The Impact of Automation on the Efficiency and Cost Effectiveness of the Quayside and Container Yard Cranes and the Selection Decision for the Yard Operating Systems

By

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Abstract

This research evaluates the impact of automated and semi-automated devices on the process of loading, discharging, stacking and un-stacking of containers using Quayside Cranes (QSCs), Straddle Carriers (SCs), Rubber Tyred Gantry cranes (RTGs) and Rail Mounted Gantry cranes (RMGs) in container terminals. The emphasis of study is on the assessment of performance and cost effectiveness of the existing automated quayside and yard cranes. The study in this thesis examines the economic implications of reducing QSCs' cycle-times brought about by automatic features installed on the post-Panamax cranes. It demonstrates that a considerable increase in the productivity of QSCs is related directly or indirectly to an expected reduction of crane cycle-times. The concept offered by the proposed improvements distinguishes between the traditional system of loading and discharging of containers and the automated methods. It implies that automation devices installed on conventional QSCs significantly reduce the total turnaround-time and hence the cost of containerships' waiting-times. It argues, however, that there should be a balance between the cost of containerships' waiting-times and the cost of automated berths' unproductive-times (idle-times). This study uses the elements of queuing theories and proposes a novel break-even method for calculating such a balance.

The number of container Ground Slots (GSs) and the annual throughput of container terminals expressed in Twenty-foot Equivalent Units (TEUs) have been used as the efficiency and performance measure for many years. The study in this thesis introduces appropriate container yard design layouts and provides a generic model for calculating the annual throughput for container terminals using semi-automated SC and RTG and automated and semi-automated RMG operating systems. The throughput model proposed in this study incorporates the dynamic nature, size, type and capacity of the automated container yard operating systems and the average dwell-times, transhipment ratio, accessibility and stacking height of the containers as the salient factors in determining a container terminal throughput.

Further, this thesis analyses the concept of cost functions for container yard operating systems proposed. It develops a generic cost-based model that provides the basis for a pair-wise comparison, analysis and evaluation of the economic

efficiency and effectiveness of automated and semi-automated container yard stacking cranes and helps to make rational decisions.

This study proposes a Multiple Attribute Decision-Making (MADM) method for evaluating and selecting the best container yard operating system amongst alternatives by examining the most important operating criteria involved. The MADM method proposed enables a decision-maker to study complex problems and allows consideration of qualitative and qualitative attributes that are heterogeneous in nature. An Analytical Hierarchy Process (AHP) technique has been employed as a weighting method to solve the MADM problem. The AHP allows for the decomposition of decision problem into a hierarchical order and enables a pair-wise comparison of the attributes and alternatives. The results of the AHP analysis provide the basis for a pair-wise comparison, judgement and selection of the best automated or semi-automated container yard operating system.

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Abbreviations

AGVs = Automated Guided Vehicles

AHP = Analytical Hierarchy Process

ALVs = Automated Loading Vehicles

ARR = Annual Rate of Return

BACT = Bandar Abbas Container Terminals

BAT = Berth Arrival-Time

BCR = Benefit-Cost Ratio

BDT = Berth Departure Time

BGP = Berth Gross Productivity

BICT = Bandar Imam Container Terminals

BNP = Berth Net Productivity

BST = Berth Service-Time

CCT = Chabahar Container Terminals

CFS = Container Freight Station

CGP = Crane Gross Productivity

CGT = Crane Gross-Time

CNP = Crane Net Productivity

CNT = Crane Net-Time

CP = Cost Parameters

CPC = Cost Per Container

CR = Consistency Ratio

CRF = Capital Recovery Factor

DBA = Division By Average

DBM = Division By Mean

DBS = Division By Sum

DC = Depreciation Cost of cranes

DCM = Double-Cycle Mode

DGPS = Differential Global Positioning System

dwt = Dead weight

EDI = Electronic Data Interchange

EDIFACT = Electronic Data Interchange For Administration, Commerce and Transport

ESA = Environmental and Social Acceptability

FCFS = First Come First Served

FCL = Full Container Load

FEU = Forty-foot Equivalent Unit

FL = Flexibility

FLs = Front-end Lift trucks

FWF = Future Worth Factor

GPS = Global Positioning System

GSs = Ground Slots

HIT = Hong Kong International Terminals

HP = Hub-Port

IC = Investment Cost of cranes

ISO = International Organisation for Standardisation

LA = Level of Automation

LC = Land Cost

LCL = Less than full Container Load

LJF = Longest Job First

MADM = Multiple Attribute Decision-Making

MCC = Maintenance Cost of Cranes

MCDM = Multiple Criteria Decision-Making

MODM = Multiple Objective Decision-Making

MPC = Matrix of Pair-wise Comparison

MST = Mean Service-Time

MT = Machinery on Trolley

NPV = Net Present Value

OC = Operation Cost of cranes

OCRS = Optical Character Recognition System

OD = Origin-Destination port

PBP = Payback Period

PC = Procurement Cost

PF = Peaking-Factor

P-K = Pollaczec-Khintchine queuing formula

PSO = Port and Shipping Organisation of Iran

PWF = Present Worth Factor

QSCs = Quayside Cranes

RF = Radio Frequency

RGA = Random Grounding Applicability

RM = Re-handling Management

RMGs = Rail Mounted Gantry cranes

RSs = Reach Stackers

RTGs = Rubber Tyred Gantry cranes

RTT = Roped Towed Trolley

SCM = Single-Cycle Mode

SCs = Straddle Carriers

SFF = Sinking Found Factor

SH = Stacking Height

TEU = Twenty-foot Equivalent Unit

TLs = Traffic Lanes

ToL = Top Loader

T-Ts = Tractor-Trailers

UNCTAD = United Nations Conferences on Trade and Development

VIF = Variable Intensity Factor

YDC = Yard Development Cost

YMC = Yard Maintenance Cost

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Chapter 1

Introduction

Summary

This chapter explains the main concept of this thesis. It describes and outlines the aims and objectives of the study and explains the organisation and framework of the chapters. It further explains the methodology and the scope of this research together with the contributions that this thesis makes. The general terms used throughout the thesis are outlined and defined.

1.1 General remarks

Modern container terminals can be described as open systems of material flow with four operational areas. These areas are:

- The shipside operation that deals with berth allocation and planning for container stowage.
- The quayside operation that deals with the crane allocation to ships, loading and discharging of the ships and assigning systematic means of transferring containers to and from the quayside to the stacking-yard.
- The landside operation that deals with the delivery and receipt of containers and controlling the in and out operation of containers through the gate complex and other modes of transport.
- The terminal communication system with efficient means of information flow down from the ship through the terminal to the end users.

The success capability and productivity of container terminals is measured with factors such as the highest number of container Ground Slots (GSs) and terminal throughput. In this respect the fundamental objective of every container terminal operator is to provide services to containerships and containers within the minimum turnaround-time and dwell-times with an acceptable cost. This can be achieved by increasing the number of servers such as berths, Quayside Cranes (QSCs), transfer and stacking cranes. On the other hand, the operators of modern container terminals employ automated and semi-automated container yard operating systems including Automated Guided Vehicles (AGVs), Automated Loading Vehicles (ALVs), Straddle Carriers (SCs), Rubber Tyred Gantry cranes (RTGs) and Rail Mounted Gantry cranes (RMGs) to minimise the turnaround-times of the containerships and to keep pace with the growing demand for the container transport. This growth imposes the container terminals to either expand their land horizontally or ultimately utilise the existing land that is available at the terminals (UNCTAD, 1985 and Constantinides, 1990). The expansion of container yard horizontally is costly and increases the cycle-time of the transfer operations. Similarly, higher land utilisation through employment of automation technology and expansion of container yard vertically is a major factor causing 'unproductive' container movements and more re-handling effort in the yard operation of container terminals therefore imposing unwanted costs.

At the quayside of today's container terminals, the total turnaround-time of containerships has been reduced considerably. However, port operators in the medium to small size container terminals such as Bandar Abbas Container Terminals (BACT) and Bandar Imam Container Terminals (BICT) in Iran and Dubai and Sharjah container terminals in the Persian Gulf region which have automated their loading and discharging operations, are experiencing very costly QSCs and berth facilities are becoming undesirably unproductive (idle) for some duration of time (Bahrani, 2004). This is mainly due to the automation being introduced without an increase in containership calls which makes the port operators unable to achieve the maximum use of the quayside capacity delivered by the high speed of the quayside operations. There is a need to profoundly analyse the economics of increased productivity and efficiency resulting from the automation of the quayside operation and further develop a break-even value model to establish a balance between the unproductive-times of the costly quayside facility and the containership waiting-times. Before employing automated devices, the terminal operators are therefore required to consider designing or re-designing their stacking-yard layouts compatible with the new yard operating technologies in order to maximise their container yard throughput and at the same time shorten the turnaround-times of containerships and dwell-times of containers. This would also require the terminal operators to review the cost models of their container yard operation compatible with the automated and semi-automated systems to operate in the container yard.

The effectiveness and efficiency of automated container yard operating systems and their associated costs are measured quantitatively and qualitatively and require a concrete economic and operational ground to support decisions to be made. An appropriate decision-support system requires incorporating most of the determining attributes before any final selection decision for any container yard operating system is made. The above issues are examined in this thesis. Furthermore, the findings from the research into the above issues have been developed in this thesis to investigate and identify the appropriate strategies for automating container terminal operations.

1.2 Aims and objectives of the study

This study discusses that container terminals should be designed and laid out compatible with the proposed automated systems. It proposes layout and capacity models for container terminals using semi-automated SC and RTG and automated and semi-automated RMG operating systems in modern container yards by considering the dynamic nature, size and capacity of the automated container yard operating systems together with the average dwell-times of containers, the transhipment ratio, the accessibility and stacking height of the containers as the salient factors in determining container terminal throughput.

For the design layout and capacity models proposed a separate study has been conducted to analyse and justify the costs factors involved. The majority of cost values discussed in this thesis are obtained from the BACT, Iran statistics reports. The cost model presented in Chapter 6 may enable a designer to make a pair-wise comparison of handling systems to determine the most appropriate container yard operating system for a port based on the required automatic capabilities and functions. The study has also developed a decision tool to assist a terminal designer or operator in selecting the most economic container yard operating system. Selection of the most economic container yard operating system is based on determining factors such as the lowest operating cost and the highest annual throughput. The generic methodologies proposed in this study may be used as the basis for decision-making and selection of the most economic operating system for container yards.

The decisions to be made are based on the complex and heterogeneous attributes including qualitative measures that are often expressed in linguistics terms and quantitative attributes often illustrated in financial and throughput measures. It is worthwhile examining the applicability of the Multiple Attribute Decision-Making (MADM) concept for the decision problems in container terminals. To solve such problems with conflicting attributes, an Analytical Hierarchy Process (AHP) technique seems to be appropriate (Saaty, 1980 and 1988). It is considered that the results of the AHP analysis would enable a decision-maker to develop a ground for pair-wise comparison, judgement and selection of the best automated container yard operating system for the purpose of this study.

The objectives of conducting this study can be categorised as follows:

1) To examine and evaluate the cycle-times of conventional and automated post-Panamax quayside cranes used for loading and discharging operations in container terminals.

2) To develop a model for analysing the cycle-times of automated QSCs and to quantify and measure the economic efficiency and feasibility that may be emanated from the shorter cycles.

3) To develop a break-even model to measure the balance between the cost of containership waiting-times and the costs associated with the probable container berth unproductive-times (idle-times).

4) To develop the design layout and throughput models for calculating the annual capacity of modern container terminals using semi-automated SC and RTG and automated and semi-automated RMG cranes by incorporating the dynamic nature, size and capacity of the equipment, together with the average transhipment ratio, stacking height, dwell-times and index of accessibility of containers.

5) To examine the determining cost attributes and to develop a cost function model suitable for container yard operating systems and terminal capacities identified in objective 4.

6) To set-up a decision-support model that can incorporate both qualitative and quantitative attributes identified in the study.

7) To use appropriate case studies to demonstrate the applicability of the models developed.

1.3 Reasons for the analysis

Most of the studies carried out on the quayside and yard cranes have only considered the appropriate optimisation functionality of the tasks and very few have examined the impact of automation on the turnaround-time of containerships and the economics of unproductive service-times of the costly cranes. The shortening of the containerships' turnaround-times would be advantageous for the shipping lines. On the other hand, when costly automated QSCs become idle and therefore unproductive, the container terminals suffer a loss of revenue in the capital cost of investment. The majority of studies suggest that the terminal operators invest in automated technologies and expand their terminal capacities but the contribution of the terminal facilities given to the port itself seems to be overlooked in the small to medium size container terminals. The cost of container terminal berth facilities needs to be investigated together with the cost of containership waiting-times when investing in automated technologies in terminal operations. In the literature, as shown in Chapter 2, there is a void in measuring the balance between the cost of berth unproductive service-times and the cost of vessel waiting-times. This thesis introduces a novel break-even model to be used as a benchmark and as a decision tool for calculating such a balance.

In the majority of container terminals in developing countries such as those located in the Persian Gulf region, and in particular the Iranian container ports, the automated and semi-automated yard cranes are purchased and deployed in the container yard operations without a proper consideration of the nature, size, capacity and other dynamic functionality of these devices. The impacts of this oversight have forced the operators to undergo undesirable costs and spend time and effort of dealing with high dwell-times, poor flow of containers in the terminals. Additionally, the operators of terminals deal with unwanted re-handling operations and insufficiently utilise the maximum throughput expected from their implemented automated and semi-automated container yards operating systems.

1.4 Organisation and framework of the study

This study will analyse and evaluate the quayside and stacking-yard cranes. The analysis is embedded into eight individual chapters (Chapters 1 to 8) as illustrated in Figure 1.1.

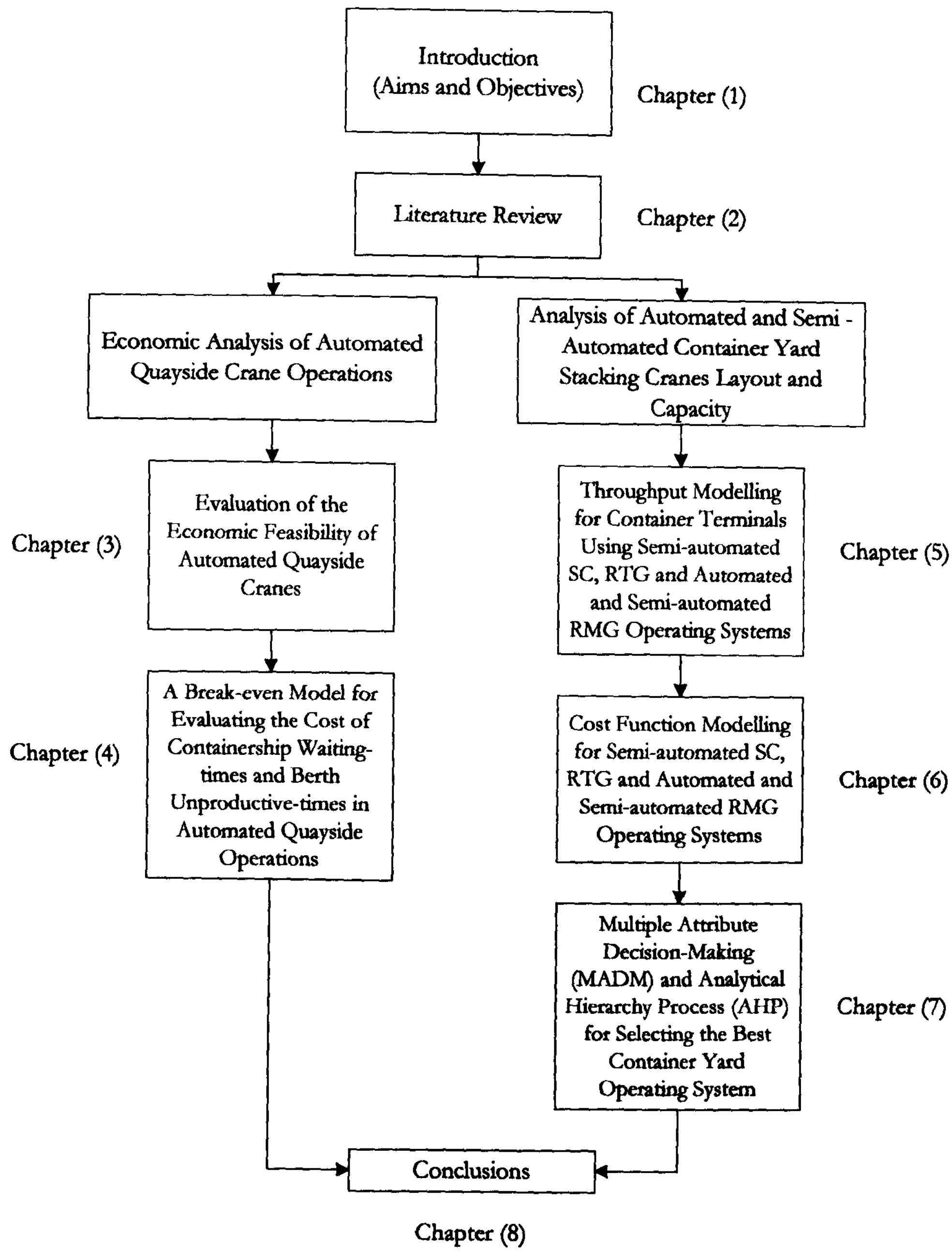


Figure 1.1 Framework of the study

The embedded chapters have been presented in a stepwise manner using the above framework as follows:

Chapter 1

Chapter 1 briefly explains the objectives, organisation, framework and scope of the study. It explains the contribution it makes to the knowledge in port management, planning and design of container terminals. It also gives the key definitions used.

Chapter 2

The general literature of the studies and their contribution to the general knowledge have been reviewed and reflected in Chapter 2. The literature of every individual study is discussed in Chapters 3, 4, 5, 6 and 7. Chapter 2 provides a general review of the literature in the following three main sections:

1) Container terminal operation.
   - Shipside operation.
   - Quayside operation.
   - Landside operation.
2) Terminal information system.
3) Decision-Making.

Chapter 3

This chapter is based on an experimental study conducted on the manual and automated post-Panamax QSCs. It examines the economic efficiency and feasibility of reducing the QSCs' cycle-times that may result from automation. It develops a comprehensive model to shorten the containerships' waiting-times in which it demonstrates that a considerable increase in productivity of QSCs is related directly or indirectly to an expected reduction of crane cycle-times. The study discusses the need for proposed improvements through automation and explains the concepts of the systems involved. This study quantifies the benefits achieved from the shortening of QSCs' cycle-times but it does not explain all the costs involved particularly when expensive QSCs become idle. A further study is conducted in Chapter 4 to examine the probable costs of QSCs unproductive-times (idle-times) where there are insufficient ship calls to utilise the extra capacities gained by the use of costly automated QSCs.

Chapter 4

The study in this chapter sets up a break-even model to enable the port operators to establish a balance between the cost of containerships' waiting-times and the probable cost of berth unproductive-times (idle-times) in automated quayside operations. The study uses the Erlang queuing theory particularly the Pollaczec-Khintchine (P-K) formula to find such a break-even value. The novel break-even model will provide examples of real data when appropriate. The application of the queuing theories may enable the port operators to determine the required rate of loading and discharging of their QSCs according to the rate of the ship calls at their ports. The analysis illustrates that automation of QSCs significantly reduces the turnaround-time of the containerships calling at ports. It is argued, however, that there should be a balance between the cost of berth unproductive service-times and the cost of container vessel waiting-times.

The productivity of the whole terminal operation is not only impacted by quayside operation but also with the efficiency of the landside operations. These activities are interrelated and needs the planners of container terminals to identify and analyse the most important and determining factors at the landside operation. This requires setting up a basis for an evaluation of the most widely used yard cranes by examining the productivity variables that are attributed to the container yard operations particularly semi-automated SC and RTG and automated and semi-automated RMG operating systems before selection decisions are made. To this end, it would be necessary to identify and classify the most determining variables and profoundly examine and develop conceptual frameworks for the analysis of the above yard cranes in the proceeding chapters 5, 6 and 7.

Chapter 5

This chapter examines the container terminal layouts and develops a basis for calculating the annual throughput of container terminals using semi-automated SC and RTG and automated and semi-automated RMG container yard operating systems. It incorporates the dynamic nature, size and capacity of the automated yard operating systems together with the average dwell-times, transhipment ratio, accessibility and stacking height of containers as the salient factors in determining container terminal throughput. The method in this study considers appropriate criteria necessary for different layouts of container terminals to serve the new generation of containerships. The results of this study are used as the basis for the cost evaluation in Chapter 6 and the decision-making in Chapter 7.

Chapter 6

This chapter analyses the cost parameters of the container yard operating systems proposed in Chapter 5 and discusses the concept of the cost comparison indicator and the variable intensity factor. It develops a generic cost-based model that facilitates a pair-wise comparison, analysis and evaluation of the cost attributes of yard equipment. The values of the examined attributes are used for decision-making in Chapter 7. The cost function analysis of this study incorporates major cost factors used in modern container terminal operations discussed in the literature.

Chapter 7

The study in Chapter 7 introduces the concept of the MADM technique and evaluates the important criteria involved for selecting the most appropriate container yard operating system examined in Chapters 5 and 6. The MADM methods enable the operator of a container terminal and a decision-maker to consider non-financial and qualitative attributes, which are often expressed in linguistic terms in addition to the common quantitative cost and capacity measures used to evaluate different container yard operating system alternatives. The evaluations use the existing body of knowledge together with up-to-date experts' opinions. This study uses an AHP technique to solve the MADM problem which may provide an acceptable ground for pair-wise comparisons for screening, ranking and selecting the best scenario amongst a group of alternatives.

Chapter 8

Finally, the study in Chapter 8 draws conclusions and makes recommendations for future studies. Chapter 8 explains the limitations involved during the study. It enumerates the findings and contributions of this research.

1.5 Scope of the work

This thesis analytically evaluates and examines the effectiveness, cost efficiency and selection of semi-automated QSCs, SCs and RTGs and automated and semi-automated RMG cranes. It introduces different methodologies to measure the above issues and proposes a decision-support system for selection of the best container yard operating system amongst those studied in this thesis. Other issues of container terminal operations are beyond the scope of this study.

1.6 Methodology

This research demonstrates an analytical study of the issues dealing with automated and semi-automated quayside and yard stacking and un-stacking cranes. It has been carried out through direct observations and use of historical data in the quantitative and qualitative forms obtained from some container ports. Use has been made of data from international publications in the port and shipping issues such as UNCTAD, annual statistics of Containerisation International and various international journals such as the World Port Development International and Lloyd's Register. According to the organisation of the study explained in Section 1.4, the following stages are taken to achieve the aims and objectives of this research:

1. Review of the current literature conducted on the analysis and examination of the efficiency, productivity and cost effectiveness of the automated QSCs.

2. Review of the current literature on the layout, throughput and cost modelling of semi-automated SC and RTG and automated and semi-automated RMG systems.

3. Quantitative analysis of the cycle-times and examination of time-savings, cost and benefits derived from the automation of QSC operations.

4. Quantitative analysis and examination of containerships' waiting-times and container berth unproductive-times for automated and semi-automated container berths using queuing theories.

5. Development of a break-even model to establish a balance between the cost of containership waiting-times and berth unproductive-times.

6. Analysis and examination of the quantitative and the qualitative data used for automated and semi-automated yard gantry cranes and development of layouts

and a throughput model incorporating the most important factors of the automated and semi-automated yard operating systems.

7. Identification, analysis and examination of the associated important factors in container yard operations and development of a quantitative cost model for an automated and semi-automated container yard operating system that enables a pair-wise comparison of the yard alternatives.

8. Development of a MADM model to incorporate both the quantitative and the qualitative criteria jointly using an existing body of knowledge and experts' judgments to enable selection of the best container yard operating system.

The research uses the advice of experts in terminal management and automation within UK universities and ports. The study attempts to bring together the experiences, observations and case studies to identify, examine and analyse the efficiency of the loading and discharging operation of semi-automated QSCs and automated and semi-automated stacking and un-stacking yard cranes and develops the layout design, throughput, cost function models and a decision-support system for container yard operating systems.

In this context, the computer programmes and software packages such as MATCAD, SPSS, IDS and EXCEL spreadsheets are used to illustrate and examine the analysis of the studies.

1.7 Contribution

This study makes a contribution in the following ways:

1) This research represents an innovative method of analysing the productivity and utilisation of automated and semi-automated container terminals in which it introduces a profound empirical study where:

    - It develops and proposes a new concept and method of measuring the productivity of the quayside operation at modern container terminals that has not been investigated before.

    - It identifies, classifies, and measures the major impacts of shortening the cycle-times of QSC loading and / or discharging.

- It identifies major factors that impact the shortening of containerships' waiting times, develops a novel break-even model to establish a balance between the cost of containership waiting-times and quayside cranes idle-times and fills an important void in the current knowledge.

- This thesis proposes a new method of planning and designing modern container terminal layouts and capacity that has not been addressed in the previous studies.

- The study contributes to the general knowledge of container terminal planning and design procedures by incorporating the most important factors attributed to the modern container terminal operating systems. These factors include in a dynamic manner the size, type and capacity of automated and semi-automated stacking and un-stacking-yard cranes together with the stacking height, transhipment ratio, dwell-times and index of accessibility. It makes a contribution to the general knowledge where:

  i) It identifies and classifies the most important factors which are impacted by automation in calculating the required area and capacity of semi-automated SC, RTG and semi-automated and fully automated RMG operating systems in modern container terminals.

  ii) It develops and proposes a new robust generic method for calculation of container ground slots and throughput by incorporating the most important factors identified. The models proposed can be used for development of new stacking yards or redesigning the conventional terminal to keep pace with technological advances. The models proposed have not been used earlier.

  iii) It proposes a novel method of measuring the cost effectiveness of a container terminal operating system and proposes a concrete ground for a pair-wise comparison of the cost attributes to help with selection of an appropriate container yard operating system for a container terminal.

2) For the first time in the analysis and planning of container terminal operations, this study introduces the concept of the MADM and the AHP methods as the effective decision-support systems for container terminal planners, operators and researchers.

3) The generic decision-support model proposed in this thesis can facilitate selection of the most appropriate container yard operating system by adopting quantitative attributes together with qualitative attributes expressed in linguistics terms in a pair-wise manner which has not been studied before.

4) This applied study into the strategies of the terminal layout, capacity, productivity and operations may be of a considerable benefit to the port industry, to the students and researchers worldwide and particularly to the planners and managers of the port operation.

1.8 Terms and definitions

The key definitions widely used in this thesis are defined as:

- **Automation**

The term 'automation' used in this study means any QSC or yard crane operating under automatic devices fitted on the equipment aimed at reducing the human intervention. Since full automation of the QSCs, SCs and RTGs are in their infancy, the phrase automation used throughout this study for the above equipment indicates semi-automation of the operation unless otherwise stated.

- **Container terminal segments and operations**

A container terminal may be divided into three interdependent operations within which different interactive activities take place. These operations and the corresponding activities may be defined as:

i) Shipside operation

The 'shipside operation' of any container terminal comprises two main activities. First, the vessel is assigned a berth according to a pre-planned berth allocation scheme. Second, a comprehensive stowage plan is drawn-up for a systematic loading and discharging operation. The shipside operation may have a considerable influence on both day-to-day performance attained in a container terminal and the quality of services provided to the ship owners.

ii) Quayside operation

The 'quayside operation' of every terminal consists of three interacting activities particularly crane allocation, loading and discharging and the quay transfer operation. In this context, the cycle-times of the QSCs and containership-times at ports need to be clearly defined. The quayside operation may also include the container transhipment operation.

- **Crane cycle-time**

The operation of a QSC and its cycle operation may be categorised and defined by the following:

a) Single-cycle

A crane is said to be operating in a Single-Cycle Mode (SCM) of operation when it picks up the delivered load, moves it to the corresponding slot and returns empty to pick up the next load. The reverse action would be a single-cycle discharging mode of operation.

b) Double-cycle

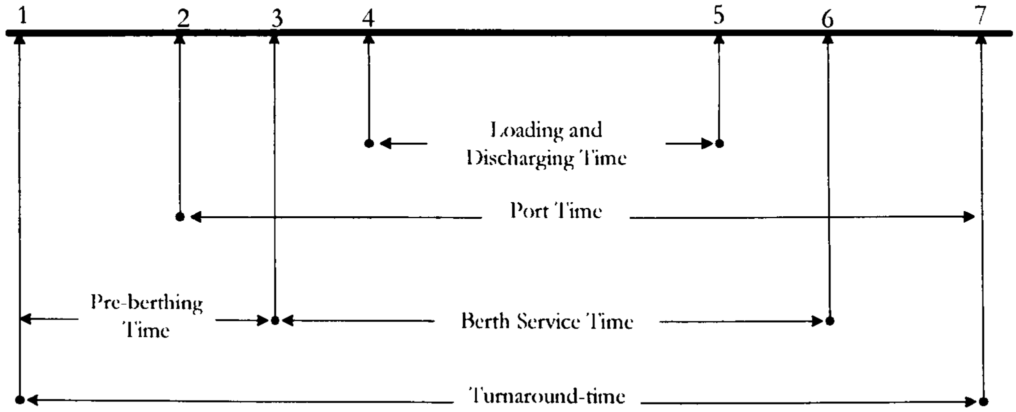
In contrast to the SCM of operation, a Double-Cycle Mode (DCM) is when the crane picks up the load, moves it into the target slot and then picks up a new load from the cells to discharge it onto the stand-by transfer vehicle.

c) Multiple-task

A crane may be required to engage in multi-task operations such as shifting loads within the cells, shuffling and repositioning loads from deck to the appropriate slots or *vice versa*. In this case, the cycle-times would be longer than the single and double cycles.

- **Containership-time at port**

Figure 1.2 illustrates the events, activities and times of a containership at a port. The events are summarised in Table 1.1.



(Source: Author)

Figure 1.2 Breakdown of a containership-time at a port

Table 1.1 Summary of events for containership calls at a port

Point	Event
1	Arrival at port (outer anchorage for instance).
2	Vessel moves from anchorage to berth.
3	Ship berthing completed (end of mooring for instance).
4	Start of loading and / or discharging operations.
5	End of loading and / or discharging operations.
6	Departure from the berth.
7	Departure from the port.

(Source: Author)

Based on the events and operations given in Figure 1.2 and Table 1.1, the following indicators and definitions can be determined:

- **Turnaround-time**

The total duration of the time taken from the time a containership arrives at and leaves the port. The time elapsed can be shown from point 1 to point 7 in Figure 1.2.

- **Port-time**

The port-time may be defined as the gross-time during which a vessel moves from the anchorage to the berth and finally casts off and leaves the berth and the port after the loading and / or discharging operation is completed. This process is the time taken from point 2 to point 7 in Figure 1.2.

- **Full Container Load (FCL)**

An FCL is a container where the whole content is sent to a common consignee. The FCL containers may not be required to be opened in the Container Freight Station (CFS) (if the CFS is located inside the container terminal) and may be stacked for a while in the stack-yard or directly sent to the receivers' premises after they are discharged from the containership.

- **Less than full Container Load (LCL)**

In contrast to the FCL containers, the LCL containers are those that contain pieces of cargo for different consignees that may be geographically scattered. The containers are required to be opened in the CFS in order to distribute the contents to multi-receivers.

- **Berth Service-Time (BST)**

The BST may be defined as the gross-time elapsed between the berthing and un-berthing periods. The BST includes break times and other stoppage times that takes place and interrupts the loading and discharging operations. This can be shown as the duration of time from point 3 to point 6 in Figure 1.2.

