getting more common for vessels with small handling volumes and with very short port staying time, especially to the transshipment hubs in Southern East-Asia. In literature, BAP and QCAP are always modeled in hourly based, and this assumption may reduce the

QCs utilization significantly and induce unnecessary vessel waiting time. Accordingly, a 15-minute based time segments DBAP-VITQCA model is proposed. It is mathematically formulated to better understand the structure of the VITQCA. Since the computational complexity of the problem is increased dramatically with using the proposed finer time segments, a new methodology named 3LGA has been developed to deal with it. A QC shifting heuristics is embedded in 3LGA to facilitate the variable-in-time quay crane assignment. 3LGA decomposes the problem into three levels. The first level aims at allocating vessels to berths, the second level aims at sequencing vessels, and the third level aims at sequencing quay cranes. The optimization performance of 3LGA is demonstrated by comparing it with other approaches including SGA and 2-level GA (which applied the idea of TLGA in Chapter 4). The results show that 3LGA outperforms the other two by obtaining better solutions. Another numerical experiment is conducted to demonstrate the significance of using 15-minute based time segments. The results show a significant improvement obtained on the waiting time and handling time obtained by the 15-minute based time segments comparing with the traditional hourly based segments. These can conclude that the proposed 3LGA is capable of providing better QCs utilization and achieving fast vessel turnover.

In this chapter, although improvement can be obtained by variable-in-time quay crane assignment approach, the berth layout is in discrete. In the literature, continuous berth layout modeling is suggested to be a better berth space utilization as it can provide a more flexible berth allocation plan to the terminals.

With a trend towards vessel owners prefer using mega-vessels, container terminals nowadays have demanded more flexibility in berth plan in order to handle different sizes of vessels. In this connection, continuous berth layout is studied in the next chapter.

In Chapter 6, multi-continuous berth layout is studied. It is observed that quay discontinuity can be found easily in many real-world container terminals. However, this problem has not been studied in most of the existing continuous berth layout models found in the literature. The neglect of the quay discontinuity problem may result in infeasible berth plan in which vessels may be assigned to the positions where sharp curves or disconnection may exist. In fact, the problem has been mentioned in some research studies, and most of the existing models have been dealt with it using discrete or hybrid models. However, such modeling approach may greatly reduce berth space utilization. In this connection, a new berth layout model named multi-continuous berth layout MBAP-VITQCA model is proposed. In the model, the quay discontinuity problem is tackled by adding a new idea named virtual berth partitions approach to the conventional continuous berth layout model. In addition, various additional constraints are introduced according to the new virtual berth partitions approach.

Lastly in Chapter 7, the MBAP-VITQCA model is further integrated with the storage space assignment model proposed by Zhen et al. (2011a) to form the MBAP-VITQCA-SSA model. The objective aims at minimizing the total vessel service cost caused by the deviation of the expected turnaround time of vessels, and the total operating cost caused by the transshipment of the containers from the berth space to the yard storage sub-block. Because of the huge problem complexity in the large scale problem, a methodology named GNS is proposed. Numerical experiments are carried out, and the results show that the proposed GNS obtains a better solution and shorter computational time when comparing with the existing CSNS approach. To demonstrate the significance of the proposed multi-continuous layout modeling, numerical experiments are carried out to compare it with the practical heuristic approach by using the conventional continuous berth layout model. Although the computational time required by the proposed multi-continuous modeling is longer than that of the practical approach, it is acceptable because it is in tactical planning level. However, more importantly, the results show that using the proposed multi-continuous approach can obtain much better improvement in the objective value. It can be concluded that the proposed model is more realistic and is feasible to be applied in the real-world container terminals with discontinuities on the quay to enhance the utilization of each quay section.

8.2 Limitations and Future Research Perspectives

Despite the achievements in this study of the BAP, it is subject to some limitations. The followings summarize the limitations and provide some suggestions for future works:

Uncertainties in operation planning

In this research, uncertainties have not been considered. In fact, many uncertainties exist in BAP and QCAP, such as vessel arrival time, QC breakdown, container loading and unloading processing time, bad weather, etc. Therefore, future research is suggested to consider the uncertainties related to vessel arrival and container handling related issues.

QC Interference

In this research, many assumptions have been made, for example QC traveling time has been ignored. The interference among the QCs is insignificant, and the container handling rate is linear proportional to the number of QCs being assigned. In fact, QCs cannot move freely among berths, a high number of QCs working for the same vessel can end up with high interference among the QCs and reduce the efficiency of loading and unloading operations. The actual QC traveling time including QC interference is studied in quay crane scheduling problem (QCSP). Thus, future research is suggested to take into the account of the actual QC traveling time by considering QCSP simultaneously.

Finer time segments modeling

In this research, the importance of using finer time segments in BAP and QCA modeling has been studied and demonstrated. It can significantly reduce berth and QC idle time to improve the overall utilization, while the complexity of the problem will soar correspondingly. With this great complexity, the problem cannot be solved by CPLEX in reasonable time. Therefore, meta-heuristics and heuristics algorithms are proposed instead to find the near optimal solutions in a shorter period of time. However, these algorithms involve some randomness, and thus cannot guarantee that the exact solution can be found in the next run even it is able to find the solutions close to the optimal solution. Therefore, developing an effective exact algorithm for solving the MBAP-VITQCA-SSA model in fine time segment units is suggested for future research.

Application of the developed algorithms in practical situation

In fact, all the proposed algorithms developed can be applied in practice. It is capable of capturing real terminal data, including number of vessels, number of QCs, number of berths, vessel arrival rate and handling volume, QC productivities, quay length, etc. These algorithms can be embedded into the existing terminal information system to capture the data as mentioned above theoretically. However, at this moment, this part has not been considered and which are suggested to be done for future work.

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