- **Loading and discharging time**

The loading and discharging operation time at the berth may be defined as the gross-time taken for loading and discharging operation of a vessel including the unexpected break and stoppage times. This can be shown as the time taken from point 4 to point 5 in Figure 1.2.

- **Berth unproductive-time**

The unproductive-time of a berth in a container terminal may be defined as the times during which the quayside facilities are ready to provide services but due to some problems such as the lack of containership availability and / or shortage and delays of the transfer vehicles they remain idle and therefore unproductive. The unproductive-times do not include the down-time of the quayside facility.

The operation at the quayside involves allocation of berths to containerships, assigning and operating a required number of QSCs served with an optimum number of transfer vehicles. Theses activities are interrelated and the productivity of each operation may impact or be impacted by each other (Valenciana, 1999). The productivity of the quayside operation is a multi-functional productivity and may be more clearly defined by the following terms:

- **Berth Arrival-Time (BAT)**

The BAT can be defined as the time at which a vessel berths at the quayside and all the mooring lines are made fast.

- **Berth Departure-Time (BDT)**

The BDT can be defined as the time at which a vessel leaves the berth and casts off the jetty.

- **Crane Gross-Time (CGT)**

The CGT may be defined as the total duration of time a crane serves a vessel at a quayside. The CGT can be measured in hours / QSC / vessel.

- **Crane Gross Productivity (CGP)**

The CGP may be defined as the total number of moves of a crane divided by the CGT in a containership loading / discharging operation.

- **Crane Net-Time (CNT)**

The CNT can be defined as the total time from the start to the finish time during which a crane serves a vessel where delays caused by stevedores and vessels, lack of transfer vehicles, etc., unusual stoppages, downtime and idle-times are deducted. CNT is measured in terms of hours / QSC/ vessel.

- **Crane Net Productivity (CNP)**

The CNP may be defined as the total number of moves of a crane divided by the CNT in a containership loading / discharging operation.

- **Berth Gross Productivity (BGP)**

The BGP can be defined as the total number of moves carried out by all cranes allocated to a vessel divided by the BST.

- **Berth Net Productivity (BNP)**

The BNP can be defined as the total number of moves carried out by all cranes allocated to a vessel divided by the CNT.

iii) Landside operation

The 'landside operation' consists of four main activities. The most important activities are the 'receipt and delivery', 'landside transport', 'container yard stacking and un-stacking' operations and the 'gate procedure'.

- **Container yard layout**

The layout of a container yard may be defined as the gross area which is mainly used for stacking and the buffer area for containers including main and sub-access roads, passageways, aisles, turning and interchange areas.

- **Yard crane cycle-time**

The stacking cycle-time of a yard crane is the total time taken to pick up a container from the chassis of a transfer vehicle or from the ground to stack it into its devoted slot in the stack and return to a stand-by position to commence the next cycle. The retrieving cycle can be assumed as the reverse cycle of the above action (Bonsall, 2001). Similar to the QSC cycle-times, the yard cranes may engage in a single, double and multi-task cycles and operations.

- **Twenty-foot Equivalent Unit (TEU)**

Container capacity is measured in TEU, which is the cargo capacity equal to one standard International Standardisation Organisation (ISO) container having a length of twenty feet, breadth of eight feet and a height of eight feet and six inches. A forty foot container with the same height and width is equivalent to 2TEUs or one FEU (Forty-foot Equivalent Unit). Some other sizes often known as non-standard sizes are in use in today's container transport industry.

- **Ground Slots (GSs)**

The GSs may be expressed as the maximum number of segments on the surface of a container yard in terms of TEUs per unit of area that are devoted to the accommodation of containers in one tier. The number of GSs would differ from terminal to terminal and from one yard operating system to another.

- **Container Freight Station (CFS)**

The CFS is a place where the export containers are stuffed with cargoes or the import containers are opened and the contents are sent to the receivers. It is also a place where Custom examinations and turnouts take place. CFS can be located outside or inside of container terminal.

- **Terminal throughput**

The throughput of a terminal may be expressed as the maximum number of containers stacked and processed in a terminal generally termed as TEUs per year. In the majority of studies in the literature the 'throughput' is referred to as a measure of productivity.

1.9 Other related terms

- **Cost-benefit analysis**

The cost-benefit analysis is the process of identification of cost factors associated with quayside cranes and container yards operating systems. It also provides the basis for comparison of the cost attributes with the likely benefits resulting from the automation.

- **Container re-handling and shuffling operations**

Re-handling and shuffling moves of containers are the unwanted and unproductive moves of top layer containers which are sometimes necessary to retrieve and restore a container underneath. These compulsory moves are considered undesirable and uneconomic. The automation technologies help to keep these moves to a minimum number.

- **Multiple Attribute Decision-Making (MADM) technique**

The MADM is a technique that enables a decision-maker to solve complex decision problems often based on the attributes and criteria with a heterogeneous nature.

- **Analytical Hierarchy Process (AHP) approach**

The AHP is a method used to solve the MADM problem. It allows decomposition of a decision problem into a hierarchical order and enables a pair-wise comparison of the attributes and selection of the best alternative scenario with an acceptable level of consistency.

1.10 Conclusions

This chapter has discussed the grounds over which this thesis has been laid. It has explained the scene of the research. This chapter has explained the aims and objectives of this study and has explained how the study is organised and constructed to achieve its objectives. It has further explained the scope and the methodology employed and the contribution it aims to make towards the general knowledge in the field of container planning, design and decision-support in this research. The general and technical terminologies used in this thesis are defined in this chapter. Chapter 2 will provide the literature review for this research project. The activities that take place in each operational area will be explained together with the contribution of the academic studies conducted in each area.

Chapter 2

Literature Review

Summary

This chapter provides a review of literature for container terminal operations. In addition to the literature review, it explains the activities that take place in a container terminal by dividing the operation areas into five main sections, namely, the shipside, quayside, landside, information flow and decision-making sections. The literature has been reviewed in a broader scope to provide a better concept of container terminal operations. The literature related to each area of operation is discussed in each corresponding operational area. The more specific review of the literature for this research is given in the loading and discharging operations, quayside crane allocation, stacking operation and decision-making sections.

2.1 Introduction

Since the introduction of containers and the voyage of the 'Ideal X' in 1956 (Containerisation International, 1996, Levinson, 2006 and Cudahy, 2006) container transport has rapidly taken over intercontinental freight transport. Mega-container vessels transport containers between continents having capacities of up to 11,000 Twenty-foot Equivalent Units (TEUs) (Cargo Systems, 2006). The demand for the transport of containers shows a growth of about 10.5% per year from 2004 to 2005 (UNCTAD, 2005 and Cargo Systems, 2006). This demand is expected to intensify in the future. Table 2.1 shows the growth of container traffic and Figure 2.1 illustrates this growth compared with other vessel types. This ongoing growth has caused an enormous demand for larger container vessels and simultaneously requires that container terminal operators keep pace with the changes and increase the productivity of their container terminals in order to handle the giant containerships calling at their ports in a minimum time and with the maximum efficiency. In the separate studies conducted by Chen, 1999, Holguin and Walton, 1999 and Volk, 2002, the competitiveness of a container terminal is demonstrated by different basic productivity factors. These factors are particularly the total turnaround-time of containerships, number of dwell-days a container stays in a port, terminal annual throughput, rate of loading, discharging, stacking, transferring and consolidating containers together with the costs associated with these operations.

To increase the capacity of the loading and discharging operations at the quayside and to reduce the turnaround-time of the containerships in ports two options can be taken. Port operators can either build more container berths or alternatively use advanced automated or semi-automated devices in their quayside and container yard operations to improve efficiency. Increasing the productivity through designing more berths is often very costly and sometimes impossible in some Asian and European countries due to land limitations, expansion restriction, ownership and large capital expenses. Instead, there has been a move towards automation and semi-automation of activities in response to the increasing demand. Although modernisation of quayside, gate and yard operations have been a niche area in science, their impact on the design, layout capacity, cost and decision-making related to theses issues have given rise to several research projects in USA, Europe and Asia. As a result they are gaining more scientific attention.

Table 2.1 Annual growth of the world container flee

Figure 2.1 World fleet by principal types of vessel for selected years

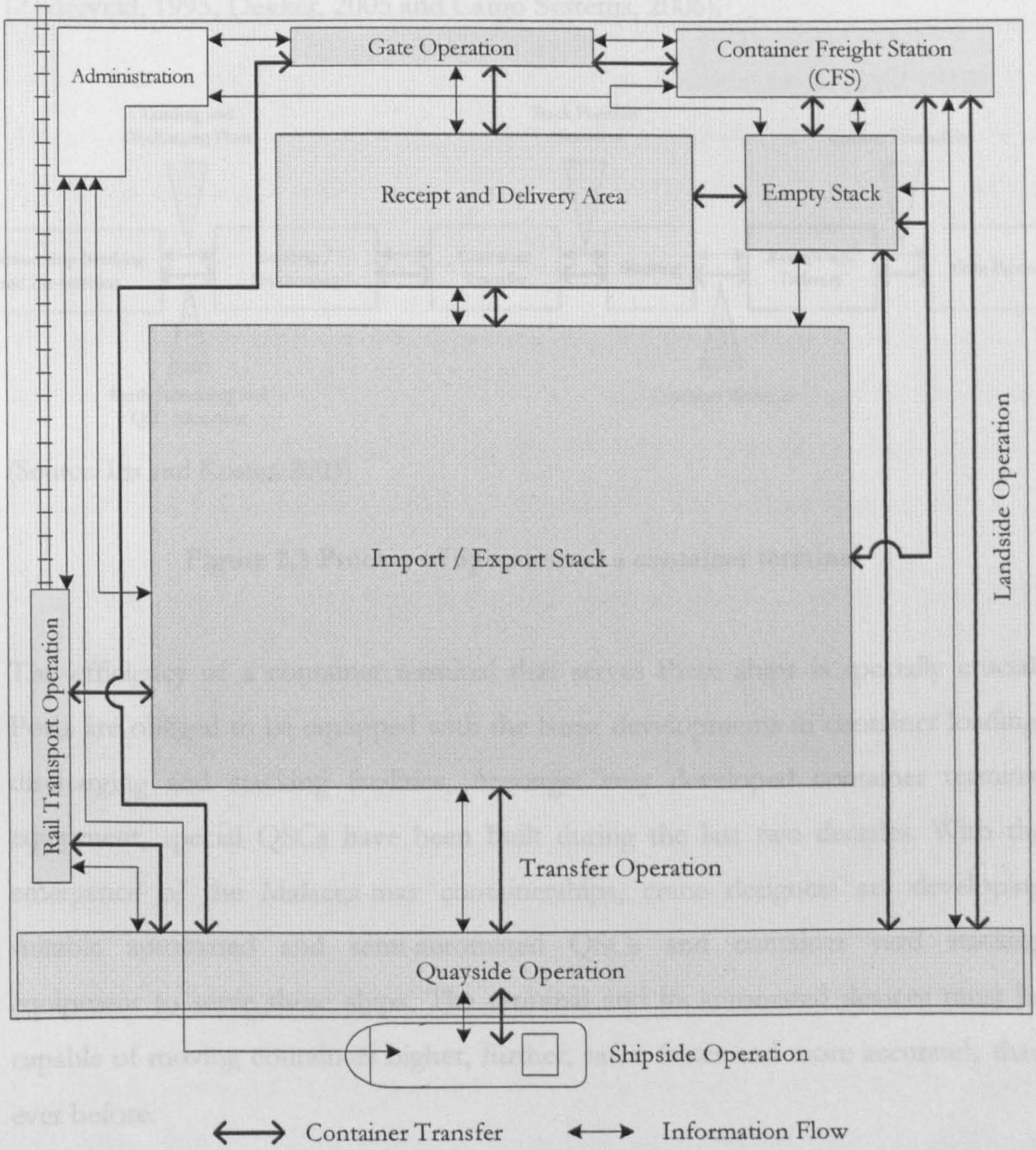
This chapter provides an overview of the published research studies for quayside, container yard planning, design and yard operation of container terminals and considers the main contributions they have made in this respect. This study does not discuss every aspect of container terminal operations and its literature.

2.2 Container terminal operation

When a container vessel arrives at a port, she will be assigned a berth equipped with Quay Side Cranes (QSCs) to load and discharge containers. The QSCs are large "heavy-scantling" cranes with open structures and booms extending over the ships they serve. They have either a single trolley or multiple trolleys with spreaders to attach to the containers from the top with container releasing mechanisms. In an automated container terminal operation, import containers are discharged by the automated or semi-automated QSCs and transported by dedicated transfer equipment such as Automated Guided Vehicles (AGVs), Straddle Carriers (SCs) or trailers to the container stacking areas. Containers are then delivered directly to the yard stacking cranes generally by Rail Mounted Gantry cranes (RMGs) or Rubber Tyred Gantry cranes (RTGs) or delivered to other dedicated stacking equipment such as SCs in a relay system, Reach Stackers (RSs) or Front-end Lift trucks (FLs) to be positioned into a pre-planned bay at the stack-yard. The stacking operation with a combination of the above equipment is also practicable.

The stack-yard is the main interface and decoupling point between the import and export container flows, either from sea to sea or from sea to land and *vice versa*. The stack-yard may consist of blocks in which containers are stacked on top of each other in a certain pattern. This method of storing containers is more common in most of the European and Asian countries due to the land restrictions. In some terminals, quite often in USA, containers are stacked on an individual chassis. Apart from the manually operated stacking cranes, there exist semi to full-automated yard gantry cranes that are capable of stacking up from as little as 2 to as much as 8 tiers (stacking tiers may be frequently referred to as 'containers high' in this thesis, which is the technical term used in container yard operations). An alternative to the container stacking cranes is the SC system which is capable of transferring and stacking 3 to 4 containers high by driving over the stacks. Additional moves may be required to be performed by transferring containers between empty stacks, Container Freight Station (CFS) and the main stack devoted to the import and export containers (Figure 2.2).

A container terminal may have several distinct operational areas (Figures 2.3 and 2.4). First, there are transfer points for road trucks, which are loaded from the stack using SCs, RSs or other cranes. Next, there can be a rail terminal or a service centre, where containers are loaded onto or from trains. Finally, there can be a barge service centre where barges are loaded using specialised equipment. The first two operations are carried out through the terminal gate complex and the latter is carried out at the special berths designed for transhipment of such containers.



(Source: Author)

Figure 2.2 Operation areas at a container terminal

Different types of containerships are served at the quayside. Amongst them are the post-Panamax deep-sea containerships with a loading capacity of about 8,000 to 11,000 TEUs. These vessels can be about 320 metres long with a breadth of 43 metres and a draught of 13 metres (UNCTAD, 2005). They may have the ability to carry containers up to 8 tiers and 17 TEUs abeam on the deck and accommodate 9 container tiers high and 15 TEUs wide in the holds (Meersman *et al.*, 2001). In the near future the operators must prepare for super post-Panamax (Malacca-max) vessels of 11,000 to 15,000 TEUs and also to serve the new generation of containerships referred to as the 'Mega containerships' (post-Malacca-max) of 20,000 to 24,000 TEUs to support the economies of scale of shipping industry (Zijderveld, 1995, Dekker, 2005 and Cargo Systems, 2006).

Figure 2.3 Process of operation at a container terminal

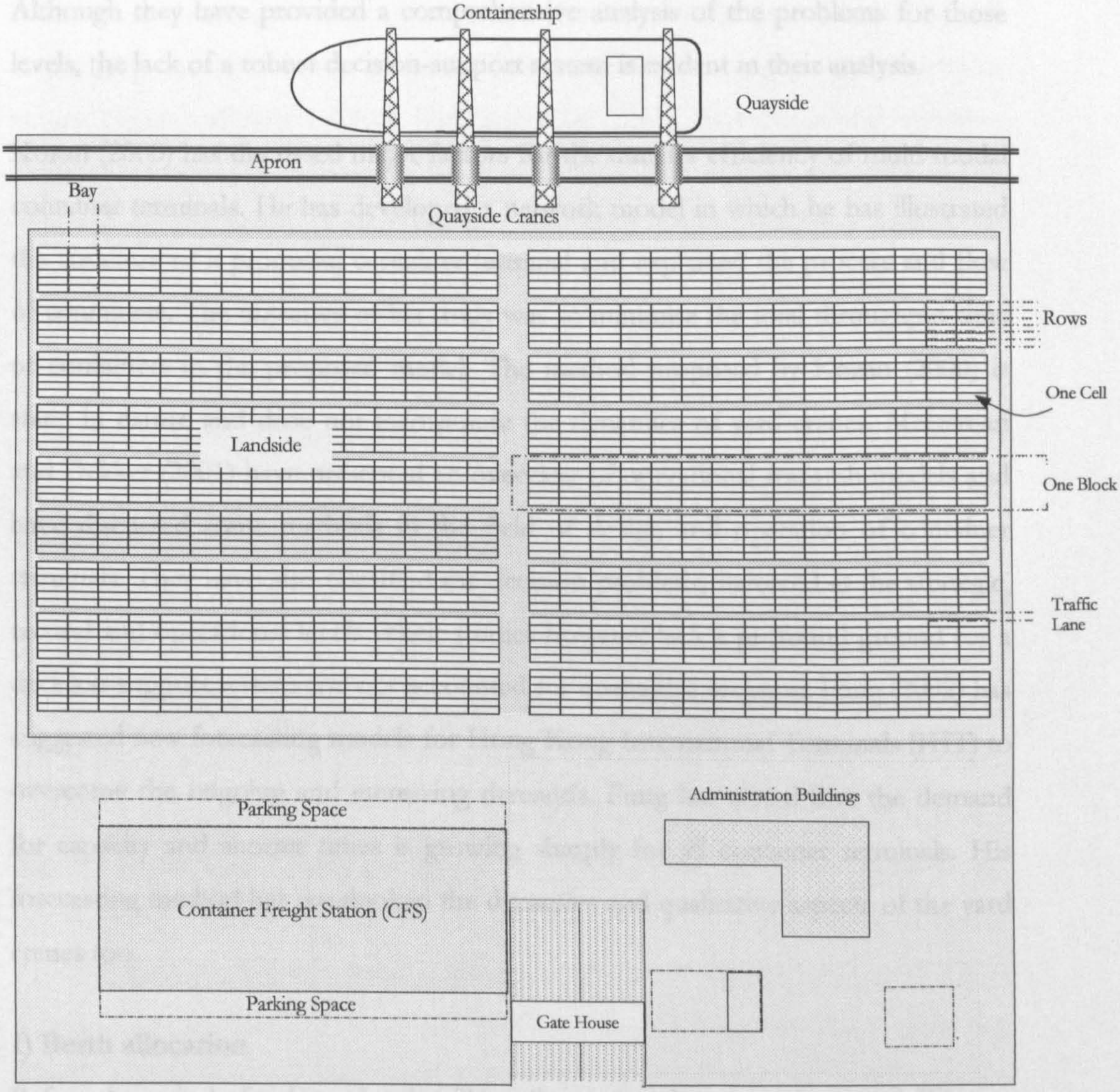
The efficiency of a container terminal that serves these ships is specially crucial. Ports are obliged to be equipped with the latest developments in container loading, discharging and stacking facilities. Amongst very developed container terminal equipment, special QSCs have been built during the last two decades. With the emergence of the Malacca-max containerships, crane designers are developing suitable automated and semi-automated QSCs and container yard stacking equipment to serve these ships. The terminal and its automated devices must be capable of moving containers higher, further, safer, faster and more accurately than ever before.

Figure 2.4 Schematic view of an example container terminal

Figure 2.4 illustrates some of the basic equipment used in the transhipment container terminals. Further, Figure 2.5 shows a simple example of a container terminal with an RTG system with a capacity of 18 blocks consisting of 15 rows and capable of stacking 6 containers in a row and having traffic lanes for access of transfer vehicles for stacking and retrieving purposes.

In Figure 2.5, containers are laid with their length parallel to the wharf (quay face) direction. The length and the shape of blocks are generally determined by the layout, terminal operating system and type of the stacking equipment used in container terminals. The following terms can be distinguished and defined in this context:

- 'Container cell' is any space in the stack yard which is occupied by one TEU container.
- 'Row' shows a number of container cells under the portal span of a gantry crane.
- 'Tier' represents a number of containers stacked vertically in a row.
- 'Bay' is the number of containers cells in a row shown in a longitudinal view.
- 'Block' consists of a group of container rows, bays and tiers that a gantry crane drives over when it moves along its pathway according to its stacking span and height capabilities.



(Source: Author)

Figure 2.5 The layout of a typical container terminal with yard gantry crane system

2.2.1 Shipside operation

The shipside operation of any container terminal comprises two main activities. First, the vessel will be assigned a berth according to a pre-planned berth allocation scheme. Second, a comprehensive stowage plan will be drawn for a systematic loading and discharging operation.

Meersman *et al.* (2001) and Iris and Koster (2003) have provided a comprehensive description of the decision problems at the container terminals. They have divided the problems into the strategic, tactical and operational decision levels and have argued that different sets of problems have to be dealt with at different levels.

Although they have provided a comprehensive analysis of the problems for those levels, the lack of a robust decision-support system is evident in their analysis.

Kozan (2000) has discussed major factors for the transfer efficiency of multi-modal container terminals. He has developed a network model in which he has illustrated the structure of a proposed container terminal and explained the process and flow of containers. The objective of his study was to minimise the total throughput time of containers in the proposed model. The method proposed by Kozan (2000) is static in nature and dose not incorporate the dynamics of yard cranes. Meersman and Dekker (2001) have presented an overview of operational research models and have discussed some methods in the field of design and operation of container terminals. They have also classified the decision problems involved at the strategic, tactical and operational levels. Their studies however lack a profound ground for a decision-support system and not accounted for qualitative measure. Fung (2002) has suggested new forecasting models for Hong Kong International Terminals (HIT) to overcome the ongoing and increasing demands. Fung has stated that the demand for capacity and shorter times is growing sharply for all container terminals. His forecasting method has overlooked the dynamics and qualitative aspects of the yard cranes too.

1) Berth allocation

Before the arrival of a ship, a berth will be allocated to that particular vessel. When a vessel arrives at a port, she will be berthed at the quay that is previously assigned to her. The decisions regarding quay allocation are generally made at the strategic level according to a comprehensive and operational queuing theory. Use has been made of simulations techniques during the last two decades to demonstrate the applied methods, including queuing methods, in a graphical manner. Edmondo and Maggs (1978) and Imai *et al.* (2003) have provided the basis for an efficient general queuing and berth allocation models for the decision problems at this level. Son and Kim (2004) have proposed a generic model based on the queuing theory to determine the optimal number of servers for a general distributed client / server system. The general queuing models proposed by Edmondo and Maggs (1978), Imai *et al.* (2003) and Son and Kim (2004), however, do not profoundly examine the variability of inter-arrival times together with service times. It should be noted that arrivals of the ships are distributed exponentially and are highly variable, whereas, services at the berths (considered as servers) provide an almost constant rate of loading and discharging operation at the quayside that imply they are nearly deterministic in nature. Gross and Harris (1998), Park and Kim (2003), Radmilovic and Branislav (2005) have developed analytical generic models that analyse and plan server requirements in a queuing environment. They have recommended that their model may determine the optimum number and capacity of servers within different transportation, communication, manufacturing, banks, management and logistics systems. Their studies have provided the account by considering that arrivals are independent of the service-times but overlooked the cost issues that play a determining role in designing more servers. Bharucha (1960) has examined the Markov process for arrivals that are independent of the service-times. He has considered that arrivals are infinite and every individual arrival stays idle in the system until he is served by the servers. The specification of containerships' arrivals discussed in his study is more applicable to real operations at the ports that characterises Poisson distribution patterns for arrivals. In a Poisson process, customers are originated from infinite population with different capacity and size (similar to the ships calling patterns at the ports) that arrive and queue at the services in an exponential way. In this process, arrivals with different inter-arrival rates will not be affected by the nature and behaviour of the previous and the next customer or with the rate and speed of the services to be given. The arrivals will remain patient in the queue until they are served. The services at the servers, however, fall somewhere between the high variability of exponential patterns and low variability of deterministic distributions that imply an Erlang service pattern.

In a study conducted by Jones and Blunden (1961) the queuing principles have been used to analyse the ship turnaround-time using Poisson arrival patterns. Plumlee (1966) has presented a ship traffic modelling methodology based on statistical analysis of containership traffic. In the literature, Plumlee (1966) has included the effect of cargo volume and handling capability of the ports in his analysis. He has made a notion to find the optimum number of berths to be designed to minimise the turnaround-time of the vessels. Mettam (1976) has used simple queuing formulas with exponential arrival and Poisson distribution patterns to illustrate the effect of service-times on the overall turnaround-time of vessels. He has concluded that a reduction in the service-times by increasing the rate of the servers would significantly reduce the overall port stay-time of the vessels. Nicolaou (1967 and

1969) has incorporated the element of cost associated with the vessels traffic in his analysis. In the above studies (Mettam, 1976, Nicolaou, 967 and 1969), however, the cost of probable idle times of the servers has been overlooked. Miller (1971), Wanhill (1974), Agerschou *et al.* (1983) and Noritake and Kimura (1983 and 1990) have conducted different studies to find the number of berths and the optimal size for a port using general queuing methods having Poisson distribution patterns. Similarly, in the studies conducted by Andreassen and Prokopowicz (1992), Radmilovic (1992), Radmilovic (1992), Zrnic and Bugaric (1994), different arrival patterns of vessels in different states using the general queuing theory have been analysed. A common drawback with the above analysis is that they have not provided an account for the probable idle-times of the servers and the cost associated with them.

Frederick and Oliver (1981) and Frederick and Gerald (1990) have taken advantage of the cyclic structure and the steady state distribution for the number of customers in their study as a linear combination of geometric series. They have suggested recognizing the cyclic structures in the transition probability matrix of the Markov chain. Similarly the above studies consider that services comply completely with Markov patterns, while in practice services are rather deterministic and more comply with Erlang patterns. Bonsall (2001) has used open network queuing analysis together with a discrete event simulation to evaluate the overall efficiency of landside operation in container terminals. He has demonstrated that in open networks individual queues at each node follow a Poisson process where service-times conform to an exponential pattern. A steady state solution is drawn in his model where the size and capacity of queues, services and service-times have been found to be dependent on the specific details of particular terminals. The probable cost due to the idle facility has not been discussed in this study. However, the study of state dependent queuing problems discussed by Bonsall (2001) has provided an account for the variability of inter-arrivals that implies Poisson process and the threshold limit of the servers that implies an Erlang model. Jagerman and Altiok (2003) and Altiok *et al.* (2004) have studied the vessel General (G) arrival processes in bulk ports handling either containers or minerals. They have introduced the SHIP/G/1 and G/G/1 queue models to study the queuing behaviour at a port. An approximation approach has been developed for the asymptotic probabilities of delays and the number of vessels at the port in their analysis. McKeown *et al.* (1999)

have considered queuing disciplines other than the First Come First Served (FCFS) policy for bulk arrivals. They have shown that in a multi-queue system a change in queue discipline from FCFS to Longest Job First (LJF) policy provides a higher throughput for the system dealing with bulk arrivals. In a multi-queue system an arrival (job) is selected to be served amongst others in the queues which requires more time than others. Asperen *et al.* (2003) have provided a model based on the ship waiting statistics and stock fluctuations under different arrival processes. Their study implies that Poisson process provides the least performance when compared with a simulation model. In the studies conducted by Imai *et al.* (1997 and 2001) and Nishimura *et al.* (2001) it is critically argued that berths can be allocated to the ships without consideration of ships' arrival patterns. They have argued that the berth facility can be allocated to the arrived ships in such a manner that it lies close to the stack area in which most containers for that particular ship are located. They have concluded that terminal utilisation will be maximised, but ship owners may be dissatisfied due to the fact that their ships may experience long waiting-times. They have suggested a trade-off between the total turnaround-time in the port and the dissatisfaction of ship owners caused by the order in which ships are served. This study attempts to solve the problem of idle-times but tilting the waiting-time and associated costs towards the shipping lines. This thesis argues that there should be a logical balance between the waiting-times of vessels and idle-times of port facilities to overcome any dissatisfaction on both sides.

In general, random and scheduled arrivals are the two main types of arrival patterns. In the scheduled arrival patterns, some customers arrive earlier than others. Although it is possible to solve the queuing problems that conform to a random arrival pattern, it is often difficult to solve the scheduled arrival patterns with exact solution methods. However, when the theory is applied to a port environment, both of the patterns can use the mean arrival rate, mean service rate and the number of servers as a salient component of the problem that is possible by using Poisson inputs and Erlang servers. Nazarov (1974) has discussed that the mean waiting-time of vessels is an important parameter to be considered when applying the theory to the port operations. In the studies conducted by Jansson and Shneerson (1982) and Evans and Marlow (1990) it has been demonstrated that the mean service rates and the standard deviation of the service-times play a significant role in minimising the turnaround-time of the vessels in ports. Their studies incorporate exponential and

Poisson processes in arrival and services patterns. Miller (1971) and Radmilovic (1992) have used mean values and have demonstrated that ships arrive randomly where the randomness of patterns can be assumed to conform to the Poisson distribution.

The drawback with Poisson patterns is that they do not account for the differences in the capacity and the size of the jobs required to be considered for individual customers (e.g. containerships). Erlang distributions overcome this shortcoming by incorporating the magnitude of variability of inter-arrivals service times in the form of a coefficient of variation and the shape parameter into the problem solving. In Jones and Blunden (1961), Saaty (1961), Frederick and Oliver (1981), Bruun (1990), Frederick and Gerald (1990) it is suggested that exponential arrivals having Erlang patterns and the constant rate models can be used to effectively solve port queuing problems. In the observations conducted by Jones and Blunden (1961) it is suggested that arrivals with Erlang patterns having exponential distributions provide the best representation for the analysis of vessels' queuing problems. It has been stated that having mean arrival rates of vessels and service rates of the berths together with the coefficient of variation and standard deviation of service-times provide a robust ground for analysis of ships queuing. They have concluded that as the rate of services of the servers increases (or the number of the servers at the berths increases), the waiting-times and the queue lengths predicted by different assumptions decrease. This statement could only be valid when a system reaches to a steady state. Providing more servers such as deployment of more quayside cranes at the quayside without consideration of the threshold limit of the servers may cause the system to collapse rather than to increase the productivity of the operation. The arrivals of containerships with a Poisson process and nearly deterministic servers having Erlang patterns such as berths in container terminals are similar to the model presented in the study proposed by Jones and Blunden (1961). The above system can be characterised by the following:

1) Arrivals are sourced from infinite population and may be originated from different population sources.

2) Customers arrive on a random variable basis.

3) Time between two successive arrivals is exponentially distributed.

4) The service time of the servers may be exponentially distributed.

5) Arrivals are independent from each other.

6) Variation in the rate and services will not affect arrivals.

7) Different action may be taken when an arrival approaches the servers:

- A customer may give-up waiting upon the arrival when the servers are busy (customer is termed to have 'balked').

- Customer may stay in the queue for a while but may give-up waiting in later stages because the servers are still busy (customer is termed to have 'reneged').

- Customer may switch to the less busy servers when the pre-nominated server is busy (customer is termed to 'jockey' for position).

The Erlang process having exponential distribution patterns, however, may have slightly different characteristics that can be compared with the arrival and services of the ships at ports. The characteristics of an Erlang distribution particularly with a shape parameter 'k' may be summarised as:

1) Similar to a Poisson process, arrivals are sourced from infinite population and may be originated from different population sources.

2) Customers arrive on a random variable basis.

3) The variability of the system may fall somewhere between the high variability of exponential patterns ($k = 1$) and almost zero variability of determinist distribution of service time times ($k = \infty$).

4) The inter-arrival time of some customers may overlap.

5) Arrivals may have different job sizes (capacity).

6) Arrivals are independent from each other.

7) Variation in the rate and services will not affect arrivals.

8) Erlang process may use mean rates for arrivals (λ) and serves (μ).

9) Customers normally keep patient and wait in the waiting lines until they are served by the servers.

2) Stowage planning

Stowage planning is the core of containership planning. It comprises a two-step process. The first step is carried out by the shipping lines involved at the operational level. The shipping lines' stowage plan is prepared for all ports of a vessel's rotation (Legato and Mazza, 2001). The stowage plans proposed by the shipping lines usually do not act with specific container identification by numbers, but on categories of containers. These categories are: the length or type of containers, the loading and discharging ports and the weight or weight-class of containers. The final positions of all containers are governed by a bay plan prepared in the terminal office according to the sequence of the ports of calls. The location of arrived containers specified by bay plans has to satisfy the commanding officer of the vessels.

Containers that are stowed have to satisfy a variety of constraints that mostly arise as a result of physical limitations of the containership and the containers and the sequence in which ports are visited (Shields, 1984). In an experimental study performed by Sculli and Hui (1988), the distribution effects and the number of different types of containers with respect to an efficient stowage planning model have been investigated. Avriel *et al.* (1998) have introduced a stowage planning based on an optimisation method to reduce the number of shifts in order to reduce the port stay and turnaround-time of containerships. In an another optimisation model Avriel *et al.* (2000) have focussed on the stowage planning of the containerships in order to minimise the number of unproductive moves. Their study however, has not considered some important factors such as the loading and discharging rotation of ports and ship's stability and other constraints to be satisfied. Wilson and Roach (2000 and 2001) have divided the container stowage process into two sub-processes and related sub-problems at the strategic and tactical planning levels. In contrast to the study conducted by Avriel *et al.* (2000), Cao and Uebe (1995) and Wilson and Roach (2000 and 2001) have addressed the complexity of the stowage planning across a number of ports and proposed the use of the branch and bound algorithms. The branch and bound algorithms in contrast with optimisation methods consider a finite and discrete number of events branched into variety of sub-branches that contain scattered evidences to satisfy a set of known and pre-defined constraints or objectives. In the process of problem solving, all the branches are examined to collectively obtain results that satisfy constraints. The stability restrictions however, have been overlooked in their study.

2.2.2 Quayside operation

The quayside operation consists of three interacting activities. First the containerships will be deployed with a sufficient number of QSCs according to their capacity, size, on-board facilities and conditions. Second the loading and / or discharging operation will commence. Third the containers will be transferred from the quayside to the stack-yard and *vice versa*. The Full Container Loads (FCL) discharged to the quayside may be transported to the consignee's premises directly and the Less than full Container Loads (LCL) may be transferred to the yard and stacks *via* a systematic means of inter-terminal transportation where they will remain stored until they are collected to be sent either to the CFS or to the receivers.

1) Quayside crane allocation

The allocation of QSCs to the containerships and the ship's holds requires a proper scheduling method. Depending on the ship type, size and capacity commonly three to five QSCs may be devoted to each ship. The feeder ships and the transhipment barges are operated with one or two QSCs. The objectives at the operational level would be to minimise the total turnaround-times of the containerships and maximise the berth occupancy of the terminals.

Daganzo (1989) has carried out a static crane allocation problem using a scheduling method with unlimited berth lengths where no additional ships enter the system during the planning horizon. There is no unique and clear objective in his proposed method of operation. Minimisation of the total ship-time can be an objective while the maximisation of the quayside performance or establishment of a well-balanced or economic utilisation of the QSCs can be another goal. In practice the achievement of all of these activities will depend on the actual terminal situation and goals. The crane allocation plan should also develop an operational strategy to clearly state how the spaces on the containership and her bays are to be utilised.

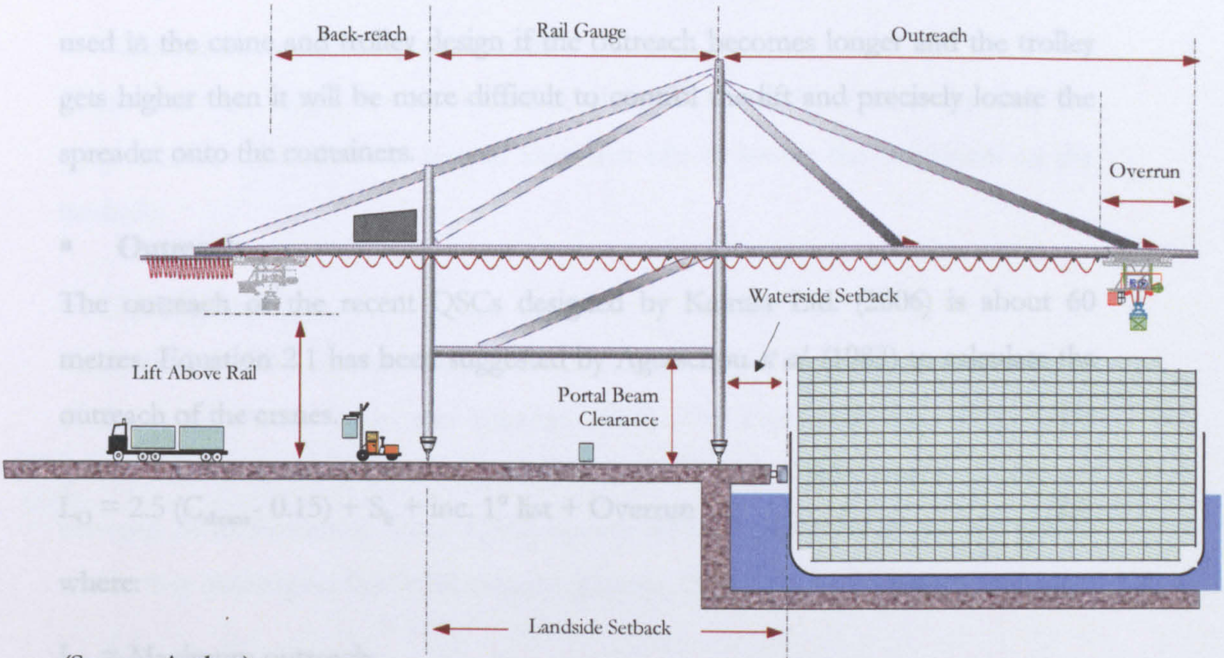
Bish (2003) has developed a heuristic method for minimising the turnaround-time of a set of ships in a multiple-crane constrained scheduling and allocation problem. The heuristic methods evaluate and incorporate the historical data to find a best-fit solution for scheduling problems. The optimisation and scheduling methods can advantage the heuristic experiences to more accurately solve resource allocation problems. Peterkofsky and Daganzo (1990) have provided a branch and bound method and proposed a set of constraints to meet to minimise the delay at the quayside. Daganzo (1989) has provided a similar solution for the scheduling problems. In the studies conducted by Jones and Blunden (1961), Wanhill (1974), Mettam (1976), Frederick and Gerald (1990) and Asperen *et al.* (2003) more aspects of the berth and scheduling problems are discussed.

2) Loading and discharging operations

The loading and discharging operation of containerships is generally performed by quayside cranes. The objective of the quayside cranes' operation at both tactical and operational levels is to minimise the turnaround-times of containerships and maximise the berth occupancy and hence berth productivity. Several studies have analysed the effects of the time reduction on the process of the loading and discharging operation of containerships. Steiner (1992), Thuesen and Fabrycky (1993), Avriel *et al.* (1998), and Kozan (2000) have proposed different analytical models to minimise the cycle-times of the container loading and discharging operations and attempt to make the most economic use of the spaces available for container stowage. Daganzo (1989), Rudolf (1995) and Michael and Jordan (2002) have proposed different qualitative and quantitative analysis of the productivity of QSCs resulting from the time-savings. The above studies have not attempted to quantify the likely benefits in a monetary form and account for the costs involved. Chen *et al.* (1995) have developed an analytical model to solve the crane allocation problems in the process of container loading by considering different size of jobs for cranes. Davis and Bischoff (1999) have considered weight distribution in the process of loading containers that has extended the study given by Davis and Bischoff (1999) by incorporating times assigned to different jobs. Nam and Ha (2001) have investigated different aspects of adoption of advanced technologies such as intelligent planning, operation and automated handling systems for container terminal operations. They have suggested criteria for evaluation and have applied their model to real case examples. They have concluded that other influencing factors such as machinery and labour performance should also be considered to guarantee a higher productivity from the automated operations. Haghani and Kaisar (2001) have developed a model to assist loading plans in order to minimise the time that a vessel spends in a port. They have investigated the container handling costs that are highly influenced by unproductive and unnecessary moves caused by an unsatisfactory arrangement of containers for loading. Studies carried out by Jordan and Rudolf (1993) and Jordan (1995) state that, in practice, the productivity of the loading and discharging operations is far behind that of their calculated cycles. Quantitative estimates of the time-savings have been analysed in the different studies conducted by Cheesman (1980) and Rosenfeld (1992).

The above studies however, have not analysed the effects of reducing loading and discharging cycle-times on the overall cost of quayside operation. In the literature, however, there is a void with regard to measuring the increased productivity in terms of the overall benefits that may be gained from implementation of new technologies such as automatic features in the quayside operations.

The productivity of a loading and discharging operation depends on the physical ability of the quayside crane. The span of the QSC plays an important role in the loading and discharging operations since cranes with insufficient outreach may be unable to discharge certain types of ships such as Malacca-max containerships or Mega ships that may now call at ports. Otherwise, they may be required to be turned round or shifted during the discharging process. Several innovations have been applied to the area of loading and discharging of the new containerships, either aiming at replacing the conventional quayside cranes or automating the existing technology. The operation of automated or semi-automated quay cranes for loading and discharging ships is a very demanding task. Amongst other reasons, positioning of the vessels that are in movement all the time will be a major problem to full automation.



(Source: Author)

Figure 2.6 A quayside crane outline

The features of a typical post-Panamax QSCs have been illustrated in Figure 2.6 to provide a clear concept of the quayside operation. The physical characteristics of the quayside gantry cranes may be distinguished by the following definitions:

- **Rail gauge**

The rail gauge is the horizontal distance between the parallel rails along the quay over which a QSC moves. The gauge is the place that provides a traffic lane for vehicles devoted to servicing the crane and the ship. The manual transfer vehicles are not usually allowed to operate in a common area provided under the crane portals. When operating automated quayside cranes, the transfer vehicles may be permitted if a systematic scheduling and traffic management is used. In this case, a barrier may be considered between the automated and the manual zones. If the barrier is located between the crane portals, the space between the cranes legs will be reduced. This may cause congestion on the wharf.

- **Lift above rail**

The lift above rail indicates the maximum vertical distance between the QSC's rail and the trolleys when it is in the park position. Some quayside cranes may have a lift above rail of about 75 metres to serve Malacca-max and Mega containerships (Kalmar Ltd., 2006). It should be noted that even with the advanced technologies used in the crane and trolley design if the outreach becomes longer and the trolley gets higher then it will be more difficult to control the lift and precisely locate the spreader onto the containers.

- **Outreach**

The outreach of the recent QSCs designed by Kalmar Ltd. (2006) is about 60 metres. Equation 2.1 has been suggested by Agerschou *et al.* (1983) to calculate the outreach of the cranes.

$$L_O = 2.5\,(C_{abeam} - 0.15) + S_b + \text{inc. } 1^\circ \text{ list} + \text{Overrun} \qquad 2.1$$

where:

L_O = Maximum outreach.

C_{abeam} = Number of containers abeam.

S_b = Setback distance.

Overrun = End of the outreach boom used for the stoppage of the trolley. Generally the overrun is about 1.2 to 1.5 metres and it is the place where the automatic de-acceleration controls are fitted.

Inc. 1° list = Additional length required when there is list of one degree acting on the crane due to the external forces such as wind, lateral sway and the bending effect of the boom caused by the load snag, load sway or a heavy weight hanging from the head block.

- **Back-reach**

Back-reach is the distance beyond the landside rail that adds to the stability of the crane and may reach as much as 22 metres (Kalmar, 2006).

- **Setback**

Setback of the waterside rail is the distance measured from the fenders lowered between the ship's hull and the apron of the jetty to the waterside rail. The setback of the landside rail is the distance measured from the fenders to the landside rail. Therefore, the setback of the landside rail equals the gauge plus the setback of the waterside rail.

- **Clearance under the portal beam**

There is a clear height for the operation of the SCs, AGVs or other types of the quay transfer vehicles or the second hoist that lifts or lowers the containers on the landside.

- **Lifting capacity**

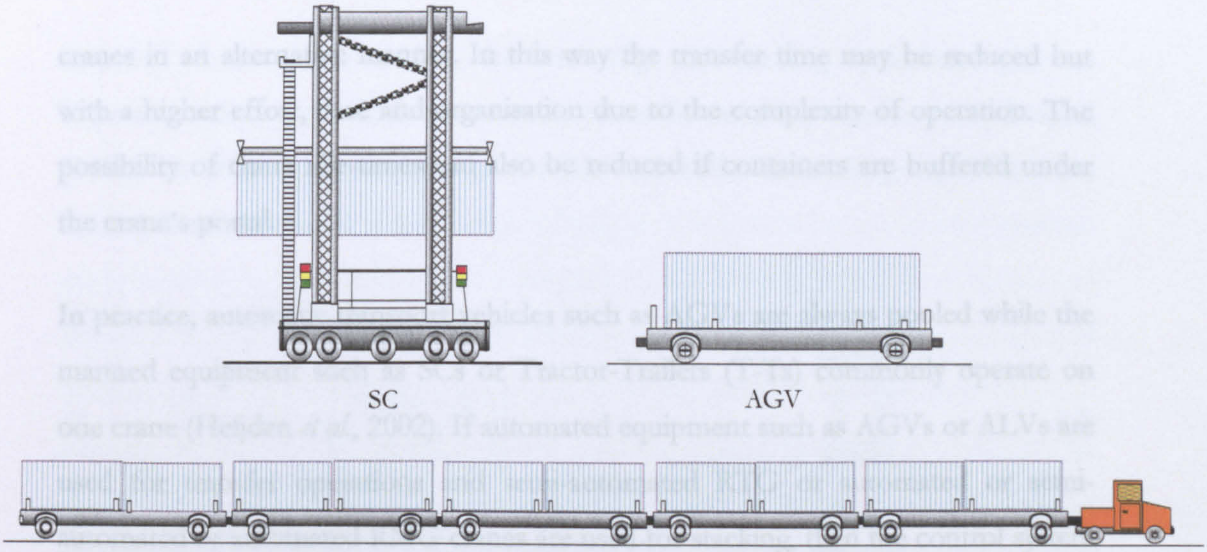
The majority of the containerships carry containers with a maximum average weight of about 12 tonnes (Arun and Kerenyi, 1995). The Forty-foot Equivalent Units (FEUs) are used for bulkier cargoes where the average FEU weight ranges are between 24 to 35 tonnes. Some QSCs operate with a capacity of about 100 tonnes where they may expect heavy lift cargoes (Kalmar, 2006).

- **Trolley**

The trolleys play a significant role in the overall productivity of the loading and discharging operation. Several types of cranes exist which are named by the number and type of the trolleys and the type of ships they serve. The trolleys can be Rope Towed Trolleys (RTT) or Machinery on Trolley (MT) type. In the RTT system, the trolley drive, main hoist and boom hoist are located in the machinery house to the end of trolley girder, through the trolley and to the tip of the boom (Arun and Kerenyi, 1995). This arrangement allows the trolley to be shallow and lightweight, allowing a greater lift height and a lighter stress and fatigue load on the crane structure.

3) Quayside transfer

Depending on the nature and layout of the container yard, transfer of containers to and from the quayside can be carried out with trucks, multi-trailers, AGVs, manned or semi-automated SCs or a combination of the two systems. Figure 2.7 illustrates three types of the most common transfer vehicles at container terminals.



(Source: Author)

Figure 2.7 SC, AGV and a multi-trailer system

Different operational strategies may occur at the quayside. The transfer can be performed either in a SCM or in a DCM of operation. In a SCM the transfer vehicles serve only one crane. According to the crane's cycle, they either transport the discharged containers from the quay to the stack-yard or transfer the export containers from the stack-yard to the quay cranes. In the DCM the transfer vehicles serve several QSCs that may be in the loading and discharging cycles and thus combine the transfer of export and import containers (Iris and Koster, 2003). The transfer vehicles can be allocated exclusively to one crane depending on the gang structure working on the vessel or to several cranes and ships. All import containers have to be transferred to the pre-planned stack locations. In practice, travel distance and hence travel time can only be reduced if the locations near to the QSCs are selected for stacking (Imai *et al.*, 1997 and 2001 and Nishimura *et al.*, 2001).

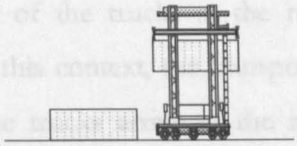
Grunow and Lehman (2004) have stated that in general, the sequence of transfer is not identical to the loading sequence of the ships. The stowage plan, the crane allocation plan and the quayside crane loading strategy determine the loading sequence. The minimisation of the dual-cycle-times with a combine of transfer time of export and import containers to and from the cranes operating on the same ship or at the neighbouring ships is a complex scheduling task (Heijden *et al.*, 2002). It can be argued that transfer vehicles may operate in a pooling system serving several cranes in an alternative manner. In this way the transfer time may be reduced but with a higher effort, time and organisation due to the complexity of operation. The possibility of crane idle-times can also be reduced if containers are buffered under the crane's portal.

In practice, automatic transport vehicles such as AGVs are always pooled while the manned equipment such as SCs or Tractor-Trailers (T-Ts) commonly operate on one crane (Heijden *et al.*, 2002). If automated equipment such as AGVs or ALVs are used for transfer operations and semi-automated RTG or automated or semi-automated or automated RMG cranes are used for stacking, then the control system should establish a scheduling programme for the equipment in such a way that containers arrive 'in-time' at the interface points in a systematic manner (Bruno *et al.*, 2000).

Evers and Coppers (2003) have focused on the movements of AGVs over the physical infrastructure for AGV traffic control systems with the aid of the semaphore technique. A semaphore technique establishes appropriate signals for the approaching transfer vehicles to adjust and synchronise a smooth flow of traffic according to the scheduling programme implemented. Wallace (2001) has presented an agent based AGV controller in order to provide an effective flow in the complex terminal structure. Heijden *et al.* (2002) have developed controlling rules for management of empty AGVs in the automated transportation systems. Lim *et al.* (2003) have suggested a dispatching method for AGVs in a general context. Kozan and Preston (1999) and Kozan (2000) have discussed the major factors associated with increasing the transfer efficiency of multi-modal terminals. Their overall objective is to minimise the vessels turnaround-time in ports. Their study indicates that shortening of the turn-around times is affected by the availability of transfer vehicles. The analysis of this issue however, is out of the scope of this study. Steenken (2003) has presented a study in which the routing of the transfer vehicles has been analysed. Kim *et al.* (2004) have discussed the transfer and load sequencing problem for export containers in container terminals using a beam search algorithm. In the studies conducted by Bonsall (2001), Chalmers and Easterbrook (2001) Roodbergen (2001), Memos (2003), Agerschou (2004) and Headlands *et al.* (2004) the conceptual layout and cycle-times models have been developed to facilitate an efficient means of stacking and retrieving of orders from the storages. In the majority of the above studies, the retrieving and stacking cycle-times play an important role in the vehicle turn-around times. In the study conducted by Bonsall (2001), the retrieving cycle-time of the SCs with different stacking capabilities has been defined as follows:

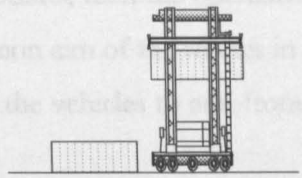
i) Two high stacking with one over two SC.

$$T_{ret} = \left[\left(\frac{9B_h}{h_s}\right) + 3L_o + \left(\frac{2B_l(N_s - 1)}{16.67T_s}\right)\right] \qquad 2.2$$



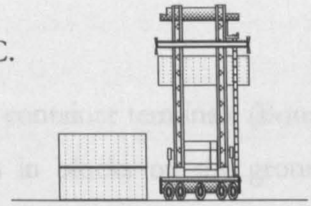
ii) Two high stacking with one over three SC.

$$T_{ret} = \left[\left(\frac{15B_h}{h_s}\right) + 3L_o + \left(\frac{2B_l(N_s - 1)}{16.67T_s}\right)\right] \qquad 2.3$$



iii) Three high stacking with one over three SC.

$$T_{ret} = \left[\left(\frac{22B_h}{h_s}\right) + 5L_o + \left(\frac{4B_l(N_s - 1)}{16.67T_s}\right)\right] \qquad 2.4$$



where:

T_{ret} = Retrieval cycle-time in minutes.

B_h = Container height (2.6 metres).

h_s = Hoist speed in metres/minutes.

B_l = Container length (6.09 metres).

N_s = Number of containers in row.

T_s = Travel speed of SCs in kilometres / hour.

L_o = Container lock-on / lock-off time in minutes.

16.67 = A constant converting kilometres / hour to metres / minute.

2.2.3 Landside operation

The most distinct activities at the landside are the receipt and delivery, stacking and implementation of container yard policies and the gate operations. Containers are finally transported to the road interface, railhead and the transhipment barges.

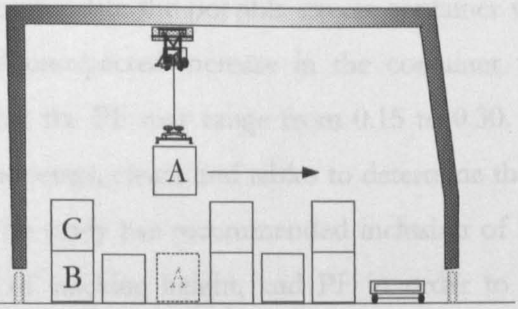
1) Receipt and delivery

The trucks and trains arrive at the receipt and delivery points particularly provided for SC systems where containers are loaded and unloaded by means of inter-terminal equipment. The receipt and delivery points are clear areas located close to the container stacks. A truck-driving schedule specifies the points to be accessed and the sequence to be followed. The arrival-time of the trucks at the receipt and delivery points cannot be precisely foreseen. In this context, the transport jobs for internal equipment cannot be decided until the trucks arrive at the interchange points. Where there is a traffic volume at these points, then the operational attempt should be flexible and conducted fast. The common aim of the studies in this area is to minimise the distance and the travel times of the vehicles to and from the stacks to the receipt and delivery points.

2) Stacking operation

Different stacking policies and systems exist in container terminals (Bonsall, 2001). Most modern terminals stack their containers in blocks on the ground. In the majority of container terminals, systems using RMGs or RTGs lay the blocks of stacks parallel to the quay face depending on the availability of land and irrespective of the automatic stacking facilities. However, in terminals that employ a direct SC system a reduction in manoeuvring time may be obtained by making the stacking blocks perpendicular to the quay face. This also improves access to the stacking blocks.

Some containers such as refrigerated containers (also known as 'reefer' containers) require special facilities and location. The determination of the stack capacities is a major design problem as the stacks occupy scarce and costly land. On one hand, the wide spread of stacks demands more transportation efforts and longer cycle-times (Zijderveld, 1995 and Chu and Huang, 2002-b). On the other hand, increased stacking height may be advocated, but the expected numbers of re-handles will increase sharply (Kim, 1994). In a separate study conducted by the author (see Appendix 1) it has been argued that the limitations caused by the extra operations for re-handling containers should be considered in the capacity and throughput calculation of container terminals. Re-handles occur when a container has to be accessed while other containers are stacked on the top have to be removed first. Re-handling of containers at the manual container terminals consume extra time that is an offset to the transfer time between the stacking-yard and the quayside crane thus reducing the productivity of the shipside operation. Castilho and Daganzo (1993) and Kim (1994) have stated that estimation of the exact number of container re-handles is a complex optimisation problem. The complexity of the problem is due to the random retrieve of the stacking cranes. The re-handling problem is illustrated in Figure 2.8 where container 'A' is directly accessible while container 'B' demands an undesirable and unwanted move of container 'C' above it. The same problem may exist on board the container vessels. In a study conducted by the author, a probabilistic approach has been examined to estimate the number of container re-handles and unwanted moves in container terminals. Yang *et al.* (2003) have discussed various decision problems that occur for the storage allocation of containers. The most productivity related factors such as dwell-times, stacking height and transhipment ratio are identified and accounted for the evaluations in the above studies. General discussions of different productivity related objectives are given in the studies proposed by Gupta and Somers (1992) and Fagerholt (2000).



(Source: Author)

Figure 2.8 Re-handles of containers at stacks

In some terminals, the main stack is separated into the import and the export sections. The import containers arrive in a predicted way and are likely to depart in an unpredictable order. This is one of the reasons for not stacking them so high. In the studies conducted by Watanabe (1991, 1995 and 2001), Bonsall (2001) and Kim (1997) it has been stated that the export containers arrive randomly and their departure is usually connected to the ships which arrive on a known schedule and therefore can be stacked higher and in a much more systematic way. Nowadays, many real time computing software packages are available for stacking and stowage management. The objective of these electronic aids is to minimise the number of re-handles, utilise the space allocated and reduce the risk of misplacement as well as establish a proactive monitoring and a record of incoming and outgoing containers. They are able to provide an information link through the logistics chain to customers. At the tactical level, the container yard stowage planning is prepared which indicates which containers to be stowed on top of which containers and at which stack (Iris and Koster, 2003).

3) Layout and capacity planning

Several studies have been carried out to calculate the area of the land required for container terminals for a given throughput. The studies carried out by Frankel and Liu (1979), Dally and Maquire (1983), Hoffman (1985), the UNCTAD (1985) and Frankel (1987) provide the basic requirement for determining the land area for a container terminal. Hoffman (1985) has proposed the average dwell-time of containers in a terminal in days and the Peaking-Factor (PF) to be considered when calculating the area required for a marshalling yard. Amongst other things, he has stated that the role of the PF is to ensure that at peak periods, there is a sufficient storage capacity to accommodate the possible excess container volume due to the seasonal variations and unexpected increase in the container volume. Hoffman (1985) has suggested that the PF may range from 0.15 to 0.30. UNCTAD (1985) has provided various processes, charts and tables to determine the area required for a container terminal. The study has recommended inclusion of the average dwell-times, maximum ratio of stacking height, and PF in order to calculate the land required and the annual throughput for a terminal.

Frankel (1987) has suggested the standard deviation of the dwell-times, average stack height and the economical utilisation of the storage area to be considered. The methods proposed by Dally (1983), Dharmalingam (1987) and Puertos and Enriquez (1991) evaluate the total throughput of a container terminal by analysing the berth utilisation, average dwell-times and the number of container GSs in their calculations. The above factors are important attributes and are required to be considered in the analysis of this research. Watanabe (1991 and 2001) has suggested that the average stacking height and dwell-times of the transhipment, export and import containers are the important factors to be considered in the analysis respectively. He has included the ratio of transhipment containers that significantly affects the number of container throughput calculation. He has argued that the ports are going through a transitional phase, in which the Origin-Destination (OD) ports are gaining a higher transhipment ratio and therefore are turning into the Hub-Port (HP) container terminal type. Dekker and Davis (1992) have discussed the applicability of their proposed terminal planning process to new hub ports. They have argued that their planning process can be used as a design and operation research tool to facilitate comprehensive development and reclamation of marine terminals. Friedman (1992) has stated that the container terminals should be planned and equipped dynamically according to the demand and supply basis indicated by the shipping lines and port users through efficient forecasting methods.

Kim and Kim (1999) have evaluated the capacity of the stack and used basic queuing formulas to formulate the relationships between the stacks and the container handling systems in a container yard by considering the rate of container arrival and departure to and from the stacks. A drawback with queuing models using for capacity calculation is that they do not account for the qualitative values in final decision-making. Jula *et al.* (2000) have introduced a design model based on simulation techniques for container terminals using automated shuttles. They have concluded that for similar automatic operations in container terminals, their automated shuttle system demonstrates a significant promise in increasing the throughput and achieving terminal performance.

A common drawback with most of simulation techniques is that the qualitative aspects of operations such as equipment flexibility, versatility, environmental concerns and efficient stacking policies cannot be incorporated into the problem solving process in a proper way.

Amongst other things, Bonsall (2001) has analysed the containers stacking and retrieving, stacking height and density and its effect on the cycle-time of yard and lorries operation in the container terminals for straddle and yard gantry cranes. He has argued that the variation in haulier operations in a terminal alters the way that each terminal can be modelled. It has also been discussed that network models and simulations techniques can be used to adequately model the landside operation of container terminals using yard gantry cranes and SCs respectively. Roodbergen (2001) has developed conceptual layout and cycle-time models to efficiently stack and retrieve picking orders from storages. His method may be used as the basis for planning container and stack layouts if the majority of the qualitative aspects of the operation are included. Chalmers and Easterbrook (2001) have studied the growth effect of containership size and capacity on the size and capacity of QSCs and terminal facility. They have concluded that container terminals may undergo a technical design revolution in order to keep pace with the doubling of ships' size and capacities that has occurred during the last thirty years.

Memos (2003) has examined a methodology for container terminal planning and operations. He has developed notations to calculate the annual handling capacity of container terminals employing SC, yard gantry crane, Tractor-Trailers (T-Ts), Front-end Lift trucks (FLs) and side loaders and lift truck systems. He has also provided criteria for construction, zoning and layout of berths and terminals from the civil engineering point of view. The important variables recognised in the study proposed by Memos (2003) are the dimension of the stack-yard, number and size of access roads, container ground slots and stacks heights. Headlands *et al.* (2004) have stated that port planners must create a balance between the demand, capacity, land, cost factors, environment and uncertainties when planning and designing ports. Not all of the issues raised by Headlands *et al.* (2004) may be included into problem solving with methods using simulation techniques. Such plans must be dynamic and versatile enough to provide room for future changes. Agerschou (2004) has proposed the following as the important parameters governing the relation between the container yard area and its annual throughput:

a) Average stacking height and the static distribution of the containers. The maximum stacking height may range from one to five, depending upon the container yard operating system and the type of transfer equipment employed. The stacking height can be assumed as an average stacking height for all of the yard operating systems.

b) A proper means of access and interchange areas must be provided for smooth operation of the yard equipment appropriate to the operating system employed.

c) Number of working days in a calendar year should be incorporated.

d) Average dwell-days of import and export containers and their static distribution should also be considered.

Dekker (2005) has provided a theoretical conceptual model for planning port capacities. The study has concluded that the application of new technologies would lead to reduced port congestion and costs. He has argued that investment in modern port facilities and designs would result in a competitive edge for the port operators. Watanabe (1991, 1995 and 2001), Dekker and Davis (1992), Friedman (1992), Kim and Kim (1999), Chu and Huang (2002-b) and Wang and Cullinane (2006) have proposed different design layouts and throughput methods using most of the variables indicated by Agerschou (2004) for the strategic levels. In a simulation study presented by Jula *et al.* (2000) different design models have been proposed for container terminals using automated shuttle systems.

The adoption of new technologies at the quayside and on the stacking-yard cranes which is the core of this thesis necessitates terminal operators reviewing and in some occasions re-designing the layout of the entire stacking blocks. Robust conceptual models are required to incorporate both quantitative aspects and qualitative concerns in the planning and design process.

4) Economics of container stacking operation

The productivity of the container stacking operation in container terminals has been viewed from economic scales particularly the cost efficiency in many studies. Hatzitheodoroue (1983) has compared the total cost of stacking over the cost of transfer operation in a container terminal under Top Loader (ToL) yard operating system. Hee and Wijbrands (1988) have proposed a model that measures the performance of the RSs in a terminal. The sensitivity analysis developed in their studies has compared the associated cost components of few real cases in the port industry. Nahavandi (1996), Chu and Huang (2002-a, 2002-b and 2003) have carried out different studies to formulate the required number of containers for container terminals based on different yard handling systems. They have discussed various cost parameters involved in their analysis. Kap and Hong (1998) have suggested a conceptual cost model to determine the optimum space and the number of yard cranes for import stacks. Kim and Kim (1998 and 2002) have developed a cost model for different space layouts and transfer systems and included different cost variables in their analysis. They have suggested a cost model which incorporates the fixed investment and variable operations costs to be used to help decision-making. Two objectives have been suggested to be met in their analysis. These objectives are the minimisation of the total cost of terminal operations and the costs associated with customers using a terminal. The most related cost factors in their study may be analysed in this study. Zhow *et al.* (2001) have proposed a cost comparison model for various container stacking and handling systems. Their model provides comprehensive methods to calculate the maximum throughput and the optimum total cost of the operating system and revenues derived from the operations in container terminals.

Nam and Ha (2001) have investigated different aspects of adoption of advanced technologies such as intelligent planning, operation and automatic handling systems for container terminals. Their studies have set different criteria for evaluation of different stacking and handling systems and have been applied to the Korean terminal environment. However, their study suggests that the application of automatic equipment should not violate the basic concept of a total cost minimisation policy in container terminals. Liu *et al.* (2002) have evaluated four different types of automated container terminal design models using a simulation model. They have provided detailed cost analysis of the models in which the performance of the systems has been discussed from the operational viewpoint of the terminal. The cost model developed in their studies evaluates the associated cost factors for each automated terminal concept. The results imply that automation could improve the performance of conventional container terminals at a considerably lower cost. Saanen *et al.* (2003) have developed a cost model to evaluate the cost values of different segments and equipment to be installed at a container terminal. The test cases analysed in their studies have compared the productivity values and cost effectiveness of a SC system over AGVs and Automated Loading Vehicles (ALVs). Amongst other things, they have concluded that a designer of a container terminal should know the threshold limit of the number of AGVs and ALVs to allocate and assign for operation beyond which the productivity of a terminal diminishes with increased cost. In different studies carried out by Yang *et al.* (2004) and Vis and Harika (2004), the optimum productivity of automated container terminals with minimum possible costs has been discussed. It has been argued that ALVs including automated SCs provide a higher productivity and cost effectiveness principally because they can eliminate the waiting-times of the transfer vehicles at the stack-yard.

5) Gate complex

In many container terminals the manual gate procedures give rise to the long delays for vehicle and develop the risk of committing mistakes. The problem will be that if data at the point of entry is fed in incorrectly, even in the smallest detail, this error will be carried through the whole system and may cause a great deal of extra effort and time in locating the error and correcting it. To minimise enormous data entry and to improve the gate flows and reduce costs, the automated gate procedures have been employed. Amongst other things, Bonsall (2001) has studied the gate operations. The gate procedure can be seen as two separate activities, pre-gate processing and the gate processing itself. The pre-gate processing is necessary to store information (submitted by the customers) about the vehicle and its container in the system database. The most sensitive and important part of the gate processing itself is the automatic identification of the containers. Different systems have been developed but virtually every system has entailed the production of the ISO code in a different, more machine-readable form. The most common systems in use are the use of barcodes, Radio Frequency (RF) tags, and Optical Character Recognition Systems (OCRSs).

In the case of the Thamesport Container Terminal using an automated RMG system, the lorry driver has to identify himself with an electronic identity card (SMART card) for security reasons. When the containers and the driver are identified, a location in the stack will be processed by the system and the lorry driver will be given a print-out to proceed to the location.

6) Landside transport

The landside transport may be divided into the train operation, truck operation and in some terminals the transport of containers to the transhipment quay cranes serving barges. A common means of operation is to allocate a dedicated number of suitable vehicles to each of these operations appropriate to the workload expected. A more advanced strategy could pool the vehicles for these three working areas. Trains are commonly loaded and unloaded by the yard gantry cranes while SCs, trucks and trailers or similar equipment generally perform the transfer between the stacks and the railhead. Operation at the railhead is analogous to the container yard and the quayside operations. A loading plan may describe the sequence and system of wagon stowage. The distribution and positioning of containers will depend on destination, type and weight, the maximum load capacity of wagons and the wagon position in the train sequence. The loading operation can be planned jointly by the railway company and the terminal operators or solely by the terminal operation planners. The aim of the rail operator will be to minimise the shunting activities during the train transport while the aim of terminal operators will be to minimise the number of re-handles and to minimise the waiting-time of the cranes.

Cao and Uebe (1995) have proposed a tabu-search algorithm in a similar way to the branch and bound methods, for solving the transportation problem. The proposed methods have included a non-linear side constraint of the problem for the assignment of storage spaces to containers with a minimum searching and / or loading costs. Kim and Kim (1998 and 2002) have discussed the determination of the optimal amount of storage space and the number of transfer cranes for import containers.

2.3 Terminal information system

The terminal information as an assisting system plays an eminent role in the organisation and operation of the container physical flow. The value of information is well respected especially for the terminal communication, automated vehicle tracking and container positioning systems.

The inter-terminal communication systems play a major role in the operation of container terminals. Radio data communication also plays a key role because it has been the main medium to transmit job data from the computer in the controlling tower to the quayside, yard cranes and the automated transfer vehicles and *vice versa* (Jones and Walton, 2002). In the studies conducted by Ghys (1988), Lissauer and Gaines (1989) and Eastaugh (1999) the radio data communication is generally considered as the technical base for implementation of operations research methods to optimise the job sequences involved. With the emergence and application of Electronic Data Interchange (EDI) employing an international standard language such as Electronic Data Interchange for Administration, Commerce and Transport (EDIFACT), Global Positioning System (GPS) in 1990, the automatic identification of container and vehicle positions brought a considerable accuracy and safety to the terminal information and operations (Recagno, *et al.*, 2001). Due to variations in the size of containers and container yard layouts and also to overcome tracking of the moving vehicles in the yard, a Differential Global Positioning System (DGPS) was employed (Eastaugh, 1999). The components of DGPS are installed on the stacking cranes but not on the containers. Whenever a container is lifted or dropped-off, the position is measured, translated into yard coordinates and transmitted to the controlling system. Alternatives to DGPS are the optical systems such as the laser reader systems. For a higher reliability, both systems are sometimes integrated. Transponder and electrical circuits are coördinated into the systems to route AGVS, RTGs and SCs and other automatic vehicles to ensure real time transmission of the container's position and conditions. More aspects of technology improvements and their impact on container terminal operations and information systems are addressed by Young (1995) and Talley (2000).

2.4 Decision-Making

Most of studies state that the decision-making techniques consist of a number of steps or stages such as recognition, formulation and generation of alternatives, information search, selection, and actions. In complex systems, decisions are usually made on the series of multiple and often uncertain criteria (attributes or objectives). Carlsson and Fuller (1994) have stated that in the Multiple Criteria Decision-Making (MCDM) theory the general assumption is to assume that the criteria are independent. This makes optimal MCDM solutions less useful than they could be and a decision-maker who accepts an optimal solution from the model may not be sure that he has made the correct trade-offs among the objectives. In the literature it is widely recognised that in many decision-making problems, the decision criteria are interdependent (Carlsson and Fuller, 1994 and 1997 and Saaty, 1996). Aldrich (1974) and Saaty (2004) have defined the interdependency as the series of conflicting objectives and attributes that support each other. Aldrich (1974) has stated that the degree of interdependency between the supporting objectives should be determined and exploited in the problem solving stage. The modelling and optimisation methods have been developed in both crisp and fuzzy environments. The concept of interdependency in the MCDM was introduced by Carlsson and Fuller (1994). The authors have stated that fuzzy set theory could be applied to resolve multiple criteria problems with interdependent objectives. Xie *et al.* (2006)

have developed a fuzzy rule-based model employing an evidential reasoning approach for location selection of the key bus stations. They have used MCDM based on the qualitative and quantitative assumptions.

The AHP has been widely accepted in a number of applied disciplines and extensively used to solve complex decision problems in different general areas. For the first time, Saaty (1980) has adopted an Analytical Hierarchy Process (AHP) solution for Multiple Attribute Decision-Making (MADM) problems. Saaty (1990 and 2004) has proposed the basis for a pair-wise comparison of alternatives using the AHP. The AHP enables comparison of two alternatives by comparing the weighted values of the attributes according to their relative importance until a winning alternative is selected. Felix (1994), Angilella *et al.* (2004) and Tzeng *et al.* (2005) have studied the application of MADM and Multiple Objective Decision-Making (MODM) techniques to support decisions. Fukuda and Matsura (1993), Zone and Chu (1996), Dym *et al.* (2002) and See (2005) have proposed the AHP method as salient ground for prioritising, ranking and selecting the decision alternatives.

Multiple Criteria Decision-Making (MCDM) methods using fuzzy set theory and AHP have been successfully applied to the marine, offshore and port environments to solve safety, risk, human error and design and decision-making problems. The applicability of such methods to maritime disciplines has been examined in the studies conducted by Yang and Sen (1998), Sii (2001), Sii *et al.* (2001), Pillay and Wang (2003), Kim (2005), Ren *et al.* (2005-a and 2005-b) and Ung *et al.* (2006).

It should be noted that MODM techniques are mostly used for optimisation problems to enhance and maximise the available capacities and potentials and MADAM techniques are used for selection decisions where the best alternative is the goal of the study. The MADM techniques utilising the AHP concept has been proposed in this study due to the following advantages over other techniques:

- It involves a set of alternatives compared with a set of attributes and sub-attributes in a pair-wise comparison manner.

- It allows consideration of qualitative assumptions together with qualitative measures.

- It allows necessary trade-offs to be made within the relevant attributes to ensure an acceptable level of consistency.

- It demonstrates the problem solving procedure in a comprehensive hierarchical manner.

- It provides a robust basis for final decision-making towards selection of the best alternative in a ranking order.

2.5 Conclusions

Container terminals have been one of the interesting areas for academic research studies during the last two decades. The automated technologies implemented in the operation of container terminals absorb a considerable amount of government, public or private funds which causes concern. Increasing the speed of operations through automation may have a direct impact on the layout, capacity, productivity, efficiency, safety, and the cost of terminal operations. This chapter has provided a comprehensive review of the literature for container terminal operation, planning and decision-making.

In the literature, however, there is an oversight in measuring the impact of automated devices employed on the efficiency and cost effectiveness of the quayside and container yard operations. The literature does not contain concrete ground for equipment selection decisions nor has it proposed a scientific decision-support system for the terminal planners and operators. Most of the studies carried out in the area of terminal operations are aimed at shortening the turnaround-times of the vessels' call at ports and provide a higher level of services to the port users. The contribution of the port operators, however, has been neglected. The evaluation of the automation impacts on the quayside and yard cranes and the appropriate selection decisions requires a fresh investigation. In the future chapters the above issues would be addressed and analysed with respect to the aims and objectives stated in Chapter 1.

Chapter 3

Evaluation of the Economic Feasibility of Automated Quayside Cranes

Summary

The majority of studies on Quayside Cranes (QSCs) focus on optimising the automatic functionalities of the cranes and very few have studied their economic implications. This chapter examines the economic feasibility of reducing QSCs' cycle-times resulting from automated features installed on existing post-Panamax cranes. It demonstrates that a considerable increase in productivity of the QSCs is related directly or indirectly to an expected reduction of crane cycle-times. The study sets up the need for the proposed improvements through automation and explains the concepts of the systems involved. The concept offered by the proposed improvements distinguishes between the traditional system of loading and discharging of containers and the automated methods. The evaluations and analyses in this study demonstrate that automation of the quayside operation enables the terminal operators to reduce turnaround-time and port stays of containerships. This chapter illustrates that the adoption of automatic features on the cranes carried out in this experiment would produce economic benefits that far exceeds the cost of adopting the various automatic devices.

3.1 Introduction

Cranes and particularly those dedicated to the loading and discharging of containers at the quayside are successfully deployed in the operation of container terminals for a longer useful working life. They have been through transition phases in which their handling capacity, size and ability to serve the new generation of containerships has grown considerably. Changes in the size and capacity of QSCs in container terminals are greatly influenced by post-Panamax and post-Malacca-max vessels that are too large to transit the Panama Canal and the Malacca Straits. A high demand for container handling coupled with rapid growth in containership size and economies of scale, forces the terminal operators to keep pace with these changes in order to survive. They either order a new generation of QSCs equipped with advanced automated technologies and / or upgrade their existing post-Panamax QSCs to serve the new generation of containerships. Upgrading the existing post-Panamax cranes by installing advanced features will enhance a higher efficiency and safety and will have significant economic implications for port operators and their customers. Indeed, quayside crane designers equip their new super post-Panamax cranes with *inter-alia* automated features such as smart spreaders, optimum path generators, automated landside trolleys, sway controlling mechanisms and smart shuttles. The advantages of automated systems and precise safety sensor technologies fitted to QSCs have not yet been fully studied. This may be due to the novelty of the technology and to the rapid changes that take place in size and capacity of the containerships which they serve.

The review of the literature on the quayside operation explained in Section 2.2.2 of Chapter 2 does not include the economic implications of the cycle-time shortening in modern QSCs. This chapter analyses the time-savings to evaluate the possible economic benefits that may accrue from the automated features installed on the QSCs.

3.2 Evaluation method

This chapter provides a fresh approach to evaluate the cycle-time analysis of the QSCs' operation in container terminals. The idea of cycle-time modelling was raised by Rosenfeld (1992) for construction cranes and would be adopted from this source to examine its applicability to quayside operation of container terminals. Use has been made of the studies conducted by Steiner (1992), Thuesen and Fabrycky (1993), Guthrie and Lemon (2004) and recommendations given by UNCTAD (2002) to incorporate cost factors. For a better concept of the analysis, a stepwise procedure is followed in this study:

- Analysis of the loading and discharging operation of the crane.
- Modelling of the crane cycle-times.
- Cost modelling.
- Identification of the benefits.
- Cost-benefit analysis.
- Sensitivity analysis.
- Analysis of the uncertainties and risks.

The generic method presented in this study would be applicable to all kinds of QSCs, very large industrial cranes and cranes used in the warehousing industry that feature automated technologies. The aim is to investigate the probable economic benefits that may accrue from investing in automatic technologies of the crane operation. An account is made for uncertainty and risk. It is assumed that the cranes operate in a dynamic and uncertain environment throughout the process life-cycle. In this environment, the market conditions such as the demand and price of the cranes and the rapidly evolving technology are uncertain. The following procedure is used to illustrate the objectives of this study:

3.2.1 Analysis of the crane operation

Data is collected for the manual and the automated modes of operation. The cycle-times are collected and tabulated for different category, size, shape and weight of the loads.

Cranes may engage in the following modes of operation:

i) Single-cycle.

ii) Double-cycle.

iii) Multiple-task.

3.2.2 Cycle-time modelling

A cycle-time can be broken-down into different steps. Some although not all of the steps may be capable of being fully optimised. A breakdown and comparison of these steps can show the percentage of reductions that can be obtained from the automated features.

The effects of the reduction of the QSC cycle-time may result in a saving in the total cycle-time of the crane. Let's consider 'j' as one of 'm' loading or discharging cycles in which a QSC is engaged during a typical working day and 'T_j' as the duration of 'j' out of the total QSC time, then total percentage of the total saving of the operation time, P(T), can be defined by Equation 3.1 derived from the study proposed by Rosenfeld (1992).

$$P(T)=\sum_{j=1}^{m}T_j(S_j\alpha_j + D_j\beta_j + M_j\gamma_j) \qquad 3.1$$

where:

T_j = Duration of the cycle-time for activity 'j'.

S_j = Mean percentage of the total cycle-time 'j' in the single-cycle mode of operation for activity 'j'.

α_j = Fraction of 'S_j' that can be saved.

D_j = Mean percentage of the total cycle-time 'j' in the double-cycle operation for activity 'j'.

β_j = Fraction of 'D_j' that can be saved.

M_j = Mean percentage of the total cycle-time 'j' in the multi-task operation for activity 'j'.

γ_j = Fraction of 'M_j' that can be saved.

m = Total number of cycles.

3.2.3 Cost modelling

The results obtained from the cycle-time analysis in the previous section can be used as the basis for economic analysis to obtain the possible average annual benefits. To do this, a generic cost model is constructed as follows:

- **Investment cost**

The cost of investment includes the initial cost of investment of the automatic features to be installed on the cranes. This study suggests that the following features can be considered in the analysis:

a) Optimum path generator.

b) Smart spreader.

c) Anti-sway system.

d) Assembly and installation.

- **Annual running cost**

The main elements of the generic annual cost modelling for the equipment are based on the following factors suggested by Hans (2004), Drewry Consultant Ltd. (1998), Thomas and Roach (1988):

i) Maintenance and repair.

ii) Labour (wages, training, insurance, *etc.*).

iii) Energy.

iv) Consumables (spare parts, lubricant, *etc.*).

v) Insurance.

vi) Inflation.

To model the benefits that may accrue from the savings in the QSC cycle-time, the following data should be clearly defined:

a) The average life-cycle of the automatic features to be installed.

b) The average working-days and the working-hours in a day per crane.

c) The average idle-times of a crane.

d) The number of crew working on a crane.

3.2.4 Total benefits

This study assumes that automation of QSCs by shortening the cycle-times and introduction of automatic monitoring, fault detection, smart safety switches, collision controllers, smart spreaders, etc., will produce both tangible and intangible benefits for the port operators. The likely economic benefits are based on conservative and / also optimistic assumptions *vis-à-vis* the uncertainties that may be present over the safety, risk and rapid changes in the technology of the quayside cranes. The benefits that may accrue from the crane automation may be categorised as direct and indirect benefits.

3.2.4.1 Direct benefits

- **Crane utilisation**

Saving in the crane cycle-times and all other time dependent activities of the QSCs' operations would produce equivalent financial benefits. To assess the economic value for better utilisation of the crane brought about by automation, the equivalent time-dependent annual cost of the automatic devices of the crane, 'R_C', can be calculated from the following formula proposed by Steiner (1992):

$$R_C = IC \times CRF - S \times SFF + A \qquad 3.2$$

where:

IC = Initial cost of investment in the automated devices.

S = Expected salvage value of the devices after 't' years of use.

A = Other time-dependent annual costs.

$$CRF = \frac{i \times (1+i)^t}{(1+i)^t - 1} \qquad 3.3$$

$$SFF = \frac{i}{(1+i)^t - 1} \qquad 3.4$$

where:

CRF = Capital recovery factor that converts the initial cost of investment (IC) into an equivalent average annual value of equal series for given 'i' and 't' (see Appendix 4).

SFF = Sinking fund factor that converts 'S' into an equivalent average annual value of equal series for given 'i' and 't'.

i = Annual interest rate.

t = Expected economic life of the crane in years.

The values of CRF and SFF can be calculated from Equations 3.3 and 3.4 proposed by Steiner (1992), Thuesen and Fabrycky (1993) and Guthrie and Lemon (2004). A sensitivity analysis can be conducted when the value of 'R_C' is obtained.

- **Manpower saving**

Another direct benefit of automated and optimised operation of the QSCs may be obtained from the savings in the number of labourers employed and hence the labour cost.

- **Safer crane operation**

The use of highly trained and skilful QSC drivers together with the application of advanced operating and safety features such as crane monitoring, crane and trolley collision avoidance, fault monitoring, self diagnostic systems *etc.*, to harmonically work with automation features may produce safer and smoother crane motions. Consequently, risk of damage would be reduced and the crane would require fewer repairs and maintenance, experience fewer and shorter down-times, and enjoy an extended useful life. The following benefits may be achieved:

a) Safety enhancement and a prolonged economic life.

b) Reduction of maintenance and repair.

3.2.4.2 Indirect benefits

There can be more economic benefits. These may include:

- Reduction of the total duration of operation, which would reduce overhead costs and management fees.

- Reduction of human errors through scheduled technical and safety training schemes for all of the staff involved.

- Safer quayside operation.

It is worth mentioning that it is often difficult to quantify the above benefits economically. However, a qualitative estimate of the benefits may be given.

3.2.5 Cost-benefit analysis

An investment in a project is deemed economically feasible, if the expected revenue meets or exceeds an acceptable pre-determined level of return on the initial investment. Traditionally, the Net Present Value (NPV), Annual Rate of Return (ARR) and Payback Period (PBP) investment appraisal techniques have formed the major component of feasibility studies. These three techniques are based upon the time-cost-of-money principle and use slightly varied procedures to forecast the expected returns on an investment. The reliability of their output depends upon the accuracy of the cost and benefit values and their timing as estimated by the investors.

- **Payback Period (PBP)**

The PBP in years illustrates how long it will take to get the investment back. An investment's payback period is equal to the initial investment divided by the expected benefits of investment in a project. This can be expressed by Equation 3.5.

$$PBP = IC / AB \qquad 3.5$$

where:

IC = Initial cost of investment in £.

AB = Expected annual benefits in £.

£ = Pound Sterling.

- **Annual Rate of Return (ARR)**

The ARR will indicate the yearly percentage of the gain in the investment. The ARR can be defined in Equation 3.6.

$$ARR = AB / IC \qquad 3.6$$

- **Net Present Value (NPV)**

The NPV of the system may be found by the traditional method that incorporates the net cash flow by deducting the total costs involved from the total benefits, which are expected from the investment at the end of 't' years, therefore:

$$NPV = \sum_{t=1}^{T}\left(\frac{B_t}{(1+r)^t}\right) - IC \qquad 3.7$$

where:

NPV = Net present value to the investor in £.

t = 1, 2, ..., T = Expected economic life of the crane in years.

B_t = Expected annual benefits.

IC = Initial cost of investment in £.

r = The discount rate calculated as follows:

$$r = \frac{i - f}{1 + f} \qquad 3.8$$

i = Expected average interest rate in 't' years.

f = Expected average rate of inflation in 't' years.

The present value of an investment should be corrected by a discount rate (r). The discount rate considers an annual interest rate together with an annual rate of inflation. Discount rate can be calculated by the equation proposed by Steiner (1992), Thuesen and Fabrycky (1993), UNCTAD (2002) and Guthrie and Lemon (2004).

- **Benefit-Cost Ratio (BCR)**

The BCR can be obtained by dividing the net value of the present benefits from the initial cost of investment in the automated technology. This can be defined as follows:

BCR = NPV / IC 3.9

3.2.6 Sensitivity analysis

Finally, for the cost-benefit analysis of the study, a sensitivity analysis is required to be carried out by generating aggregated combinations of the costs and benefits.

3.2.7 Uncertainty and risk

A fundamental limitation of the above procedures is that the various investment parameters cannot be practically assumed with a higher degree of certainty. The value of each parameter may be affected by a number of uncertainties and risks which are often difficult to quantify. An element of uncertainty lies with each prediction, which, alone or in combination, may have a significant impact on the outcome of the economic analysis. Uncertainty, emanating from the operating environment of the cranes and / or external factors, will always be present and needs to be clearly identified in the decision-making process. The sources of uncertainties and the likelihood of the risks involved in the investment and operation of the cranes under study need to be identified.

3.3 Test case

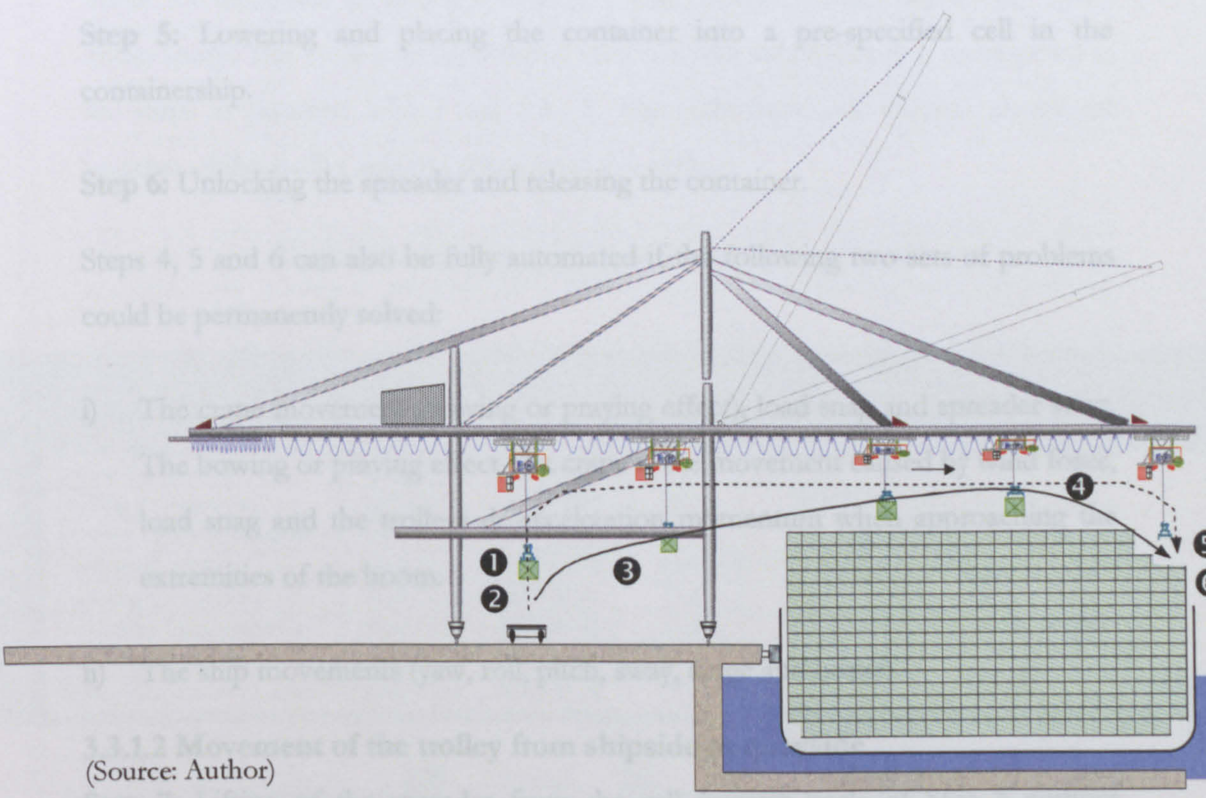
The generic models produced in Section 3.2 are applied to a test case to demonstrate their applicability to the QSCs in the container terminals.

Figures 3.1 and 3.2 illustrate a comprehensive schematic view of a conventional single hoist post-Panamax QSC with a single trolley in a Single-Cycle Mode (SCM) of a loading operation.

3.3.1 Quayside crane operation

For the concept of the analysis, the operation of a single hoist QSC with a single trolley is broken-down into different steps. The crane operator can load or discharge containers manually with a longer cycle-time or use automated optimum path generators installed on the QSCs to complete the cycles in a much shorter time. In the following illustrations, the dotted line indicates a manual operation and the solid curved line a possible automated and optimised line of operation. For the clarity of illustration, the cycle-paths graphs have been exaggerated in the diagrams.

3.3.1.1 Movement of the trolley from quayside to shipside



(Source: Author)

Figure 3.1 Loading a container onto the ship

Step 1: Setting of the spreader over the container delivered either by a Tractor-Trailer (T-T), by a Straddle Carrier (SC), or with an Automated Guided Vehicle (AGV). With the application of smart identification and positioning systems, this process can be fully automated.

Step 2: Automatic locking of the spreader onto the container.

Step 3: Transport of the container from the quayside with gradual hoisting of the spreader towards a specific cell in the containership.

This process can be totally automated through systems in which optimum path recognition techniques are used. These systems help the driver to automatically shift the trolley and the spreader towards the intended cell and *vice versa*. If the driver does this manually and the path seems to be more optimised than that of the one previously stored in the memory of the crane system, then it can be re-stored in the memory for the next run and perhaps for the next operation.

Step 4: Finding the cell guides.

Step 5: Lowering and placing the container into a pre-specified cell in the containership.

Step 6: Unlocking the spreader and releasing the container.

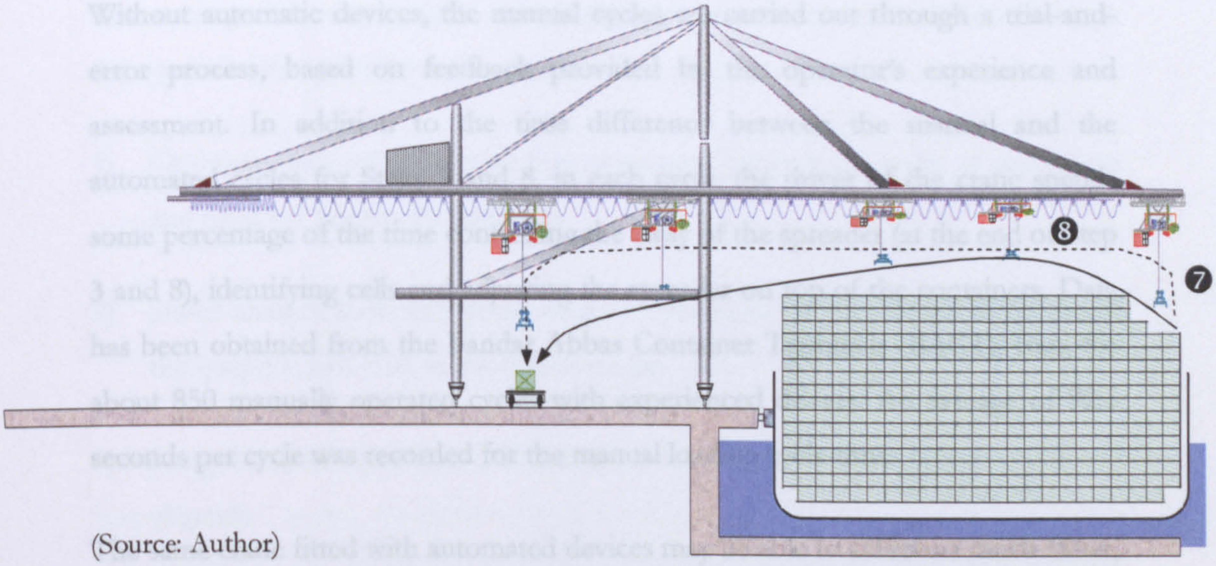
Steps 4, 5 and 6 can also be fully automated if the following two sets of problems could be permanently solved:

i) The crane movement (bowing or praying effect), load snag and spreader sway. The bowing or praying effect of a crane is the movement caused by wind force, load snag and the trolleys de-acceleration momentum when approaching the extremities of the boom.

ii) The ship movements (yaw, roll, pitch, sway, surge and heave).

3.3.1.2 Movement of the trolley from shipside to quayside

Step 7: Lifting of the spreader from the cell (reverse cycle of Step 5 without container).



(Source: Author)

Figure 3.2 Returning the empty spreader to the quayside

Step 8: Transfer and gradual lowering of the spreader towards the quayside (reverse cycle of Step 3 without container).

3.3.1.3 An example

Table 3.1 illustrates an example of a cycle-time obtained from one of the QSCs under study. The cycle is broken-down into different sub-cycles that correspond to the steps in Sections 3.3.1.1 and 3.3.1.2. The right hand-side column shows the position of the trolley and the spreader in the cycle.

Table 3.1 A loading cycle-time obtained from a QSC

Step	Actions	Start	Finish	Duration / Seconds	Total Cycle-time = 67.3 Seconds
1	Setting the spreader	00:00:00:00	00:00:04:00	04.0	
2	Locking the spreader	00:00:04:00	00:00:12:00	08.0	
3	Moving the spreader to shipside	00:00:12:00	00:00:30:42	18.7	
4	Finding cell guides	00:00:30:42	00:00:33:42	03.0	
5	Lowering the spreader	00:00:33:42	00:00:44:54	11.2	
6	Un-locking the spreader	00:00:44:54	00:00:49:42	04.8	
7	Hoisting the spreader	00:00:49:42	00:00:55:12	05.5	
8	Moving the spreader to quayside	00:00:55:12	00:01:07:18	12.1	

Legends: Spreader movement; Trolley movement; Driver justification; Spreader locking / un-locking

(Source: Author)

Without automatic devices, the manual cycles are carried out through a trial-and-error process, based on feedback provided by the operator's experience and assessment. In addition to the time difference between the manual and the automated cycles for Steps 3 and 8, in each cycle, the driver of the crane spends some percentage of the time controlling the sway of the spreader (at the end of Step 3 and 8), identifying cells and adjusting the spreader on top of the containers. Data has been obtained from the Bandar Abbas Container Terminals (BACT), Iran, for about 850 manually operated cycles with experienced drivers. An average of 92.5 seconds per cycle was recorded for the manual loading cycle-time.

The same crane fitted with automated devices may be able to achieve a much faster, safer, more efficient and accurate cycle than the manual version. Referring again to Figures 3.1 and 3.2, the position and path of the spreader, except its sway, can be determined accurately by measuring its movement and controlling it at each pre-planned point. With the automatic mode of operation, intelligent spreader positioning, and container identification systems, the actual position of each point can automatically be fed into the computer in real time and compared with the pickup and drop-off positions. The computer will be able to make the necessary calculations and instruct every motor to move accordingly, until the target is reached and the container is positioned into the intended slot.

An automatic optimum path system linked with smart container identification systems may produce considerable time-saving in the loading and discharging operation. The robust scantling and configuration of QSCs can be equipped with reliable, inexpensive, computer-based automated devices. As examined in the separate studies conducted by Rosenfeld (1995) and Cranes Today (1996-a and 1996-b) automatic operation, spreader positioning and container identification systems installed on a post-Panamax crane can benefit from the synergy among three parties:

a) The operator's human intelligence, judgment and improvisation skills.

b) The computer's programmability, vast memory and rapid calculation capabilities.

c) The sensory devices' accurate, real-time measurements and feedback.

The concept inherent in QSC automation systems makes a distinction between three parts of the spreader movement.

1) Optimum path travelling with fine movement between the point of picking-up and drop-off points of containers.

2) Smart identification and positioning of containers on the chassis of trailers at the quayside and slots in the containership cells.

3) Long-distance operation of the spreader between the quayside and the shipside.

The automation systems offer an additional enhancement that addresses the subsequent intelligent identification and positioning of the containers and smooth manoeuvring steps of the trolley cycles with a view to reducing the number of personnel involved in the process of loading or discharging of the containership. This enhancement is based on the observation that manual operation and controlling of the sway of the loads is neither efficient nor adequately safe. This is particularly true when the container is far away from the driver, becomes obscured from his or her sight, or when the positioning of the spreader demands high precision such as when the containers are deep in the holds. The observations conducted by the author during the research at the BACT, strongly support the idea of minimising crane cycle-times, which should result in a shorter duration of the container vessels turnaround-time.

3.3.2 Cycle-time analysis

The data collected for this study has been obtained by personal observation from the ten newly automated QSCs in BACT. The QSCs were equipped with optimum cycle path generating systems coupled with computing systems installed on the cranes that enabled the drivers to measure, edit and provide a print-out of the time and distance of different points in the cycle path with respect to a fixed point on the quayside or onboard the ship. For one of the QSCs, these points were essentially the same points indicated in Figures 3.1 and 3.2 (about 100 reliable single cycles of automatic loading operations were obtained and compared with the similar results from the manual cycles).

The results obtained from one of the cranes are summarized in Table 3.2. The duration of the cycle-times for each step or the combination of steps were obtained. The mean duration of cycle-time, 'T_j', corresponding to the automation operations was 67.3 seconds and will be used as a basis for the analysis. The mean and standard deviations of the above cycle-times were calculated using Microsoft Excel. The mean percentage of the spreader manoeuvring time out of the total cycle-times, 'S_j', for the observed automated loading operations was found to be in the range 15.3% to 27.8% (these values are obtained by dividing the automated cycle-times of steps with the average total cycle-time of the QSCs). For example, the percentage for Steps 1 and 2 in the automated cycles is 12.0 divided by 67.3 that equals 0.178. Automation would produce a potential saving in the crane's manual cycle-times derived mainly from the reduction of these percentages. The savings are significant when the driver properly uses the optimum path generator and sway control systems to automatically control Step 3 and Step 8. On average, the automated cycles were found to be about 25.2 seconds faster than the manual ones.

Table 3.2 Cycle-times obtained from a QSC

Operation Phases	Automated Operations			Manual Operations	
	Duration of Cycle-time / Seconds T_j	Mean Percentage of Spreader Manoeuvring Times / % S_j	Effected Spreader Manoeuvring Time T_jS_j	Average Duration of Cycle-times / Seconds T_j	Standard Deviation
Steps 1+ 2	12.0	0.178	2.100	16.2	±4.0
Steps 3	18.7	0.278	5.200	25.6	±5.0
Steps 4+5	14.2	0.211	3.000	19.3	±7.0
Steps 6+7	10.3	0.153	1.600	14.6	±3.0
Steps 8	12.1	0.180	2.200	16.8	±6.0
Σ =	67.3	1.000	14.100	92.5	

(Source: Author)

The automated and manual cycle-times were obtained where competent drivers were appointed for the operations of the cranes under study. The comparison of manual and automated cycles in Table 3.2 demonstrates that when QSCs operate automatically, the efficiency would be increased by 27.24% (92.5-67.3 / 92.5 x 100). This value is the fraction of 'S_j' that can be saved by using automatic devices. Therefore, α = 27.24% may be used as a basis for calculation of the cycle-time saving for all of the cranes. The observations however, showed that in some time-demanding cases, such as controlling the load snags and sway and time taken to lower the spreader into the cells, only a smaller fraction of the cycle-time may be saved when compared with longer segments of the cycle, therefore, 'α' can be assigned a smaller value. One may consider a smaller percentage of saving by considering saving only the time taken by craned driver to justify and find cell guides and where, setting, locking and unlocking of the spreader is done manually and consumes a considerable portion of cycle-time. This is particularly valid since observations showed that competent drivers load and discharge containers without using optimum path generator system and dampen the sway of the load in a competent way to the automated systems. Therefore, 'α' can be conservatively assigned with a smaller fraction.

The data obtained from the QSCs and Equation 3.1 are used to demonstrate the mean percentage of time savings of the crane time. In calculating Equation 3.1, the potential time-saver 'β' was taken to be zero because the experiments took place only under single-cycle mode of operation. For the same reason, the analysis of time cycles for a multi-task operation and therefore any 'γ' related potential savings for Equation 3.1 were left unexamined in the present analysis. Therefore, Equation 3.1 may be modified as:

$$P(T) = \sum_{j=1}^{m} T_j \ (S_j \alpha_j)$$

Other factors that may have an effect on the time-savings are the processes explained in Steps 1, 2 and 4 and the values assigned to 'T_j'. This study uses the method proposed by Rosenfeld (1992) to find the effected percentage of time-saving and then apply 'α' to find the average percentage of crane operation time. The effected percentage of saving in cycle-time, $\Sigma T_j \ S_j$, for each crane operated manually is calculated using the 'T_j' and 'S_j' values. The calculations for about ten QSCs are summarised in Table 3.3. The table represents three different manual loading experiments involving 20-foot and heavy 40-foot export containers and empty containers. In a similar way to Table 3.2, the effected duration of the spreader manoeuvring times ascribed to the steps, '$T_j \ S_j$' was obtained for all cranes. The total $\Sigma T_j \ S_j$ for each row and hence each crane may be considered as the saving contribution of the crane's productive time taken by the spreader travelling for that respective full-cycle.

Table 3.3 The percentage of spreader manoeuvring times

Operation Phases			Steps 1+2	Step 3	Steps 4+5	Steps 6+7	Step 8	Total (Seconds):	$\Sigma T_j S_j$
Loading 20-foot Containers	QSC. 1	T_j	14.700	23.300	17.900	13.800	15.500	85.200	
		S_j	0.173	0.273	0.210	0.162	0.182		
		$T_j S_j$	2.536	6.372	3.761	2.235	2.820		17.724
	QSC. 2	T_j	15.600	22.100	17.300	13.800	14.900	83.700	
		S_j	0.186	0.264	0.207	0.165	0.178		
		$T_j S_j$	2.908	5.835	3.576	2.275	2.652		17.246
	QSC. 3	T_j	21.300	25.600	21.300	19.600	17.5	105.300	
		S_j	0.202	0.243	0.202	0.186	0.166		
		$T_j S_j$	4.309	6.224	4.309	3.648	2.908		21.397
Loading 40-foot Very Heavy Containers	QSC. 4	T_j	23.900	28.100	21.300	21.800	14.300	109.400	
		S_j	0.218	0.257	0.195	0.199	0.131		
		$T_j S_j$	5.221	7.218	4.147	4.344	1.869		22.799
	QSC. 5	T_j	22.200	28.600	22.800	20.000	15.200	108.800	
		S_j	0.204	0.263	0.210	0.184	0.140		
		$T_j S_j$	4.530	7.518	4.778	3.676	2.124		22.626
	QSC.6	T_j	23.800	26.800	26.600	24.500	17.800	119.500	
		S_j	0.199	0.224	0.223	0.205	0.149		
		$T_j S_j$	4.740	6.010	5.921	5.023	2.651		24.346
	QSC. 7	T_j	22.100	27.000	27.100	22.700	15.900	114.800	
		S_j	0.193	0.235	0.236	0.198	0.139		
		$T_j S_j$	4.254	6.350	6.397	4.489	2.202		23.693
	QSC. 8	T_j	22.200	27.400	28.300	26.700	18.200	122.800	
		S_j	0.181	0.223	0.230	0.217	0.148		
		$T_j S_j$	4.013	6.114	6.522	5.805	2.697		25.152
Loading Empty Containers	QSC. 9	T_j	16.900	22.500	20.600	19.000	16.800	95.800	
		S_j	0.176	0.235	0.215	0.198	0.175		
		$T_j S_j$	2.981	5.284	4.430	3.768	2.946		19.410
	QSC. 10	T_j	15.400	22.200	21.800	20.500	15.500	95.400	
		S_j	0.161	0.233	0.229	0.215	0.162		
		$T_j S_j$	2.486	5.166	4.982	4.405	2.518		19.557
								Average:	21.395

3.3.3 Analysis of the results

The results obtained for $\Sigma T_j S_j$ in Table 3.3 indicate that the possible cumulative percentage of time-saving of the spreader travelling is in the range of 17.246 to 25.152 of the crane's productive time. The average of $\Sigma T_j S_j$ is therefore 21.395%. Using the modified version of Equation 3.1 and the proposed method offered Rosenfeld (1992), the total percentage of saving of the entire crane time is calculated as follows:

$$P(T) = 0.21395 \times 0.2724 = 0.058 \approx 6\%$$

Thus, a fraction of 6% is used as the basis for the economic analysis of this study.

3.3.4 Economic study

The economic feasibility analysis framework provided in this study aims to set-up the basis for the terminal operator to make decisions regarding the application of automated features. However, there are uncertainties and tied with them will be risks from the sourcing data, costs, and expected benefits due to the ongoing advances in automation technologies. To overcome the inherent difficulties involved in the economic feasibility study of QSC, the following measures have been taken for the purpose of this study:

a) A conservative approach is adopted owing to the sensitivity of having high cost values of automated features on the one hand and low benefit values on the other.

b) Data from previous studies may be used only as long as they are applicable to QSCs. This includes those conducted by Michael and Jordan (2002), Davis and Bischoff (1999), Rudolf (1995), Jordan and Rudolf (1995) and those conducted on very large industrial cranes particularly in the analysis carried out by Cheesman (1980) with the required modifications.

c) Appropriately the modified data from simulation studies may be used only as long as they are applicable to a QSC environment.

3.3.4.1 QSCs costs

The cost-benefit analysis carried out in this section is based on the terminal operators' interest rather than marketing costs and values for the producers. The cost values are obtained from the BACT, Iran for the purpose of this research only. The initial price of a QSC greatly depends on the ability of the crane to serve the new generation of containerships and the number of moves it makes per hour. The cranes under study in the BACT had an initial investment cost of about £3,500,000 (Bahrani, 2004). Table 3.4 provides a summary of the components of the time-dependent annual costs that are considered as follows: maintenance 2.0% of the initial price, (£68,750); energy 0.38% of the initial price, (£13,250); consumable costs 0.16% of the initial price, (£5,500); labour cost 11.25% of the initial cost, (£393,750); insurance and other fees 1.5% of the initial cost, (£52,500) (Bahrani, 2004). These costs are based on the following assumptions:

a) There are 3 shifts (3 x 8 hours) in a day and 2 crane drivers are working on each crane in each shift.

b) Annual labour cost is estimated to be about £65,625 per person / year (Bahrani, 2004). On the basis of the assumption made in section (a), the total labour cost per crane for the manual operations would be 3 x 2 x £65,625 = £393,750.

c) The economic life of the automated devices installed on the cranes according to the manufacturer statement is about 5 million moves (Kalmar Ltd., 2004). By considering an average cycle-time of 67.3 seconds per move, the economic life-cycle of the devices, 't', is calculated to be approximately 10 years as follows: $t = \frac{5{,}000{,}000 \times 67.3}{365 \times 24 \times 60 \times 60} \approx 10$ years

d) An average energy cost of £0.045 kW-hour (4.5 pence per kW-hour) is considered for the QSCs while they are fully operational (Thomas, 2002 and Bahrani, 2004).

e) An interest rate of about 8% is considered (Bahrani, 2004).

f) An inflation cost of 1.5 to 3.0% is considered throughout (Bahrani, 2004).

g) An equipment insurance cost of 1 to 1.5% of the initial cost is considered for this study (Bahrani, 2004).

Table 3.4 Summary of the annual running costs, £ / QSC

Total Labour Cost / QSC	Maintenance	Energy	Consumables	Insurance and Other Costs	Total
393,750	68,750	13,250	5,500	52,500	533,750

(Source: Author)

Table 3.4 shows a summary of the annual running costs and Table 3.5 shows the initial investment costs of automated devices that were installed on the single hoist conventional post-Panamax QSCs in BACT.

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Table 3.5 Initial cost of an automated system in £

All of the parameters for the analysis are available and the study can be carried out for cost-benefit analysis on the basis of time dependent components.

3.3.4.2 Direct benefits

Some of the benefits that are likely to be achieved from the investments are monetarily quantifiable. These benefits may be categorised as the crane utilisation benefits, manpower reduction benefits and the benefits to accrue from the safety enhancement brought about by automation.

- **Benefits to accrue from crane utilisation**

A considerable benefit to the terminal operators and consequently the customers and end users may be attributed to a better utilisation of the crane through the adoption of the automatic spreader travelling, identification and positioning system. The economic value of 'R_C' brought about by a better utilisation of the crane stated earlier in Section 3.2.4.1 may be calculated from Equation 3.2 as follows:

$R_C = 135{,}600 \times 0.149 + 533{,}750 \approx £553{,}954$

where:

IC = £135,600.

S = 0.

It is usually difficult to estimate any market value for second hand QSCs and automated devices. However, since the price of the devices installed on the QSCs at the end of their economic life is very low relative to their purchase price, the effect of its salvage value on 'R_C' will be marginal. For this reason 'S' is initially taken as zero.

Using Equation 3.3, the CRF was calculated approximately to be 0.149 for 't' = 10 years and 'i' = 8% as follows:

$$CRF = \frac{0.08 \times (1+0.08)^{10}}{(1+0.08)^{10} - 1} = 0.149$$

A = £533,750 (taken from Table 3.4).

With the application of automatic features, the crane would, on average, perform its assignments 6% faster, as concluded above in the results of the time analysis in Sections 3.2.2 and 3.2.3. Therefore, the economic value, B_1, of this benefit can be quantified as:

B_1 = £553,954 x 6% ≈ £33,237 / crane / year

- **Savings in manpower**

Usually in container terminals there will be a spare QSC kept ready for operation in any unexpected breakdown of the cranes under operation. Therefore, this study considers that the dedicated cranes are continuously operational and the economic impacts that may result from probable emergency stoppages and down-times are negligible. In this study, the automatic operation will require only one crane driver for each shift. Therefore, three crane drivers can be eliminated from the operation which yields a labour cost saving of B_2 as follows:

B_2 =1 x 3 x £65,625 = £196,875 / crane / year

- **Risk reduction benefits**

All of the safety measures in a container terminal are taken to provide optimum control and minimal hazards and risks. Application of safety equipment and implementation of risk reduction and hazard monitoring and control policies mean that the cranes may require fewer repairs and maintenance, experience fewer and shorter stoppages and down-time. Therefore, the cranes would have extended economic life. Extension of the cranes' economic life even for one or two years would be valuable and well respected by the port operators. However, it is difficult to exactly quantify the expected savings to accrue from the prolonged economic life monetarily and will be left as qualitative benefits in this study.

Thus, the annual direct benefits, B, are:

$B = B_1 + B_2$ = £33,237 + £196,875 = £230,112

3.3.4.3 Indirect benefits

A safer operation of the QSCs, reduction in human errors, optimised and integrated operation of the QSCs with container yard systems will produce economics savings which are difficult to quantify. Thus, in this study, they are left in a qualitative form.

3.3.4.4 Cost-benefit analysis

The cost-benefit analysis carried out for installing the automated features in this study yielded the following results:

- **Payback Period**

A £230,112 benefit on an initial investment of £135,600 may be recovered within (£135,600 / £230,112) 0.59 years (about 7.1 months).

- **Annual Rate of Return**

The Annual ARR can be obtained by dividing the total benefit by the initial cost of investment in automation (the reverse action of Payback Period). Thus, the ARR for a £135,600 cost would be about 1.70 (£230,112 / £135,600).

- **Net Present Value (NPV)**

The net value of the system is obtained for the average benefits over the expected life of the automated devices by Equations 3.7 and 3.8 as follows:

$$NPV = \sum_{t=1}^{10}\left(\frac{230{,}112}{(1+0.064)^t}\right) - 135{,}600 =$$

$$230{,}112 \times \left(\frac{1}{(1+0.064)^1} + \frac{1}{(1+0.064)^2} + \frac{1}{(1+0.064)^3} + \ldots + \frac{1}{(1+0.064)^{10}}\right) - 135{,}600 = 1{,}526{,}153$$

where:

B = £230,112

t = 1,2,3, …,10 years

IC = £135,600

$$r = \frac{0.08 - 0.015}{1 + 0.015} = 0.064$$

i = Nominal interest of 8%

f = Inflation rate of 1.5% (H.M. Treasury 2003 and Bank of England 2004).

- **Benefit-Cost Ratio**

BCR = £1,526,153 / £135,600 = 11.25

3.3.4.5 Sensitivity analysis

Terminal managers may require different schemes and hence, different alternatives for an investment to be analysed before a final decision is made. A sensitivity analysis helps to examine different alternatives by varying the values of the initial costs of investment, the expected annual benefits, PBP, *etc.*, to find the most suitable scheme to suit the needs of a particular terminal. Table 3.6 provides a sensitivity analysis under assumptions of the above cost-benefit analysis. Instead of addressing the numerous variables separately, aggregated combinations of costs and benefits have been generated.

Table 3.6 Sensitivity analysis of the economic criterion

Alternatives	Initial Cost (IC) (£)	Annual Benefit (AB) (£)	Economic Criterion			
			Payback Period (PBP) (months)	Benefit-cost Ratio (BCR)	Net Present Value (NPV) (£)	Annual Rate of Return (ARR)
1	135,600	230,112	7.1	11.25	1,526,153	1.70
2	271,200	230,112	14.1	5.13	1,390,553	0.85
3	135,600	196,785	8.3	9.48	1,285,482	1.45
4	135,600	33,237	49.0	0.78	104,421	0.25

The details of the alternatives in Table 3.6 are:

(1) The original assumptions remain unchanged. A cost of £135,600 and the annual benefits of £230,112 provide a NPV of £1,526,153. The initial cost may be covered within 7.1 months.

(2) The annual benefits of £230,112 remain unchanged and the initial cost is doubled to £271,200, as a provision for possible rises of cost due to changing market conditions, as well as for various other costs initially based on estimation. Therefore, using Equation 3.7 the NPV would be £1,390,553.

(3) The initial cost of £135,600 remains unchanged. The expected benefits are limited to B_2 (£196,785) if the automated devices are not used and the cranes are run under the manual mode of operation. Under the above assumption, the

system would generate a net present value of £1,285,482 that is about 9.5 times of the initial cost of investment. The initial cost of investment would be covered in about 8.3 months.

(4) The initial cost of £135,600 remains unchanged, but the benefits are reduced to B_1 (£33,237). This is the case where the terminal operator particularly in developing countries does not intend to save on manpower but is only interested in utilising the crane operation time and the safety enhancements.

The various economic criteria results obtained in this study illustrate that alternative (1) is the most desirable case where the initial investment may be recovered within 7.1 months. The net benefits expected to be obtained for Cases (2) and (3) are significant. Even under the least favourable assumptions considered in Case (4), the cost of investment would be recovered in about 4 years and there would be a marginal net benefit of about £104,421.

The results of the sensitivity analysis demonstrate that under a variety of situations the system can generate positive benefits. The safety margin that the system provides may yield additional un-quantified benefits.

3.3.5 Uncertainty and risk

The uncertainties and risks associated with them are dispersed throughout the quayside operation of the container terminals. They need to be identified and analysed before decisions are made. There may be uncertainty about the achievement of the objectives and effectiveness of an immature automation technology in the long-term. Uncertainty is dispersed particularly in the environment of the QSCs operation and the rapid technological advances that take place both in the expected containership size, capacity and equipment and in the quayside operating systems of the container terminals. The study may also indicate a degree of uncertainty due to an optimistic estimation of the NPVs and thus the values of ARR. However, the final decision-making of the terminal operator would depend upon the strategies they take for mitigating risks and also their attitude towards risk (Levy and Sarnat, 1994).

Table 3.7 provides a summary of the uncertainties and the probable risks associated with them in the quayside operation environment. It should be noted that an exact and accurate evaluation of the sources of uncertainties and risks requires a much more profound examination and analysis that should be included in future studies.

Uncertainties in data estimation and technological innovations may lead to business uncertainties and risks in the operational environment of the QSCs. These kinds of risks are capable of being insured. However, the terminal operators should consider the following assumptions in their decision-making:

- **Reducing the risk** by finding an alternative way of increasing the productivity of the QSCs.

Some-times the risk is so severe that it causes concern. This may be the case when the potential impact on the overall operation of the quayside is severe and the project is very likely to fail. An insurable risk should be reduced if it has both a high likelihood of occurring and a high impact if it does occur. In the same way a business risk should be reduced if the expected costs are very much greater than the expected benefits.

- **Transferring the risk** to other parties such as insurance companies or contractors.

Risks with a low probability of occurring but with large impacts and also risks with a high probability of occurring, but with a small impact are often insured.

Table 3.7 Summary of uncertainty and risks in QSC automation

	Sources of Uncertainty	Associated Risks
Data estimate:	1. Prices. 2. Costs. 3. Time element. 4. Rates: ▪ Inflation. ▪ Insurance. ▪ Discount rate. ▪ Recovery factor.	Business risks
Technology advances:	1. Sudden appearance of full automatic QSCs. 2. New generation of self loading and / or discharging containerships.	
Operational environment:	1. The crane: ▪ Physical restrictions such as out reach, single or twin lift, *etc.* ▪ Crane handling capacity. ▪ Idle-times and unexpected stoppages. ▪ Ability to operate 24 hours / day. 2. The transfer and the yard: ▪ Transfer vehicle availability. ▪ Vehicle scheduling. ▪ Storage availability. 3. The containership: ▪ Availability. ▪ Capacity. ▪ Size. ▪ Stability (e.g. the limitation of list, roll, pitch, heave, *etc.* and their effects). 4. Containers: ▪ Standard, Non standard, empty, full. 5. The weather condition. 6. The sea state. 7. Social considerations such as strikes, national holidays *etc.*	Insurable risks

- **Accepting the risk** can be the best strategy on some occasions. This is usually the case for risks with a small to medium probability of occurring and a small to medium impact if they occur. An example of this is the case where automation of the traditional QSCs in the small to medium size container terminals may result in the idling of the cranes due to a limited number of ship calls. This may lead the terminal operators into an undesirable loss of revenue in which expensive cranes become idle and cannot provide extra services due to the non arrival of extra containerships.

3.4 Conclusions and recommendations

This chapter has examined the economic efficiency and productivity of automated QSCs. It has illustrated that QSCs can be made more productive by reducing loading and discharge cycle-times. The feasibility of reducing the cycle-times by installing automatic features on existing QSCs is discussed.

This chapter has analysed the 1st and 2nd aims and objectives presented in Chapter 1. The issues discussed in this chapter have not been analysed before. The cycle-time and economic models proposed in this chapter make a contribution to container terminal general knowledge since it demonstrates that the enhancement of the loading and discharging operations through automation would achieve the following two. Firstly, employment of automated devices at the quayside can substantially reduce the time required to load and or discharge a containership. It was demonstrated that the adoption of automated technologies would substantially reduce the overall quay stay-time of the vessels allowing terminal operators to serve more ships at the quayside with the same facilities. Secondly, the shipping companies may gain significant benefits due to shorter port stays of their containerships.

The possible economic benefits lie mainly in the ability of the port operators to either purchase the new and expensive versions of automated QSCs or upgrade their existing cranes by installing the automated technologies at a lower cost. Eventually, the automated systems will gradually transform the QSCs into more efficient, user-friendly and safer cargo handling equipment. The economic feasibility and sensitivity analysis carried out in this study demonstrated that benefits achieved from the adoption of automated devices could far exceed the initial cost of investment.

Section 3.3.4 has analysed the possible benefits that port operators may accrue from QSCs' automation and modernisation. In the small to medium scale container terminals where there are not enough containership calls to avoid possible idling of the QSCs, it is worthwhile conducting a study to account for possible revenue losses which may occur due to the idle cranes. A comparison of containership waiting-time (cost) and berth idle-time (cost) will be conducted in Chapter 4. The attempt will be to produce a break-even point to evaluate the automated berth idle-times and containerships' waiting-times to assist decision-making for port operators.

The evaluations in this chapter were made for single-cycle modes of quayside operation for selected containerships secured alongside with no ship movements in a port located in a warm climate region. The results may appear different for ports with different operational environments, situated in different climatic, economic and political regions than the present study. Further analysis may be usefully conducted for double and multi-tasks operations and for places where climate and environmental factors such as rain, snow and ice accretion may interfere and affect the efficiency of crane operation. The impact of the crane movement (bowing or prying effect) and ships movements (yaw, roll, pitch, sway, surge and heave) on the efficiency and productivity of the operation and the costs involved is required to be investigated in the future studies. Some issues such as safety, uncertainties, risks and staff training require more profound analysis in the future studies.

Chapter 4

A Break-even Model for Evaluating the Cost of Containership Waiting-times and Berth Unproductive-times in Automated Quayside Operations

Summary

This chapter integrates some principal elements of queuing theory with the element of cost to formulate a break-even point to measure the cost of containership waiting-times and the cost of berth unproductive-times for container terminals aiming to automate their quayside operation. This chapter illustrates that automation devices installed on conventional Quayside Cranes (QSCs) significantly reduce the turnaround-time of the containerships calling at ports. It argues, however, that there should be a balance between the cost of berth unproductive service-times and the cost of vessel waiting-times. The study introduces a novel break-even model for calculating such a balance. The analysis in this study can be used as a decision tool for the operators of container terminals in the medium to small ports to measure the cost effectiveness of automation or expansion of quayside facilities.

4.1 Introduction

The planning, design and development of a container terminal with optimum size and capacity and with a minimum capital cost depends mainly on the loading and discharging operations at the quayside. The quayside function of container terminals is dependent basically on the number of berths available to service the incoming containerships. The objective of the container terminals dealing with and admitting the ongoing ship calls is to provide immediate berth and loading and discharging services to the containerships with a minimum costly waiting-time and a maximum efficiency. Traditionally terminal planners used to build extra berths to provide service. During the last two decades, terminal operators have adopted automation technologies in the loading and discharging operation of containerships as an alternative to designing extra berths. Ship owners naturally expect least waiting-times for their containerships. On the other hand, it is also natural for port operators in a container terminal with costly facilities to see minimum idle-time and hence a high berth occupancy and productivity at the quayside.

In the container terminals, the arrival pattern of containerships and the number and rate of berths serving these vessels tend to vary considerably. This makes it very difficult to determine the required service capacity in order to minimise the total turnaround-times of containerships and the unproductive-times of the quayside operation. The unproductive service-times of any berth may be expressed as the times during which the quayside facilities are ready to provide services to the ships but due to the reasons such as the lack of ship calls, tidal limitations, *etc.* they remain unoccupied, unused and therefore unproductive without contributing any revenue generation for the terminal. The berth unproductive-times and the containerships' turnaround-times are the main issues to be addressed in this study. Therefore, it is important to provide a proper balance between these two factors. The turnaround-time of a vessel consists of the waiting-time and the service-time in a port. To minimise the turnaround-time of a ship, two options exist for the port operators. They either build extra capacity by expanding the number and size of their berths or increase the service rate of their quayside facilities. In busy ports where there is always a vessel available to be serviced, investment in quayside automation may be economically justifiable. In contrast, the shortage of ship calls in the medium and small ports results in the costly berths and facilities becoming idle and therefore unproductive for some duration of time. In this case, the port may not be considered as profit making from idle quayside cranes.

The observations conducted in the Bandar Abbas Container Terminals (BACT), Iran revealed that increasing the productivity of the QSCs through automation to reduce the waiting and service-times of containerships has made some of the QSCs unproductive without making any additional revenue. Using the case study of the BACT, this investigation analyses the costs of waiting-times of the containerships and the unproductive service-times of the terminal facilities to find a break-even point for decision-making. It uses general queuing theory to evaluate its objective. The cost of a container terminal berth facilities must be investigated when investing in the automated technologies in the terminal operations. When the costly automated QSCs are not productive, the terminals suffer a loss of revenue. This chapter offers an extension using the principles of queuing theory to include the cost of the terminal berth facilities. The algorithms derived in this study are tested with the data obtained from the BACT. A cost-benefit analysis approach would have been preferred, but due to the lack of financial data on benefits, this study has analysed only the cost functions.

The optimisation models and the queuing theories reviewed in the literature in Section 2.2.2 may be considered as significant tools to quantify the costs and savings for both the shippers and the terminal operators. The general idea of these theories is to minimise the overall turnaround-time of containerships, maximise the productivity of quayside operations and hence optimise the entire operation of container terminals. However, most of the studies carried out do not account for the implications of possible unproductive-times of quayside operations, but only consider the appropriate optimisation functionality of the tasks. Due to land restrictions in the majority of container ports including the ports located in the Persian Gulf region, the terminal operators may be encouraged to invest in automated technologies and expand their terminal capacities. In this context, the economic contribution of the terminal facilities given to the port itself seems to be overlooked in small to medium size container terminals.

4.2 Proposed methodology

The academic studies reviewed in Section 2.2.2 of Chapter 2 do not provide a clear analysis for the cost of containership waiting-times and the cost of berths' idle-times. From the port operators' perspectives there should be a reasonable balance between the cost of ships' waiting-times during the busy periods and probable cost of berth unproductive-times during the times where there are not enough ship calls to maximise the berth occupancy, and using the existing body of knowledge in queuing theories, a fresh approach is required to evaluate the quayside operation of container terminals. The performance of the majority of container ports particularly the small and medium size container terminals, including the Iranian ports, is sensitively dependent on the number of containerships arriving, the volume of cargo they carry and the terminals' ability to load and discharge those ships. The effort to find the optimum rate of berth services or the required number of berths for medium to small size ports should include both the probable unproductive-time and cost of berths services and the probable waiting-time and cost of the containerships for the actual volume of containers that pass through these ports.

The berths in container terminals backed up by reliable facilities such as QSCs and their mean service rate per unit of time can be considered as the principal parameters of the analysis of this study. The operation of a container terminal should be optimised from the viewpoint of both the terminal operators and the shippers. In addition to the studies conducted by Jones and Blunden (1961), Plumlee (1966) and Radmilovic (1992), Wadhwa (1992) has suggested building of extra berths to reduce traffic congestions in order to minimise the turnaround-time of containerships. The adoption of automation technology at the quayside of the container terminals has increased the rate of loading and discharging operations by a considerable amount. In the observations conducted during this study the rate of a single server berth under study in BACT has been increased by 2.4 times. This study develops a methodology that can be applied to any container terminal including the small to medium size container terminal such as the BACT. It examines different parameters of a typical queuing system and includes the probability of containerships' waiting-times together with the cost of berth facilities for both the manual and the automatic operations to calculate a break-even point. The break-even point is expressed monetarily as cost / day / ship. It also assumes that designing additional costly servers for the system would have the same result as increasing the rate of loading and discharging through automation.

The arrival patterns in queuing algorithms generally comply with the Markov process. The Markov process assumes a high degree of variation when used for inter-arrival or service-times and assumes a random or negative-exponential distribution. When there is no variability, then the distribution would be a deterministic (constant) distribution. A family of probability distribution that covers a range of variability from deterministic to Markov is a special type of gamma distribution called the Erlang distribution (named after the early pioneer of queuing theory). The ships calling at ports usually have a large amount of variability of inter-arrival-times that implies Markov arrival pattern. The services at the berth, however, have a low variability and are near-deterministic distributions. The $M/E_k/1$ represents an Erlang queuing model in which the Kendall's notation represents 'M' as the Markov process and hence an exponential arrival and 'E_k' as an Erlang process for servers with shape parameter 'k', and '1' denotes the number of servers (berths). The selection of 'k' for the low variation service distribution of the berth allows a match to a very reasonable level of accuracy between the large value of the variability of Markov (k=1) and the zero variability of deterministic distributions (k=∞) (Brahimi and Worthington, 1991). At this stage, the study could have used the general M/G/1 single-server model that was developed by Pollaczec-Khintchine (P-K). The P-K queuing formula uses Mean Service-Time (MST) together with the standard deviation of service-times (σ) (Riggs *et al.*, 1996). Although there might be very marginal increases in the accuracy of results by using M/G/1 rather than $M/E_k/1$, the Erlang has been chosen as it would provide an extra flexibility for eventual comparisons with a multiple berth terminal when the general queuing model is no longer valid.

The following assumptions are considered for the purpose of this study:

- It is assumed that there is always room for another containership in the queue to be served. That is to say, the queue length can be theoretically infinite in length.

- Vessels will be served on the FCFS basis. This also means that it is not possible to swap the vessels turn due to the differences of the service-times required for different ships.

- Containerships entering the system remain patient enough to be served at the berth and do not give up and leave the queue and the system at any stage of the operation.

This study uses the following process to demonstrate its objectives:

Step 1: Data collection and analysis

When the theory is applied to the quayside operation of a container terminal, the first two primary components of the queuing system are sought. These components are the mean waiting-time of the vessels and the probability that the berth becomes unproductive. However, in a classical queuing system, the magnitude of these components is directly proportional to the number of arrivals, the rate of the QSCs loading and discharging operation and the standard deviation of the service-time. Therefore, the analysis of actual data will constitute a major factor determining the different values of the queuing system for Step 2. The factors that are required to be analysed are:

a) Mean arrival rate of the containerships.

b) Mean Service-Time (MST).

c) Standard deviation of service-time.

Step 2: Analysis of the P-K components

Using the data from a container terminal, the fundamental component of the P-K queuing formula should be calculated for a single server ($M/E_k/1$). These components may be calculated using basic queuing formulas proposed by Gross and Harris (1998) (equations 4.1 to 4.7) for $M/E_k/1$ and extensively identified in the literature in the following sub-processes:

i) Berth occupancy (traffic intensity or utilisation ratio):

$$\rho = \frac{\lambda}{\mu} \qquad 4.1$$

where:

λ = Mean arrival rate (expected number of arrivals per unit of time).

μ = Mean service rate.

i) Probability that the server becomes unproductive

$$\rho_0 = (1 - \rho) \qquad 4.2$$

ii) Coefficient of variation of the service-time

$$k = \left(\frac{MST}{\sigma}\right)^2 \qquad 4.3$$

where:

MST = Mean Service-Time.

σ = Standard deviation of the service-time.

iii) Expected number of arrivals in the queue

$$L_q = \frac{\frac{\lambda^2}{k\mu^2} + \rho^2}{2(1-\rho)} \qquad 4.4$$

iv) Expected time an arrival must wait in the queue to be served by a single server system

$$W_q = \frac{1+k}{2k}\frac{\lambda}{\mu(\mu - \lambda)} \qquad 4.5$$

v) Mean turnaround-time of an arrival

$$W_{ship} = W_q + \frac{1}{\mu} \qquad 4.6$$

vi) Total number of arrivals in the system (Little, 1961)

$$L_s = \lambda W_{ship} \qquad 4.7$$

Step 3: Development and analysis of break-even model

The terminal planners generally manage containership queuing by considering the mean service rate of their quayside operation to be sufficiently greater than the mean arrival rate of the containerships, that is, 'μ' would be sufficiently greater than 'λ', which means $\rho<1$. The terminal designers and planners should note that the increased rate of the berth services may shorten the turnaround of the containerships and reduce the cost of waiting-times, but it does it by introducing unproductive-time into the costly services of the terminal. To fully optimise the quayside operation, one must minimize the total cost of berth unproductive-times and waiting-times of the containerships. Therefore, increasing the number of berths, dedicating more QSCs and / or increasing the service rate of the present facility through automation to reduce the cost of waiting-times and to minimise the turnaround of containerships has to be justified by the increases of the berth unproductive-times and running costs of a given quayside facility.

Assume that at the break-even point, the total cost of containership waiting-times, C_{Wm}, plus the total cost of berth unproductive-times, C_{Um}, for a manual single server terminal may equal the total cost of containership waiting-times, C_{Wa}, plus the total cost of berth unproductive-times, C_{Ua}, for an automated single server terminal.

Therefore, at the break-even $C_{Wm} + C_{Um} = C_{Wa} + C_{Ua}$, or

$C_{Wm} - C_{Wa} = C_{Ua} - C_{Um}$ 4.8

To simplify the above relation and produce a generic break-even model, the above relationship can be defined as:

$T_{cx} = C_{wx} + C_{ix}$ in £ / day 4.9

where:

T_{cx} = Total cost of a berth facility in £.

$C_{wx} = D\ (W_x)$ in £ / day / ship 4.10

$C_{ix} = C_{fx}\ (\rho_{0x})$ in £ / day 4.11

where:

C_{wx} = Cost of waiting-times for a containership to be served in £.

C_{ix} = Cost of unproductive-times for a quayside operation in £.

D = The break-even value in £ / day / ship.

W_x = Annual mean waiting-time of a containership in days = W_q x 365.

C_{fx} = Average cost of a berth facility in £.

ρ_{0x} = Probability that a berth may become unproductive.

£ = Pound Sterling.

'x' can be substituted with 'm' and 'a' to represent a manual single server and an automated single server berth.

The analysis of data from BACT has shown no or very negligible changes in the daily waiting cost of containerships waiting to be served during 2002 to 2004 (Bahrani, 2004). Therefore, Equations 4.10 and 4.11 may be substituted in Equation 4.8 to find the break-even 'D' in £ / day /ship as follows:

We have $C_{wx} = D\ (W_x)$ and $C_{ix} = C_{fx}\ (\rho_{0x})$

Thus, $D_{Wm} - D_{Wa} = C_{fa}\ (\rho_{0a}) - C_{fm}\ (\rho_{0m})$ or $D\ (W_m - W_a) = C_{fa}\ (\rho_{0a}) - C_{fm}\ (\rho_{0m})$

therefore,

$$D = \frac{C_{fa}(\rho_{0a}) - C_{fm}(\rho_{0m})}{W_m - W_a} \text{ in £ / day / ship} \qquad 4.12$$

The break-even analysis may be crucial to the port operators since it may amount to the demurrage cost that is paid for delaying the vessel's turnaround beyond an agreed duration of time. The value of the break-even may be used as a benchmark to determine the feasible values of the cost of waiting-times and the cost of berth unproductive-times. In other words, the cost values of the containership waiting-times and container berth unproductive-times should match or be close to the value of the break-even. The break-even point may also be considered as a decision tool to benchmark and evaluate the performance of an automated or an expanded capacity of a quayside operation.

The break-even value provides a cost-based criterion for decision-making. However, in cases where the cost of berth unproductive-times does not match the break-even value, then it is important for the terminal operator to know the optimum rate of vessels' arrival to make the operation feasible. Where the cost of waiting-times does not match the break-even value, then the service rate or the number of servers needs to be increased to make the operation cost effective and feasible. In this regard, two processes may help the decision-making process:

i) Ascertain the practicable level of berth occupancy (ρ) considering the present rate of berth services (μ).

ii) Calculate the mean arrival rate of ship calls (λ) or the mean service rate of the servers (μ) that may justify the decision for automation.

4.3 Test case

Automation of the quayside operation has taken place in BACT since January 2003. The data for arrival of containerships and the rate of berth services was obtained from the manual berths and after they were automated. The berth facility cost for both the manual and the automated operations was also obtained from the terminal operators. This study uses the three steps described earlier in the methodology to verify and evaluate the applicability of the model to a real example. The applicability of the model has also been evaluated with some operational considerations as follows:

4.3.1 Operational considerations

The following operational factors are considered in the analysis of this study:

- The data and analysis in this study are for import containers only.
- The berths under manual and automatic operations are considered to be operational for 365 days / year and 24 hours / day.
- The characteristics of the motor and trolley hoist and lowering speed of the conventional Panamax QSCs are the theoretical figures given by the manufacturer for the new cranes although the cranes were about four years old at the time of study.
- The average single cycle-time for the manual QSCs has been observed as 92.5 seconds / move.
- The theoretical life-cycle of the conventional cranes given by the manufacturer is 3,500,000 cycles / crane.
- The approximate economic life (t) of the crane may be calculated as: $t = \frac{3{,}500{,}000 \times 92.5}{365 \times 24 \times 60 \times 60} \approx 10.3 \text{ years}$.
- The specification of the conventional cranes is given in Table 4.1. The automated devices installed on some similar cranes were put into operation from mid-December 2002.

Table 4.1 Specification of the conventional cranes under manual operations

- The vessels served at the berths under study were containerships of different size and capacity. In some rare occasions there had been general cargo or conventional cargo vessels carrying containers that were served by the QSCs. These vessels were also assumed to be containerships and included in the analysis.

- The vessels concerned had full bays.

- The operational times of the vessels indicate the gross berth-times and the time taken for the stoppages were considered negligible.

- The container terminal under study can accommodate only one ship at a time.

- The container terminal under study had a smooth operational condition. There has been no record of QSCs waiting for the transfer vehicle or other supporting services at the quayside. The berth is about 350 metres in length that admits only one post-Panamax ship at a time and is protected by a breakwater where the incoming and outgoing traffic has had very little effect on the smooth operation at the quayside.

- The level of technology and improvements made to the cranes are summarised in Table 4.2.

The objectives of the cranes modification and modernisation were:

1) To increase the size, capacity and speed of the quayside operation.

2) To improve the efficiency of the cranes components.

3) To improve the safety and maintenance requirements.

   - The theoretical economic life of the automatic devices installed on the cranes given by the manufacturer is about 5,000,000 moves / crane.

   - The average single cycle-time for automated QSCs was experienced as 67.3 seconds / move.

   - The economic life of the automated crane therefore, may be expressed as:

$$t = \frac{5{,}000{,}000 \times 67.3}{365 \times 24 \times 60 \times 60} \approx 10.6 \text{ years.}$$

Table 4.2 QSCs improvements

4.3.2 Data collection and analysis

The data has been collected from the BACT. The statistics illustrates the performance of the manual quayside operation from January 2002 until December 2002 and automated operations from January 2003 to May 2004 (see Appendix 2). The data illustrates a fairly constant traffic flow of containers through the quayside operations. Tables A.2.2 and A.2.4 that show the summary of the containership visits and berth throughput for the above port are used.

The data shows that the terminal has received an average of 10.92 vessels in a month while serving the arrived ships with 4 manual QSCs. The productivity of the quayside operation has been about 86.16 containers / berth / hour. This indicates that each of the conventional cranes has handled an average of 21.53 containers per hour. With the introduction of automated devices installed on the QSCs, the terminal has served an average of 13.59 ships in a month with the same number of QSCs but with an increased productivity of 207.3 containers / berth / hour indicating that each crane has handled 51.83 containers / hour which is about 2.4 times of the manual rates.

A higher productivity has been achieved since the vessels on average have spent only 13.96 hours at the berth whereas in the manual berth operation the previous vessels spent an average of 26.58 hours to discharge their containers. This indicates that under automatic operations more containerships can be served at the terminal under study.

4.3.3 Analysis of the P-K components

The arrival rate of the containerships (λ), the rate at which they are served in the terminal (μ), and the berth occupancy (ρ) provide the basic components for a queuing problem which can be used to economically analyse the costs of containership waiting-times and the cost of berth unproductive-times of the quayside operation. It is considered that the manual and the automated operation conform to $M/E_k/1$ where arrivals conform to Markovian process and services to Erlang with unlimited capacity with shape parameter 'k' in the P-K formula with $\sigma^2 = \mu^2 / k$ for a single-server queuing system. Further, it is considered that arrivals and services conform to a FCFS queue discipline where no vessel gives up or joins the queue. Using the above data, the equations for a queuing system in Step 2 of the proposed method, the mean waiting-times of the containerships visiting the manual and the automated terminals are analysed as follows:

Case (1): Terminal under manual operations

i) Utilisation ratio of the manual berth:

$$\lambda = \frac{10.92}{365/12} = 0.359 \text{ ships / day}$$

$$\mu = \frac{24}{26.58} = 0.903 \text{ ships / day}$$

$$\rho = \frac{0.359}{0.903} = 39.8\%$$

ii) Probability that the manual berth becomes unproductive:

$$\rho_0 = 1 - 0.398 = 60.2\%$$

iii) Coefficient of variation of the berth service-time:

$$k = \left(\frac{26.58}{2.27}\right)^2 = 137.11$$

iv) Expected number of containerships in the queue:

$$L_q = \frac{\frac{0.359^2}{137.11 \times 0.903^2} + 0.398^2}{2 \times (1 - 0.398)} = 0.133 \text{ ships}$$

v) Expected time a containership must wait in the queue to be served by a manual berth:

$$W_q = \frac{1 + 137.11}{2 \times 137.11} \times \frac{0.359}{0.903 \times (0.903 - 0.359)} = 0.368 \text{ days / ship} \approx 8.8 \text{ hours / ship}$$

vi) Mean turnaround-time of a containership:

$$W_{ship} = 0.368 + \frac{1}{0.903} = 1.475 \text{ days / ship} \approx 35.4 \text{ hours / ship}$$

vii) Total number of vessels in the system:

$$L_s = 0.359 \times 1.475 = 0.530 \text{ ships}$$

Case (2): Terminal under automatic operations

i) Utilisation ratio of the automated berth:

$$\lambda = \frac{13.59}{365/12} = 0.447 \text{ ships / day}$$

$$\mu = \frac{24}{13.96} = 1.719 \text{ ships / day}$$

$$\rho = \frac{0.447}{1.719} = 26.0\%$$

ii) Probability that the automated berth becomes unproductive:

$$\rho_0 = 1 - 0.260 = 74.0\%$$

iii) Coefficient of variation of the berth service-time:

$$k = \left(\frac{13.96}{0.96}\right)^2 = 211.5$$

iv) Expected number of containerships in the queue:

$$L_q = \frac{\dfrac{0.447^2}{211.5 \times 1.719^2} + 0.260^2}{2 \times (1 - 0.260)} = 0.046 \text{ ships}$$

v) Expected time a containership must wait in the queue to be served by an automated berth:

$$W_q = \frac{1 + 211.5}{2 \times 211.5} \times \frac{0.447}{1.719 \times (1.719 - 0.447)} = 0.103 \text{ days / ship} \approx 2.5 \text{ hours / ship}$$

vi) Mean turnaround-time of a containership:

$$W_{ship} = 0.103 + \frac{1}{1.719} = 0.685 \text{ days / ship} \approx 16.43 \text{ hours / ship}$$

vii) Total number of vessels in the system:

$$L_s = 0.447 \times 0.685 = 0.306 \text{ ships}$$

Table 4.5 summarises the above analysis.

Table 4.3 Summary of the data analysis

Operation Mode	Manual (m) From January 2002 to December 2002	Automatic (a) From January 2003 to May 2004
Mean Arrival Rate of the Vessels, λ, Ships / Day	0.359	0.447
Mean Service Rate of the Berth, μ, Ships / Day	0.903	1.719
Mean Service-Time, Hours / Ship (STD)	26.58 (2.27)	13.96 (0.96)
Berth Occupancy, ρ, %	39.80	26.00
Probability that a Berth Becomes, Unproductive, ρ0%	60.20	74.00
Average Number of Ships in the Queue, L_q	0.133	0.046
Mean Vessel's Waiting-time, Days / Ship, W_q	0.368	0.103
Turnaround-time of the Ships, Days / Ship, W_{ship}	1.475	0.685
Total Number of Ships in the System, L_s	0.530	0.306

The mean service rates of the berth under manual and automatic operations were found about 0.903 and 1.719 ships / day respectively. Analysing the actual service rates of both the manual and the automated operations with queuing components, it may be possible to consider that mean service rates up to 0.903 are the manual and from 0.903 to 1.719 are the automated ranges of operations. Beyond 1.719 ships / day may be considered as the possible future development of the quayside operation to serve the calling ships faster than the present mean rate. In this study, the minimum and maximum mean service rate is limited between 0.5 and 2.5 ships /day. Therefore, similar to Cases (1) and (2), different levels of services ranging from 0.5 to 2.5 ships / day are calculated that resulted in the different values of ρ, L_q, L_s and W_{ship}. The results have been illustrated in Figures 4.1 to 4.6. Due to space limitation, the calculations have not been reflected in the study. The calculations are carried out by having the arrival rates constant for 2002 and 2003-2004 and varying the service rates for up to 0.903 ships / day, 0.903 to 1.719 ships / day and 1.719 to 2.5 ships / day. The lower graphs in Figures 4.1 to 4.4 indicate the data values for year 2002 for the manual operations and the top graphs indicate the value for year 2003-2004 after the quayside operation had been automated. Figure 4.1 uses the berth occupancy and the mean rate of services to demonstrate the performance of the operations. The points calculated in the Cases (1) and (2) are indicated in Figures 4.1 to 4.4. The figures are created to provide the basis for comparison of the values for the manual and the automated mode of quayside operations. Figure 4.1 indicates that as the arrival rate increases from 0.359 ships /day in manual operations to 0.447 ships / day in automated operations the berth occupancy decreases from 39.8% to 26.0%. From Figure 4.1 it is evident that although the automated operations (indicated by letter 'A') provide a better level of berth productivity in terms of rate of service compared with the manual mode of operations (indicated by letter 'M'), it does not guarantee a higher berth utilisation in terms of berth occupancy.

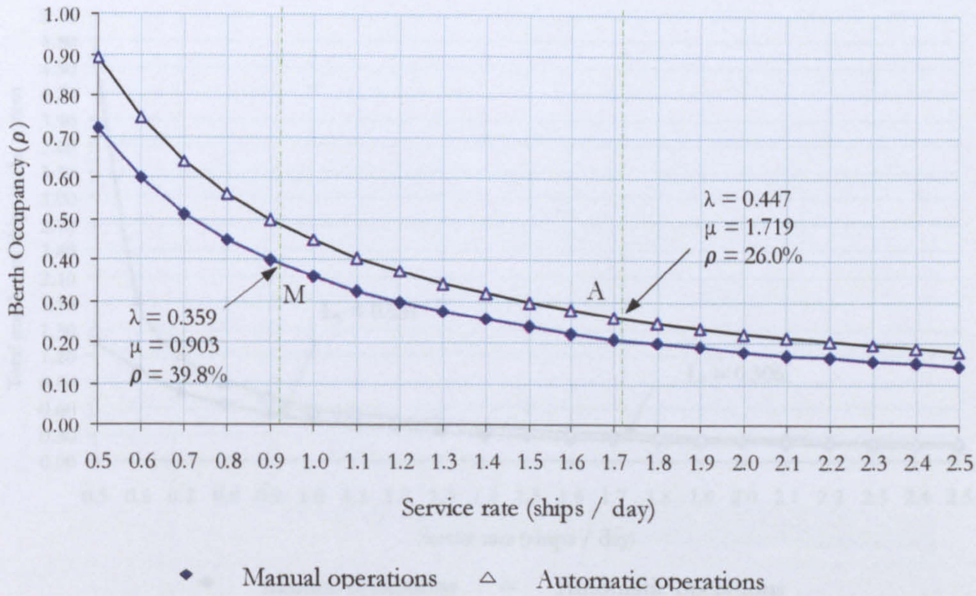


Figure 4.1 Berth occupancy *vs.* mean service rate

Figures 4.2 and 4.3 show the expected number of containerships in the queue and in the system versus the mean rate of services. They demonstrate that as the mean service rate of the berth increases, both the number of ships in the queue and in the system decrease more significantly in automated than the manual operations.

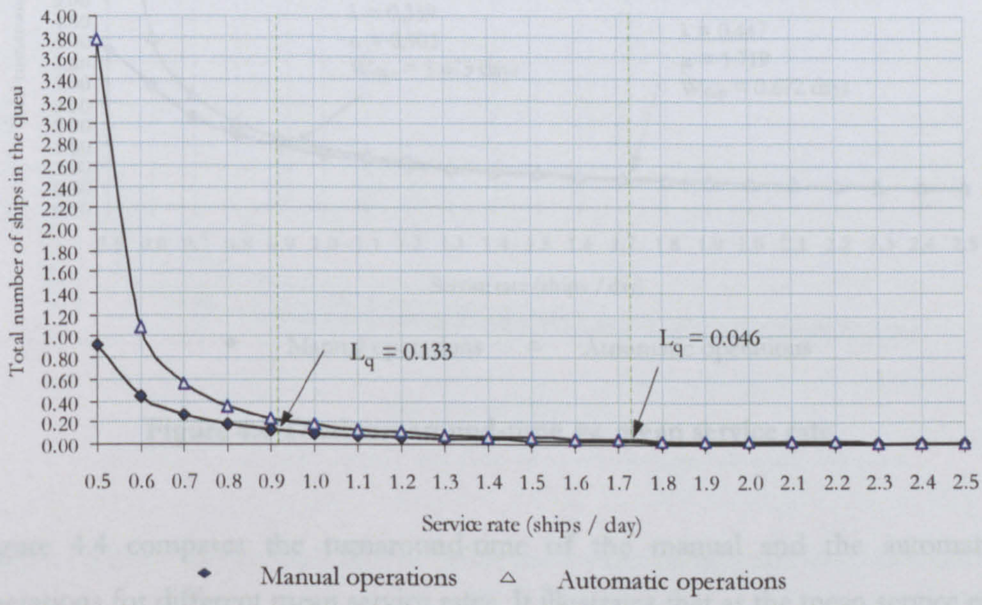


Figure 4.2 Expected number of ships in the queue *vs.* mean service rate

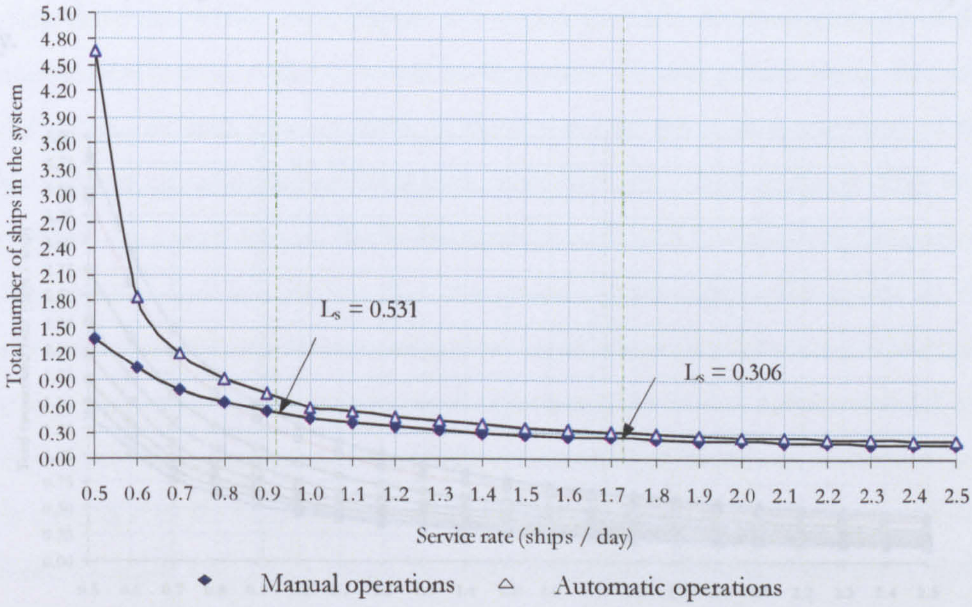


Figure 4.3 Total number of containerships in the system

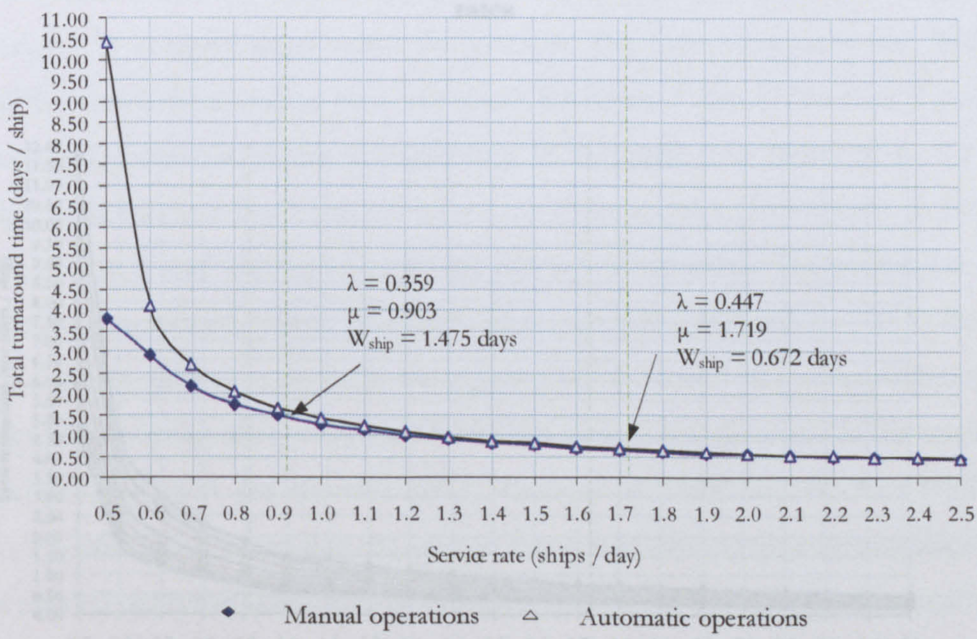


Figure 4.4 Total turnaround-time *vs.* mean service rate

Figure 4.4 compares the turnaround-time of the manual and the automated operations for different mean service rates. It illustrates that as the mean service rate of the automated berth increases the turnaround-time of the ships decreases more sharply compared with the manual operations. However, it shows a smaller amount of reduction in ships' turnaround-time from mean service rate of about two ships / day.

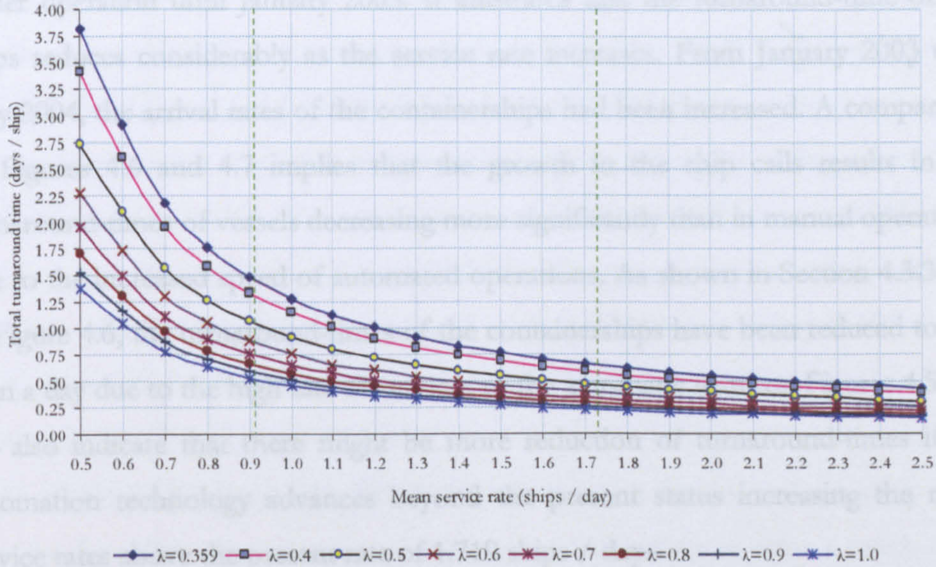


Figure 4.5 Total turnaround-time *vs.* mean service rate using year 2002 arrival rates

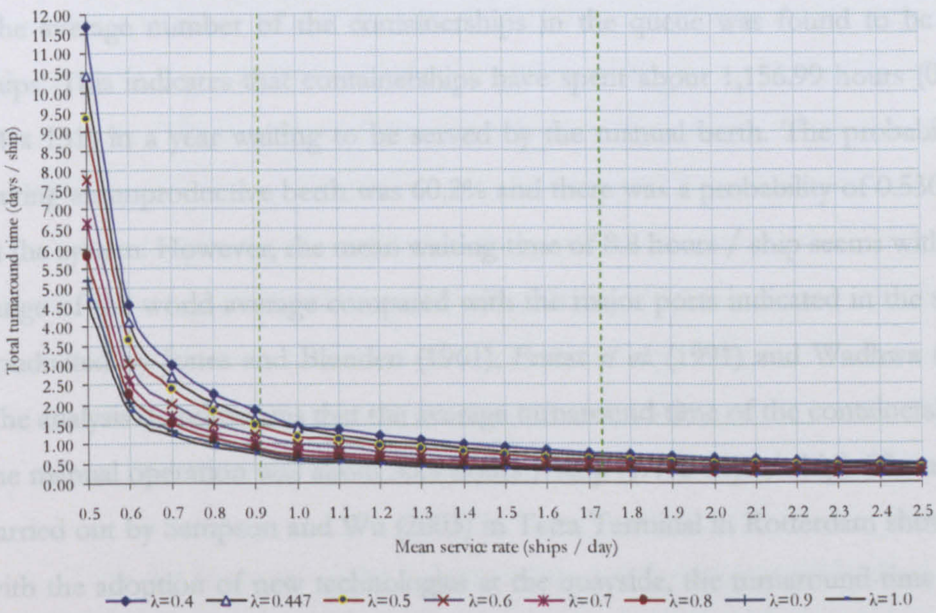


Figure 4.6 Total turnaround-time *vs.* mean service rate using years 2003-2004 arrival rates

Figures 4.5 and 4.6 are derived from the Little's Law (Little, 1961) in which the value of L_s is found using old (0.359) and new (0.447) mean arrival rates. Equation 4.7 may be used to observe the changes in the total turnaround of the vessels by varying the mean arrival rates. Figure 4.5 shows the total turnaround-times of the containerships versus different mean service rates for the manual berth that was under operation until January 2003. It illustrates that the turnaround-time of the ships reduces considerably as the service rate increases. From January 2003 until May 2004, the arrival rates of the containerships had been increased. A comparison of Figures 4.6 and 4.7 implies that the growth in the ship calls results in the turnaround-times of vessels decreasing more significantly than in manual operations due to the increased speed of automated operations. As shown in Section 4.3.3 and in Figure 4.6, the turnaround-times of the containerships have been reduced to less than a day due to the high rate of services of the automatic features. Figures 4.5 and 4.6 also indicate that there might be more reduction of turnaround-times if the automation technology advances beyond the present status increasing the mean service rates above the present rate of 1.719 ships / day.

The analysis of the case under study indicates that under the manual operations, on average, 131 containerships visited the terminal. The berth occupancy was 39.8% and the vessel mean waiting-time was about 8.8 hours / ship (0.368 days / ship). The average number of the containerships in the queue was found to be 0.133 ships. This indicates that containerships have spent about 1,156.99 hours (0.368 x 24 x 131) in a year waiting to be served by the manual berth. The probability of having an unproductive berth was 60.2% and there was a probability of 0.530 ships in the system. However, the mean waiting-time of 8.8 hours / ship seems within the range of the world average compared with the major ports indicated in the studies conducted by Jones and Blunden (1961), Fratar *et al.* (1991) and Wadhwa (1992). The analysis demonstrates that the average turnaround-time of the containerships in the manual operation was about 35.4 hours / ship (1.475 days / ship). The analysis carried out by Sampson and Wu (2003) in Tetra Terminal in Rotterdam shows that with the adoption of new technologies at the quayside, the turnaround-time of the ships has been reduced from 23.19 hours / ship in 1997 to 20.50 hours / ship in 2002. The Hong Kong Container Terminals Authority (2005) has reported that the average turnaround-time of containerships by introducing automated terminals has been reduced from 34 hours / ship in 2001 for the manual operations to about 10 hours / ship in 2004 for the automated operations.

In the automated mode of operation, on average, 163 containerships visited the port in a year. The berth occupancy was reduced to 26.0% implying that the probability of having the berth unproductive was 74% and there was a probability of almost zero (0.046) containerships in the queue. The vessel mean waiting-time was considerably reduced to about 2.5 hours / ship (0.103 days / ship) due to the higher mean service rate. This indicates that all containerships calling at the port have reduced from 1,156.99 hours for a manual berth to 402.94 hours (0.103 x 24 x 163) in a year for an automated berth. Additionally, the average turnaround-time of the ships calling at port has been reduced to about 16.4 hours / ship (0.685 days / ship). A reduction of about 19.0 hours / ship (35.4-16.4) may be considered as a new era in BACT operation. However, when it comes to the possible unproductive-times of the costly quayside facility due to the possible lack of containership calls, then the feasibility of application of automation technology requires a much more profound analysis.

4.3.4 Analysis of the break-even model

Tables 4.6 and 4.7 demonstrate the annual facility costs for the manual and the automated operations provided by the BACT for years 2002 and 2003 respectively. The terminal has received subsidies at different stages to further its quayside development. These values of the subsidies are the annual values that can be considered as a bonus and therefore must be deducted from the annual costs. The annual depreciation may be defined as the purchase cost minus the salvage value divided by the equipment lifetime. The data obtained for the purpose of this study shows that the total annual facility cost yields an average daily cost of about £7,001 (£2,555,292 / 365) for the manual berth and has been increased to about £8,206 / day (£2,995,061 / 365) for the automated berth.

Table 4.4 Summary of the annual facility cost for the manual berth, £

Table 4.5 Summary of the annual facility cost of the automated berth, £

Expenses	Variable Cost	Fixed Cost	Total
Direct expenses (facility: breakwater, wharf, dredging, *etc.*)	-	1,970,516	1,970,516
Indirect expenses, running costs (energy, maintenance, labour, consumables, insurance, *etc.*)	241,325	423,220	664,545
Subsidies	-	(-) 1,023,000	(-) 1,023,000
Depreciation	-	1,383,000	1,383,000
Total Cost	241,325	2,753,736	2,995,061

(Source: Bahrani, 2004)

It has been argued that at the break-even, there should be a balance between the costs of containerships' waiting-times and the cost of unproductive-times for a berth. Using Equation 4.12 the break-even value, 'D', is calculated as follows:

- The annual waiting-time for an automated berth was 134.320 days (0.368 x 365) where, the probability of having the berth idle was 60.2%.

- The annual waiting-time for a manual berth was 37.595 days (0.103 x 365) where, the probability of having the berth idle was 74.0%.

therefore;

$$D = \frac{2{,}995{,}061 \times 0.740\ -\ 2{,}555{,}292 \times 0.602}{134.320 - 37.595} \approx \text{£}7{,}010\ /\text{day}$$

The theoretical value of break-even 'D' as a benchmark expressed as cost / day / ship is calculated using the cost of the manual and automated operations together with the corresponding waiting times at the quayside. The manual operation shows a cost of £7,001 / day which is close to the break-even value. Alternatively, the automated operations show a cost of £8,206 / day which is £1,196 / day above the break-even value. This indicates that about £436,540 (£1,196 x 365) in a year is left unutilised by the terminal operators due to the lack of containership calls. It can be reasonably argued that automation of the quayside operation would cause this loss of revenue if the terminal operators fail to attract sufficient number of containerships to cover this £436,540 cost.

The operator of a container terminal must determine the appropriate degree of automation and the required rate of berth services for the terminal before purchasing costly automated devices for the quayside operation. By knowing the actual and expected rates of the vessels' arrival, it is possible to calculate the rate at which the berths must provide service in order to minimise the queue length of the vessels and retain the maximum berth occupancy. In cases similar to BACT where the quayside operation has already been adopted with automation features regardless of the shortages in the ship arrivals, then it is crucial to calculate the feasible number of arrivals that justifies the present cost of unproductive berth-times. Therefore, the following must be calculated:

i) The practicable level of berth occupancy (ρ)

First, the operator must decide on the percentage of the berth occupancy of his / her terminal. Practically and according to the elementary queuing theory it is not possible to obtain a 100% of berth occupancy (ρ = 1.00) and a zero unproductive-time from a berth facility. The utilisation of a berth may be reduced with some percentages due to the time required for berthing / un-berthing of the ships, delays of cranes and transfer vehicles, shift changes, breaks, possible down-times, repairs, *etc.* In this study and on the basis of experiences and experts opinions obtained, a fraction of about 7 hours / day is considered for the quayside operations. A fraction of 7/24 approximately equals an expected unproductive and idle-time of ρ_0 = 0.300. Thus, the maximum berth occupancy will be 70% (ρ = 0.700).

On the basis of Erlang distribution and P-K queuing formula that uses mean values of arrival and service times, the required number of ships' arrival may be obtained as follows:

ii) The required rate of ships' arrival, λ = 0.700 x 1.719 $\approx$ 1.203 ships / day, or

1.203 x 365 / 12 $\approx$ 36.59 ships / month

The above analysis is summarised in Table 4.8. The analysis indicates that the port operators must find the ways to encourage an extra number of 23 containerships / month (36.59-13.59) to visit the BACT in order to keep QSCs busy and productive.

Table 4.6 Comparison of the manual, automatic and the required rate of arrival

Operation Mode	Service Rate of the Berth, μ Ships / Month, (Ships / Day)	Berth Occupancy ρ, %	Arrival Rate of the Vessels, λ, Ships / Month, (Ships / Day)
Manual	27.47, (0.903)	39.80	10.92, (0.359)
Automatic	52.28, (1.719)	26.00	13.59, (0.447)
Required values	52.28, (1.719)	70.00	36.59, (1.203)

4.4 Conclusions and recommendations

This chapter has used some elements of queuing theory and formulated a novel break-even model to find a balance between the cost of containership waiting-times and probable costs of berth unproductive-times for the manual and the automated quayside operations. The analysis in this study has revealed that the terminal operators of the port under study are required to attract more containerships to cover the unutilised capacity of their quayside operation that has resulted from the quayside crane automation. It has argued that port operators may be required to review their policies to attract more containerships, so that the actual cost of waiting-times and the average cost of unproductive-times for a vessel to berth at the automated terminal match the break-even value offered by the equations and analysis of this study. Otherwise, the investment in the automated devices may not be a valid policy and the terminal operators may make a loss just because of putting their effort into shortening the turnaround-time of the containerships mainly for the benefit of the ship-owners and the shipping companies.

This chapter has achieved the 3rd objective presented in Chapter 1. The analysis of this chapter is unique and makes a contribution to the knowledge of port operation since it recommends finding a balance between the cost of containership waiting-times and the cost of berth facilities before the purchase and implementation of automation technologies at the quayside. It is recommended that container port designers and operators appraise the expected arrival rate and capacity of the containerships to be serviced for the duration of the expected economic life of the terminal or at least for the expected economic life of the QSCs. An average rate of containership arrival and average expected berth throughput predicted would enable more accurate calculation of the required berth rate or rate of loading and discharging of the automated QSCs for a terminal that may be considered economically feasible and match a break-even value in order to keep a balance between the cost of containership waiting-times and berth unproductive-times. Uncertainties will exist for the investments costs, technological changes in QSCs and containerships, *etc.* It would be worthwhile investigating the impacts of uncertainties on the productivity of terminals in future studies.

In Chapter 5 appropriate layouts and a throughput model will be produced for SC, RTG and RMG cranes.

Chapter 5

Throughput Modelling for Container Terminals Using Semi-automated SC, RTG and Automated and Semi-automated RMG Operating Systems

Summary

This chapter analyses the automated and semi-automated container yard stacking cranes indicated in the organisation and framework of the study in Chapter 1. It evaluates two different but inter-dependent aspects of container terminal throughput capacities for the yard cranes discussed. The methods proposed in this chapter first discuss the appropriate considerations for different layouts and facilities for container terminals to serve the new generation of containerships. The second part of the study proposes a model for calculating the annual throughput for container terminals using semi-automated Straddle Carrier (SC) and Rubber Tyred Gantry crane (RTG) and automated and semi-automated Rail Mounted Gantry crane (RMG) operating systems in modern container yards. It considers the dynamic nature, size and capacity of the automated yard operating systems together with the average dwell-times of containers, transhipment ratio, accessibility and stacking height of containers as the important factors in determining container terminal throughput. The proposed generic formulas and the analysis in this study may be used as a decision tool for selecting the appropriate operating system for a container terminal on the basis of different determining attributes.

5.1 Introduction

A high demand for container handling coupled with a rapid growth in containership size and economics of scale suggests that the terminal operators employ automated equipment to load, discharge, transfer and stack containers to reduce the turnaround-time of the containerships entering their ports. The layout of terminals may be required to be designed and or modified to facilitate the accommodation of heavily congested container terminals and the fast moving nature of automated stacking and transfer systems in order that they operate in harmony. Therefore, planning to design modern container terminals and / or modification of old container terminals is basically concerned with a proper identification of the terminal capacity, type, number and the degree and the level of automation technology of the equipment to be used in terminals. The principal facilities are the transfer vehicles and stacking cranes. The number of containers that enter and leave the stack-yards, the capacity of buffer storages to be used for transhipment containers and the duration of time that containers stay in the terminal (dwell-times) are the basic elements to be used to calculate the annual throughput of a terminal. The capacity of container terminals is clearly concerned not only with the physical design and facilities but also, and equally importantly, with the stacking policies adopted, organisation, management and operation of the terminal. The later three however, are beyond the scope of this study.

When planning the design and layout for a container terminal, it is essential for the terminal operators to provide a required level of container storage capacity to facilitate the smooth operation of all segments. In this process, a particular consideration must be made to calculate the required annual container handling capability on the basis of the operational facts rather than the storage capacity based on the dimensions of the container yards. The capacity of the majority of container terminals is designed in such a way that the available land area is multiplied by the average capacity of the storages that are in turn obtained from the product of container Ground Slots (GSs) and the average number of tiers that yard cranes are capable of stacking. It may be argued that the above approach is a design with a static nature in which the dynamic nature of arrival and departure of import, export and transhipment containers, arrival-time and rate of containerships, trains and trucks, container movements such as their accessibility, required re-handling effort, different dwell-times and the transhipment ratios have not been considered in an integrated way. The automated container terminals are of a highly dynamic nature. In addition, the automatic delivering, receiving and stacking of containers in modern terminals are based on a real time information flow, which is also of a dynamic nature. Therefore, the dynamic nature of container terminals requires calculating the annual throughput of a terminal based on the determining factors and also the limitations imposed by the specific layout of the marshalling yard together with the dynamic nature of the automatic and semi-automatic operating system to be employed. It should be noted that the throughput capacity of container terminals is also dependent upon and may be affected by the number and handling capacity of the available quayside and yard cranes, rail-head buffering and transportation, transfer vehicles and barge handling capacities. The analysis of the above however, is considered beyond the scope of this study.

Section 2.2.3 has provided a comprehensive review of the studies for container yard operations and capacity of container terminals. However, the studies do not consider the automatic functionality and the dynamic nature of container accessibility, equipment size and capacity and the limitations imposed by the stacking height of their container yard operating and stacking systems. Therefore, the general equations developed in the literature need to be re-examined and modified to meet the dynamic nature of the container yard operating systems. For an easier concept of the container yard operating systems, and before providing the proposed methodology for calculation, this study would provide some examples and assumptions.

5.2 Layout, operational and stacking policies and considerations

SCs, RMG and RTG cranes are the most common equipment under automatic and semi-automatic operation consideration and are the most widely adapted to container handling systems in container ports. In some terminals, Tractor-Trailers (T-Ts) together with heavy-duty Front-end Lift trucks (FLs) are used to stack and un-stack empty containers. However, it has been observed that a combination of different stacking systems is employed to fulfil the operational demands of individual terminals. The operational features for most of the existing terminal layouts are as follows:

5.2.1 Straddle Carrier (SC) operation

In the majority of container terminals a manual or a semi-automated SC system has been employed to fulfil most of the container yards transfer and stacking / un-stacking operations. The new SCs have been designed to create a resource capable of matching, if not exceeding the capability of the conventional manual SC fleets. The dimensions of the semi-automated SC have not changed significantly from the manual ones. Therefore, the number of container GSs to be calculated for this system may not vary significantly from the conventional SC systems. In contrast, the vertical stacking capability of the semi-automated SC has been increased to about five tiers (one over four) that will affect the annual throughput of the terminals employing the new systems. The additional features installed on the new systems include a high-tech navigation system combined with microwave, Radar, Differential Global Positioning System (DGPS), container recognition, identification, and positioning systems.

Advanced SCs equipped with semi-automated technologies in which a network controlling system possesses a direct supervision over the vehicle performance have made them more reliable for stacking and retrieving operations in today's container terminals. The containers can be stacked end-to-end and laid vertical or parallel to the quay face in rows. In a vertical layout, a SC directly and independently accesses containers from the shipside. The system is sometimes called as a 'direct system'. Where containers are transferred to and from the quayside to the roadways and interchange area by other modes of transfer systems such as T-Ts or FLs, the system is called the 'relay system'. In a relay system, some SCs are solely devoted for relaying purposes. An interchange area has been provided at the landside end of the container yards for the convenience of the road vehicles and terminal equipment to receive and deliver containers from the land carriers (see Figures 5.3 and 5.4). Containers may be stacked up to one over four or even higher depending on the ability of the SC employed. In most of the container terminals that have employed a SC system including the Bandar Abbas Container Terminals, Iran, (BACT), the stacking-yard is divided into several blocks. Passageways and roadways (W) have been provided for easier access to the blocks by SCs.

Different factors such as the length of the quay face, depth of the marshalling yard, width of the surrounding roadways, passageways between the blocks and access aisles, Custom regulations and procedures (in some occasions) and the limitations imposed by the main road and railways determine the length of the container rows, and hence, impact on the terminal capacity. In BACT and the Bandar Imam Container Terminals, Iran, (BICT), inspection areas away from the main stack-yard have been provided for the Custom inspection purposes where the selected containers are randomly scanned with x-ray machines. In cases like this only about 30 to 40 centimetres width may be required between the end of the containers for the convenience of the terminal operators and the automatic devices to identify, access and manage the containers and the stacks. Most of the manual and the semi-automated SC carriers have a turning radius between 8.5 to 9.2 metres (Watanabe, 2001 and Chu and Huang, 2002-a). UNCTAD (1985) has suggested allowing about

20 metres for the SCs to easily access, turn and travel between the access roads and passageways. In terminals two and three in BACT, in addition to the normal passageways, a 30 metre main passageway has been provided in the middle of the yard whereas in the study conducted by Chu and Huang (2002-a) it has been found that most of the international terminals have been allowed to have passageways' width of about 20 to 22 metres. Although narrower roadways may increase, the terminal capacity but they may limit the freedom required for manoeuvring of the semi-automated and unmanned SCs in the yard. On some occasions, on either side of the stacking-yards and outside of the stacking blocks a piece of reserved land has been provided for a maintenance building, special containers (reefer, oversize and hazardous containers) light stands and *etc.*

Taking all of these factors into account, it is possible to calculate the length of container rows or blocks. Atkins (1983) has suggested that the length of container rows could be any length, and rows of 60 to 90 metres long [10 to 15 Twenty-foot Equivalent Units (TEUs)] were commonly used. UNCTAD (1985) has suggested arranging each row to contain about 10 to 16 TEUs long (60 to 96 metres). Longer rows are likely to increase the risk of damage and reduce accessibility. In BACT, the length of SC rows was found to be 11 to 13 containers whereas in BICT two blocks were found to have a row length of 15 and 16 and the rest to have 17 containers in row. Whether the containers are placed parallel or perpendicular to the quay face, three important factors should be considered in planning and determining the number and the length of container rows:

i) The size of the SCs to work within the rows.

ii) The length and the depth of the container yard.

iii) The number and size of the passageways and roadways.

The total number of TEUs for each row is divided by the number of passageways to determine the number of container TEUs in each working row. A SC has to freely manoeuvre along the rows in order to accurately reach the intended slots to straddle and transfer the containers. Therefore, the internal span of a SC and the wheel space directly affect the size and arrangement of container slots. Most of the SCs observed had an internal span of 3.1 to 3.25 metres. In many pioneered container terminals such as Tilbury and Southampton, Shanghai, Singapore and

Europe Combined container Terminals (ECT) in Rotterdam the wheel travelling space was found to range from about 1.5 to 2.0 metres.

In most of the Iranian container terminals and container terminals in the Persian Gulf region with SC systems, an interchange area near the gate has been provided to facilitate the receiving and the delivery of the containers to and from the inland transport vehicles. In BACT the interchange area is about 60 metres in width and the area for truck movement has also been included. In BICT the width of the interchange area is found to be about 40 metres.

5.2.2 Rail Mounted Gantry crane (RMG) operation

RMGs travel on the fixed rail-tracks. They generally stack higher, span wider and are easier to automate. However, they are more expensive to install and maintain, less flexible in operation and are more difficult to change their layouts. One of the important advantages of having an RMG system in a container terminal is that they provide separate lanes for road, terminal trucks and more recently Automated Guided Vehicles (AGVs) to facilitate smooth working of the quayside operation. The queues at the gate and interchange area will ease-up to allow road vehicles to receive and deliver their containers along the Traffic Lanes (TLs) provided on one or each side of the RMGs. This has enabled application of 'random grounding' as a favoured stacking policy (see Section 5.2.6). The width of the traffic lanes would be designed in such a way to safely provide access of the AGVs and in the case of manual transfer operations, the external and internal trucks to travel under the spans of the RMG cranes. In this system, containers are also laid parallel or perpendicular to the quay face. Normally, in container terminals with RMG system, wider surrounding roadways outside of the storage blocks would be provided when compared with SC system. This will enable the AGVs or trucks and trailers to move quickly within the terminal. Within the blocks, passageways of smaller width will provide access for the trucks to travel at right angles to the quayside to shorten the transfer time.

Automation has been introduced into the RMG environments in a much broader range than SC and RTG systems. A full automation technology has been applied to the container storage area in which the commands are transmitted to the automatic crane *via* fibre optic cables. The cranes can be of any design such as a double or a single cantilever in which the traffic lanes lie under the cantilever or with no cantilever where the traffic lanes are positioned under the main portal of crane. The operation of the crane in the traffic region may be done in a semi-automatic or even in a manual way. Where an AGV is assigned to deliver or take over the container to and from the automated RMGs, the area may be covered in a semi-automatic manner since the AGVs would be addressed to exactly position itself in a pre-defined position that would be automatically arranged with the crane. Where an external or manned internal truck is used, the operation in the traffic lanes may be carried out manually with a margin of safety. The automated RMGs are capable of identifying and positioning the containers in the storage slots and at the same time transmitting the information to the controlling station which is not easily and accurately possible in the manual operations.

In an automated mode, for example in an un-stacking event, the operation may include:

i) Identification of a container that is intended to be picked up from the stack.

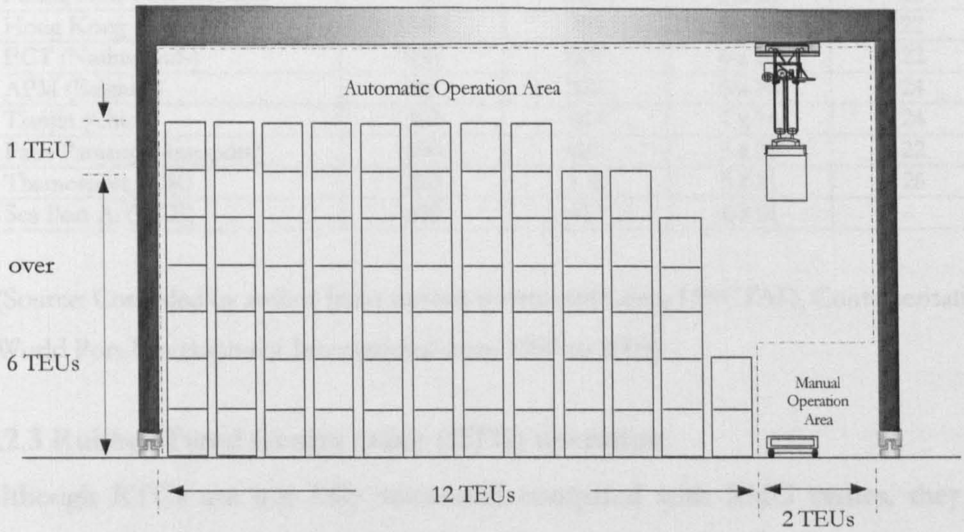
ii) Detection and recognition of the AGV or chassis of the transfer vehicle in the traffic lane.

iii) Retrieval of the container from the stack and movement of the container in an optimum path and with an optimum cycle-time towards the transfer vehicle.

iv) Safe landing of the container on the chassis.

v) Transmission of the completion of the assigned task to the central controlling computer.

In the automated RMG systems the distance between the containers may be fixed and can be about 25 to 40 cm. The number and the size of the passageways and traffic lanes are optimally designed to safely accommodate the transfer vehicles. The under span of the crane which is used for the storage of the containers may accommodate 8, 12, 14, 18 and 24 container rows. Figure 5.1 shows a typical RMG crane with a span of 12+2 (12 rows and 2 traffic lanes) capable of stacking 1 over 6 containers high with automatic and semi-automatic areas. An observation of the Thamesport Container Terminal showed that the vertical stacking ability of the very fast and fully automated RMGs might be increased to 8 to 9 tiers. The size and particularly the vertical stacking ability of the automated RMG cranes may have a direct impact on the annual throughput of a container terminal. One crane row encompasses two rails. The total length of a crane is equal to the internal span plus one or two traffic lanes at one or either side of the crane. Containers are stacked within the internal span of the cranes. The maximum number of containers that can be stacked and the traffic lanes determine the width of the crane.



(Source: Author)

Figure 5.1 Front view of an automatic RMG crane

Table 5.1 shows an example of the average berth length, rail length, passageway width and width of the surrounding roadways in the container yards using the new generation of RMG systems. The data has been collectively obtained from the recent academic studies, BACT statistics (Bahrani, 2004), Containerisation International (1990-2005), UNCTAD (1990-2005) and World Port Development International (1990-2006). The surrounding roadways in the majority of container terminals range from 22 to 24 metres and the width of the passageways from 24 to 28 metres. In some terminals, the passageways at the ends of the RMGs rails are used as a maintenance area. By subtracting the width of the passageways from the length of RMGs' rail, the length of container stacking may be obtained. After accounting for the width of the passageways, an average length of each container row may be obtained ranging from 100 to 200 metres.

Table 5.1 Specifications of the rail, roadways and passageways in the RMG systems in some terminals

Terminal	Width of Container Yard (metres)	Length of Rail (metres)	Number and Width of Passageways (metres)	Width of Roadways (metres)
Hamburg (Germany)	815	670	2 x 30	30
Kaohsiung (Taiwan)	817	665	3 x 31	28
Shanghai (China)	750	480	4 x 30	22
Euromax, TCV, (Netherlands)	420	380	3 x 22	22
Pusan, New Port, (Korea)	950	300	5 x 22	22
Hong Kong (8 west)	740	700	5 x 10	22
ECT (Netherlands)	860	800	6 x 22	22
APM (Belgium)	445	322	5 x 14	24
Tianjin (China)	368	363	7 x 14	24
Pasir Panjang (Singapore)	650	600	3 x 20	22
Thamesport, (UK)	320	175	5 x 11	26
Sea Port A. (UAE)	600	417	6 x 21	-

(Source: Compiled by author from various sources including UNCTAD, Containerisation World Port Development International from 1990 to 2005)

5.2.3 Rubber Tyred Gantry crane (RTG) operation

Although RTGs are not fully automated compared with RMG cranes, they are progressively becoming more standardised than SCs. They are more space efficient than SCs and offer scope for advanced automation. Since they do not necessarily follow a fixed track, they are more flexible than RMGs. Dedicated T-Ts and the external trucks may make the movement of containers between the quayside and the container yard. In the later case, the width of the traffic lane may be increased for an easier access of the road trucks. In an RTG system, containers are stacked with spans of 4 TEUs + 1 traffic lane, 5 TEUs + 1 traffic lane, 6 TEUs + 1 traffic lane and more recently 8 TEUs + 1 traffic lane (Watanabe, 2001). T-Ts have been the main transfer vehicles to receive or deliver containers to and from the quayside but AGVs may replace them within the next two or three decades (Agerschou, 2004). Factors determining the number of container rows are almost similar to those of the RMG systems. However, because the crane wheels are sometimes required to turn through 90° to get access to an adjacent block, heavy concrete or steel pads must be provided at the turning points and at the termination of the passageways or roadways or between the loading rows for this purpose. Sometimes, a turning area is merged into the adjacent passageways to provide a better turning and also to increase the efficiency of truck movements and operation.

The stack height would be different from terminal to terminal, while considering the availability of the land, container status, crane's vertical stacking and un-stacking ability and the degree of automation employed. Generally, import containers are stacked 4 to 6 containers high, export and transhipment containers sometimes are allowed to be stacked to 7 to 8 tiers (wind effect on very highly stacked blocks in some areas may cause some concerns). In a direct observation from the Port of Felixstowe Container Terminal in 2004 it was found that empty containers are stacked up to and average height of about six tiers. Tables 5.2 and 5.3 show some details of the turning area, width and side width of the RTGs for some newly developed container terminals in Asian ports, namely, Hong Kong, Hutchison (Korea), Kaohsiung (Taiwan), Rokko and Port Islands (Kobe, Japan), Laemchabang (Taiwan), Shanghai (China), Batam (Indonesia) and Karachi (Pakistan). The widths of RTGs turning areas are about 11 metres and the total width of the passageways and truck operations are about 22 metres wide. In some cases the turning area is merged with the passageways. The length of the operation rows is almost equal to the total length of the berths minus the total width of area used for surrounding roadways, passageways and turning areas.

Table 5.2 Examples of accessibility provided for the RTG system in some terminals

Terminal	Width of Container Yard (metres)	Number and Length of Rows (metres)	Number and Width of Turning Areas (metres)	Number and Width of Passageways (metres)	Number and Width of Perimeter Roadways (metres)
Port Island (Kobe, Japan)	425	3 x 105	-	2 x 31.0	2 x 22.0
Hutchison (Korea)	640	4 x 114	3 x 12.5	3 x 25.0	2 x 35.0
Hong Kong (T-9)	700	4 x 136	3 x 10.2	3 x 25.0	2 x 25.0
Shanghai (China)	370	2 x 140	1 x 11.5	1 x 25.0	2 x 25.0
Laemchabang (Taiwan)	336	2 x 125	1 x 11.2	1 x 25.0	2 x 23.0
Batam (Indonesia)	320	2 x 115	1 x 10.9	1 x 26.0	2 x 25.0
Karachi (Pakistan)	327	2 x 115	-	1 x 35.0	2 x 30.0
Kaohsiung (Taiwan)	455	3 x 113	2 x 11.3	2 x 22.0	2 x 24.0
Rokko Island (Kobe, Japan)	430	3 x 107	-	2 x 30.5	2 x 22.0

(Source: Compiled by author from various sources including UNCTAD, Containerisation World Port Development International from 1990 to 2005)

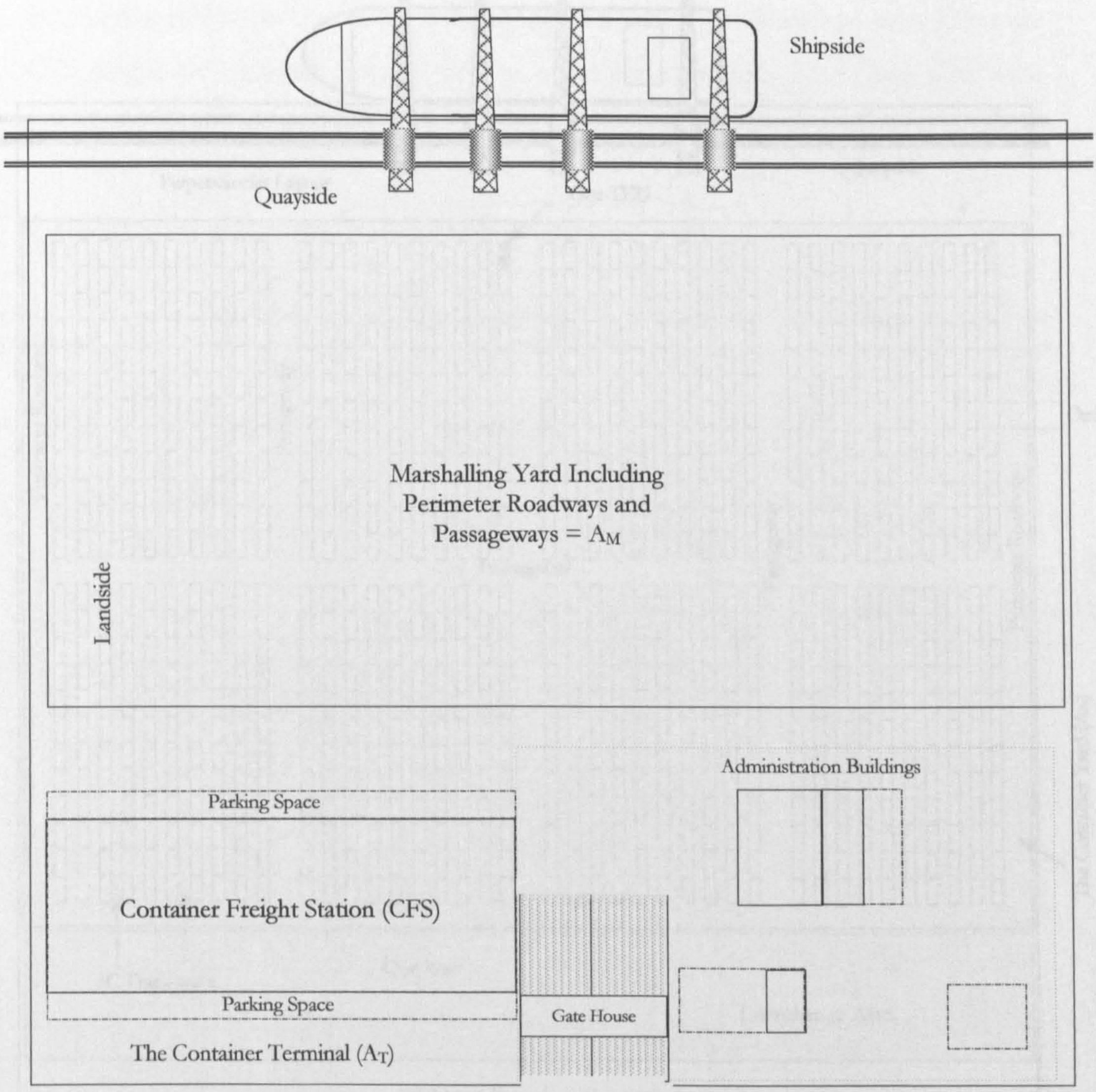
Table 5.3 General specifications of an RTG system

Table 5.3 shows the general specifications for a typical RTG system. Referring to the experience, direct observations and investigations conducted by the author and considering that one TEU requires a width of 2.438 metres and 30 to 40 centimetres space for a safe operation between the container rows and about 4.342 metres for a TL width and the track-ways for an RTG crane, a total width of about 18.0 metres will be required for a 4+1, 23.5 metres for a 6+1 and about 29.0 metres for an 8+1 RTG. By knowing the required number and the length of the stacking blocks it is possible to calculate the net stacking area for an RTG system.

5.2.4 Layout considerations

The BACT is a rectangular shape with one automated and three manual berths. The Bandar Imam Container Terminals (BICT) is located in Arvand-Rood having 8 berths and is almost a rectangular shape. The busiest container ports in the Persian Gulf region are Dubai, Jabal-Ali and Sharjah Container Terminals, each with 16, 17 and 14 berths. Their shapes are almost rectangle (Nahavandi, 1996).

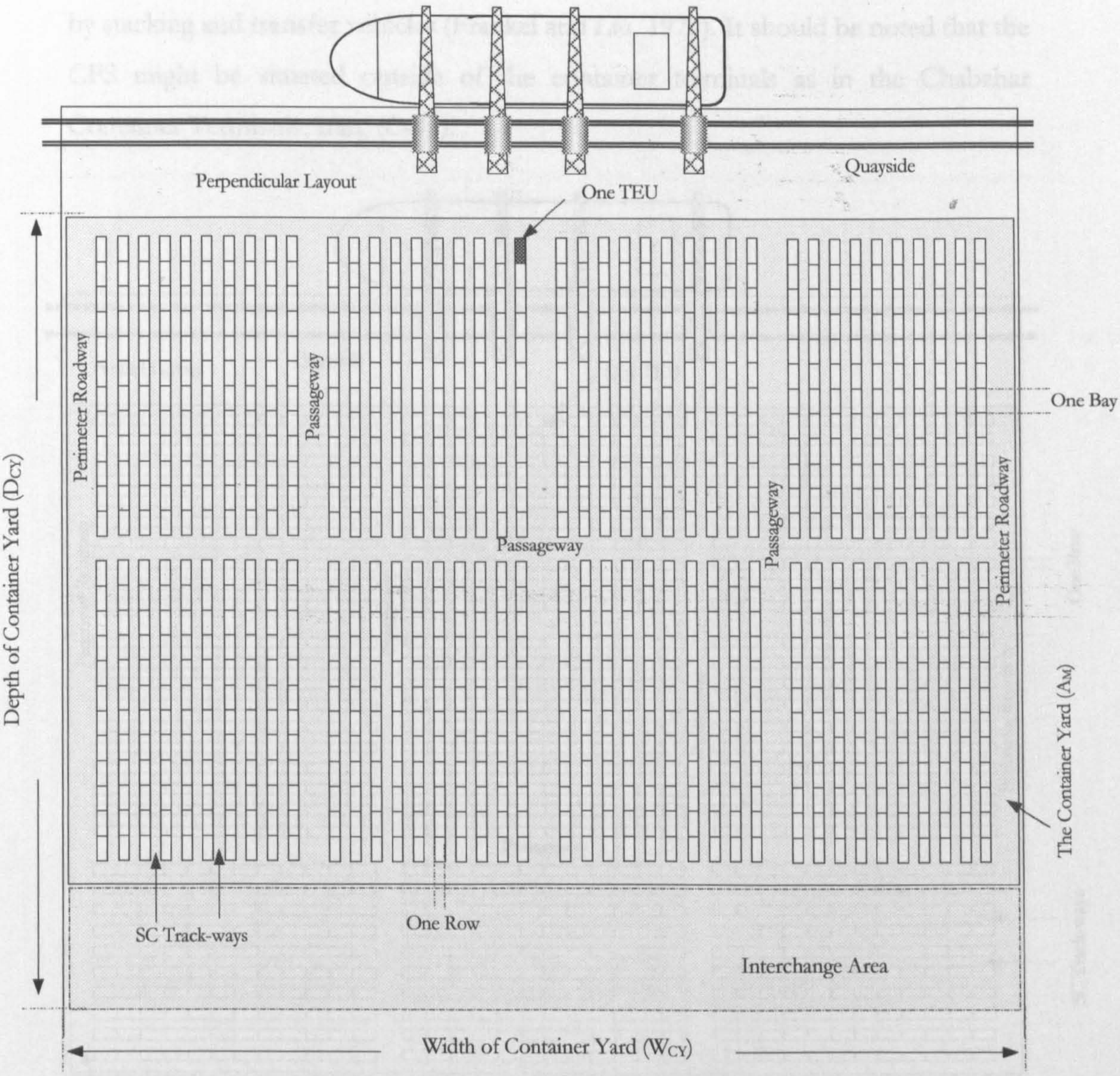
The foremost container terminals in the world such as Hong Kong, Singapore, Rotterdam, Amsterdam, the Thamesport Container Terminal, Felixstowe, *etc.*, are nearly all of a rectangular shape too. On average, most of the Asian container berths have a quay face length corresponding to the container yard width (W_{CY}) of about 250 to 350 metres for a single-berth, 600 to 700 metres for a double-berth, and are horizontally 300 to 400 metres deep (D_{CY}) for single-berths and 500 to 600 metres deep on the landside (Watanabe, 1995) (see Figure 5.3). Therefore, the average area for the single-berths and double-berths would be about 7.5 to 14.0 and 18.0 to 42.0 hectares (ha) respectively.



(Source: Author)

Figure 5.2 Spaces at a typical container terminal

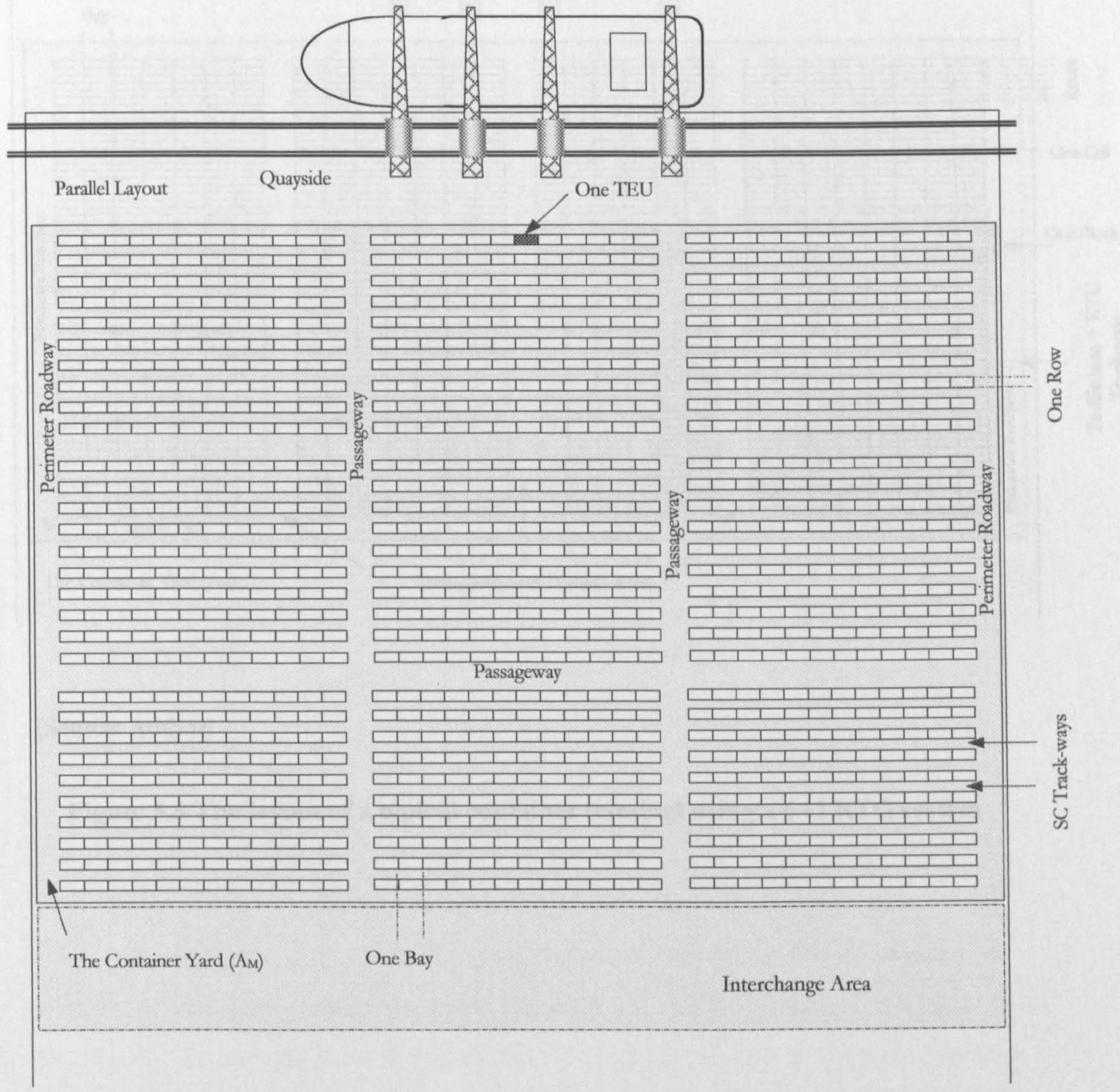
Figure 5.2 illustrates a typical layout of a container terminal. The figure shows that the terminal may be divided into different segments such as an apron area, stacking-yard area, Container Freight Station (CFS), administration buildings, gate complex, workshop area, main roads other than those of stacking-yard and apron areas, *etc.* This study will propose different methods to be used as the basis for calculating the number of GSs required by different stacking systems in the stack-yard for semi-automated SC, RTG and automated RMG crane systems only and other segments and operations of the container terminals are beyond the scope of this study.



(Source: Author)

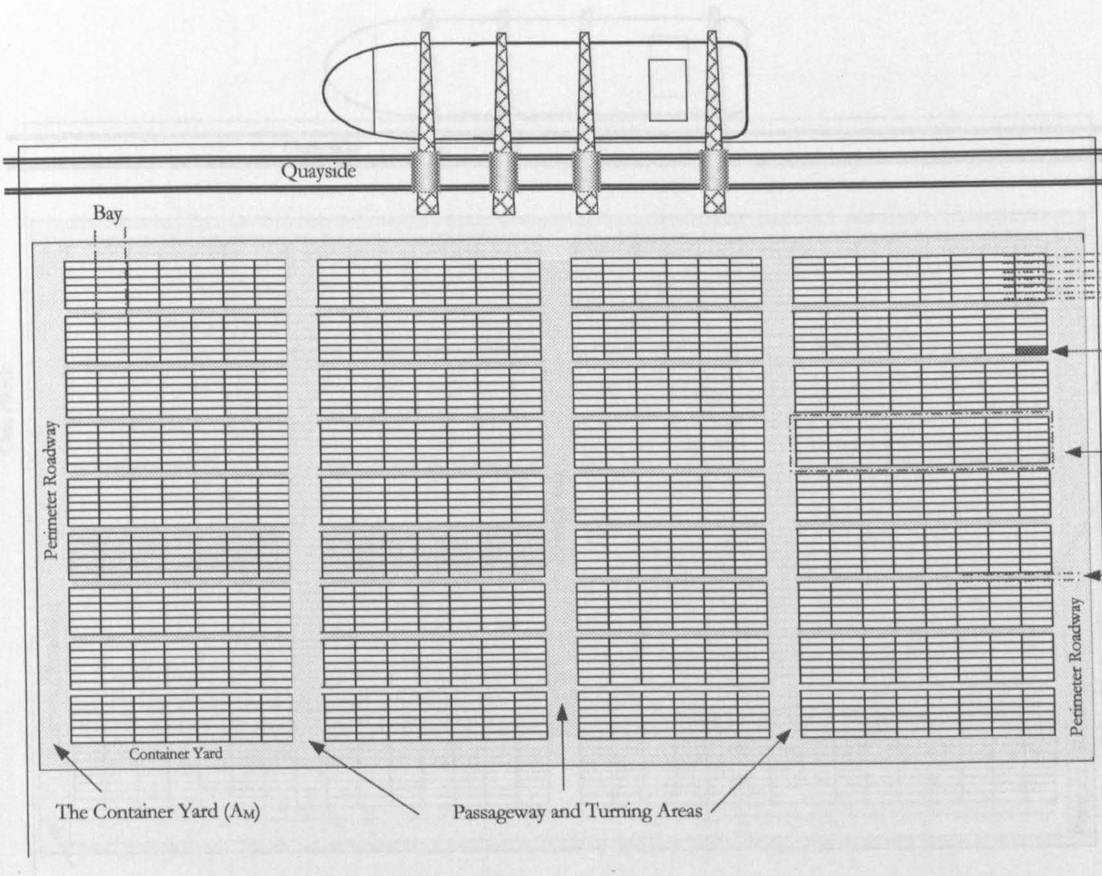
Figure 5.3 The perpendicular layout of a typical container terminal using a SC system

Figures 5.3 and 5.4 illustrate two typical stack-yards for SC systems in perpendicular and in horizontal layouts. Figures 5.5 and 5.6 illustrate the total area of the marshalling yard (A_M) for the RTG and RMG systems that are commonly used in modern container terminals. A_M is a product of container yard inland length which is commonly called and will be referred to as the 'depth of container yard' (D_{CY}) in this research and the 'width of container yard' (D_{CY}) which is measured along the quay face. The A_M corresponds to the total area in m^2 occupied by rows and blocks of containers that is determined by transfer and stacking systems in the yard. This area includes the surrounding roadways, inter-yard passageways and turning areas used by stacking and transfer vehicles (Frankel and Liu, 1979). It should be noted that the CFS might be situated outside of the container terminals as in the Chabahar Container Terminals, Iran, (CCT).



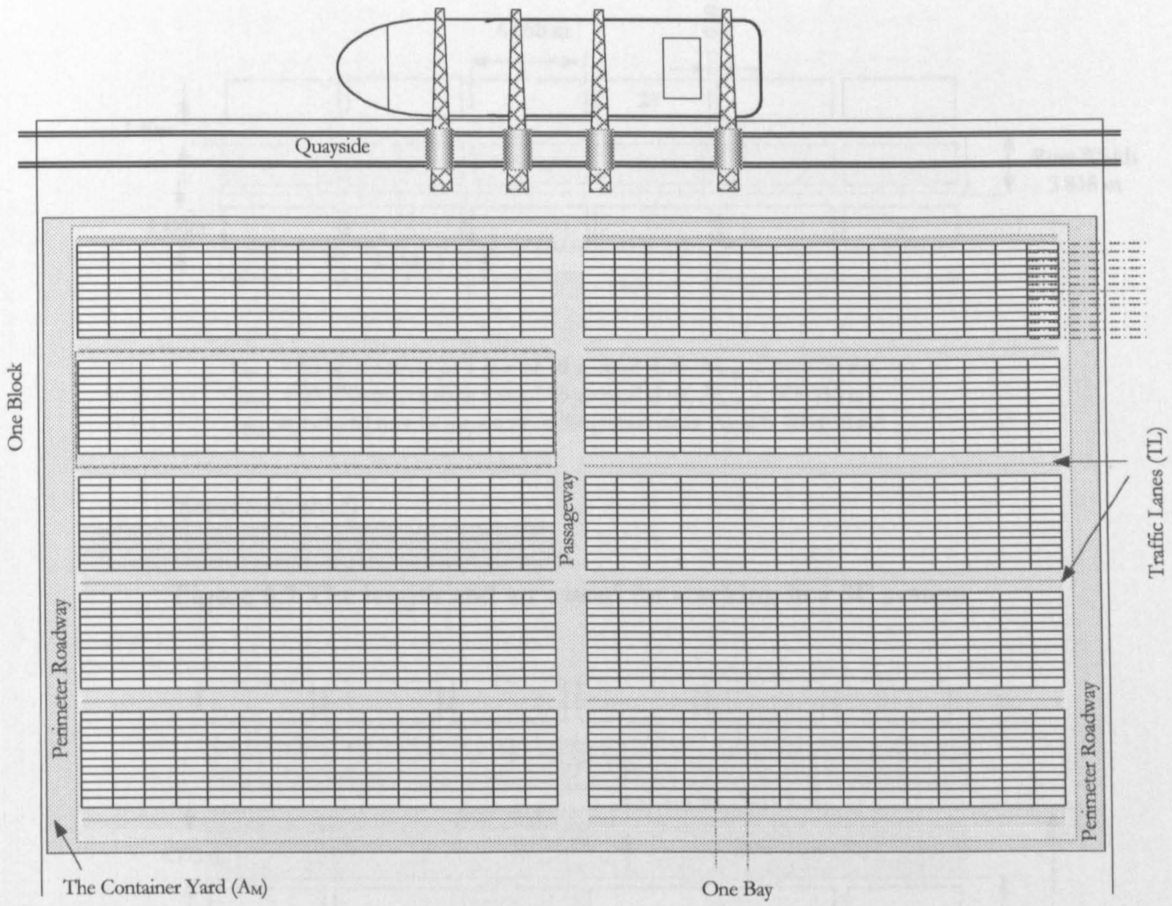
(Source: Author)

Figure 5.4 The parallel layout of a typical container terminal using a SC system



(Source: Author)

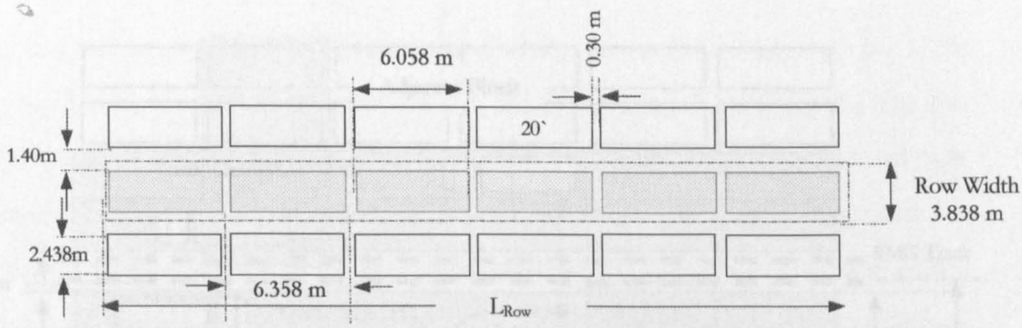
Figure 5.5 The layout of a typical container terminal using a 6+1 RTG system



(Source: Author)

Figure 5.6 The layout of a typical container terminal using a 12+2 RMG system

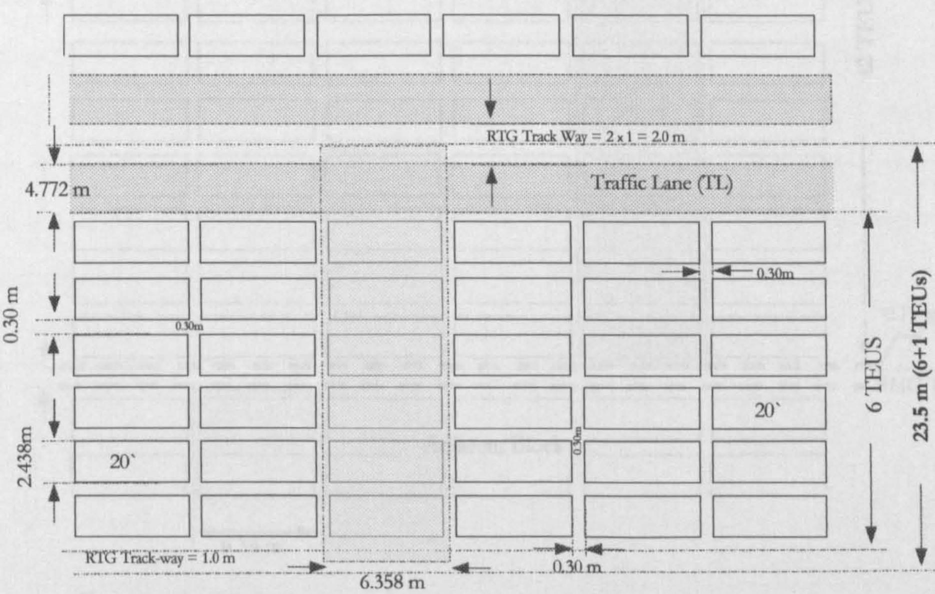
The area used for any of those container-stacking blocks should include the minimum road and passageway areas required to handle containers amongst the blocks but it may exclude the perimeter roadways for the respective handling systems. Figures 5.7 to 5.9 illustrate the examples of the area that may be required for one stacking block or a row to help to formulate the number of container GSs in the SC, RTG and RMG systems.



L_{Row} = 63.580 metres for a row of 10 ground slots, A_{Row} = 244.020 m^2
L_{Row} = 95.370 metres for a row of 15 ground slots, A_{Row} = 366.030 m^2
L_{Row} = 127.160 metres for a row of 20 ground slots, A_{Row} = 488.040 m^2

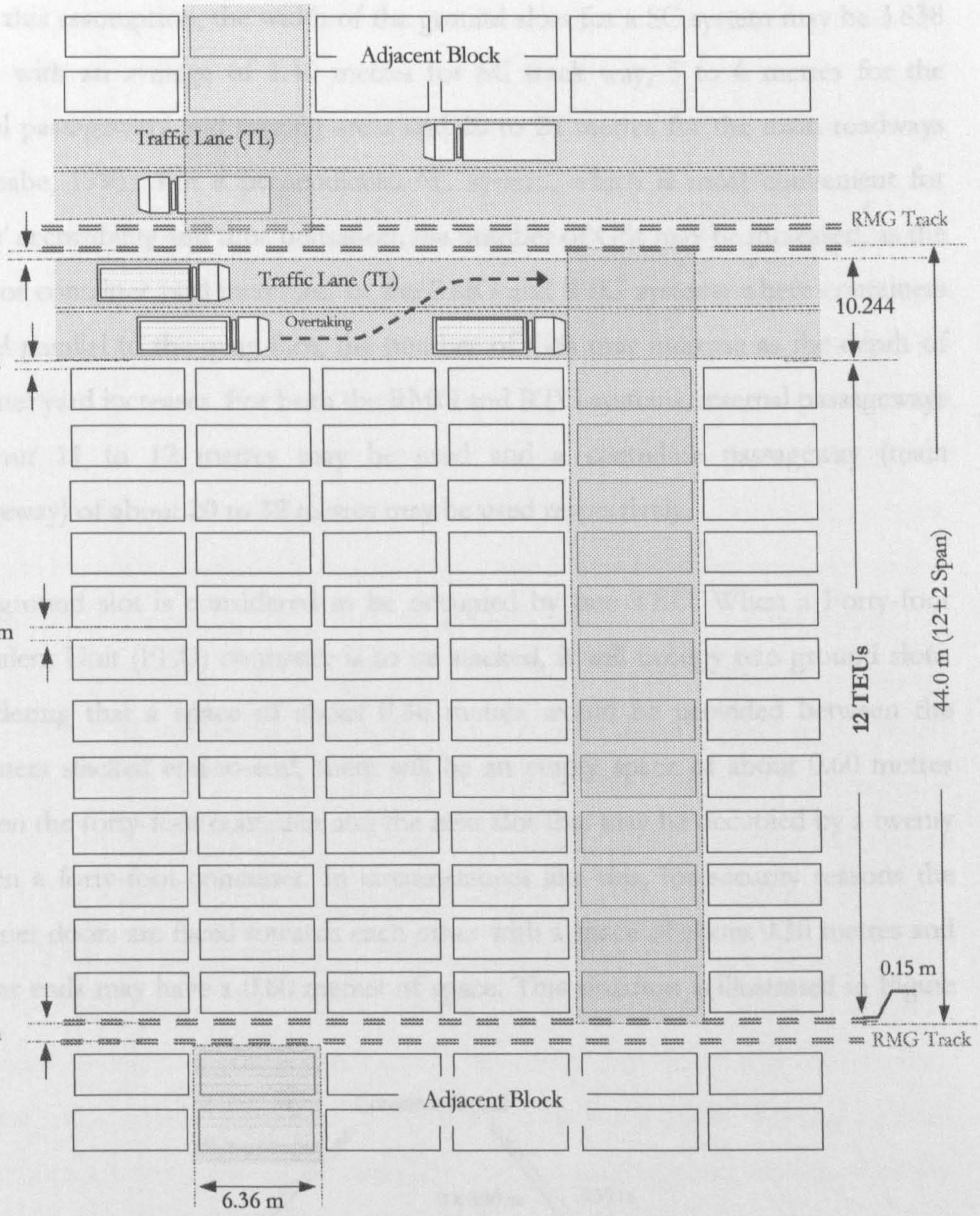
(Source: Author)

Figure 5.7 The length and area used for stacking in a SC system



(Source: Author)

Figure 5.8 The area used for stacking in a 6+1 RTG system



(Source: Author)

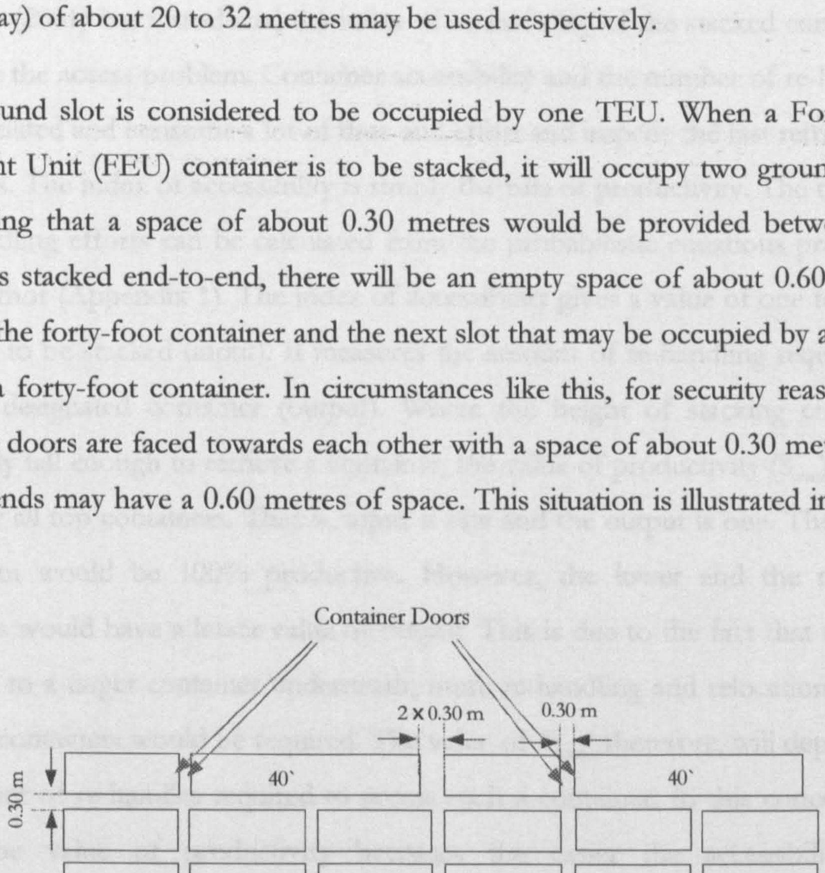
Figure 5.9 The area used for stacking in a 12+2 RMG system

5.2.5 Operational considerations

Container terminals should normally employ only one of the scenarios (SC, RTG or RMG operating systems) to avoid complexities of the operation. Generally to account for any future developments that ideally take place along with the coastline, most of the terminals with RMG crane systems are developed parallel to the quay line. The number of container ground slots in RMG, RTG and SC systems that are laid parallel to the quay face will be directly proportional to the depth of the marshalling yard (D_{CY}) on a utilised basis.

Under this assumption, the width of the ground slots for a SC system may be 3.838 metres with an average of 1.40 metres for SC track way, 5 to 6 metres for the internal passageways and turning areas and 20 to 26 metres for the main roadways (Watanabe, 1995). For a perpendicular SC system, which is most convenient for drivers' accessibility and time utilisation, the number of GSs may be increased, as the depth of container yard increases. In the RMG and RTG systems where containers are laid parallel to the quay face, the number of GSs may increase as the depth of container yard increases. For both the RMG and RTG systems, internal passageways of about 11 to 12 metres may be used and a centreline passageway (main passageway) of about 20 to 32 metres may be used respectively.

Each ground slot is considered to be occupied by one TEU. When a Forty-foot Equivalent Unit (FEU) container is to be stacked, it will occupy two ground slots. Considering that a space of about 0.30 metres would be provided between the containers stacked end-to-end, there will be an empty space of about 0.60 metres between the forty-foot container and the next slot that may be occupied by a twenty or even a forty-foot container. In circumstances like this, for security reasons the container doors are faced towards each other with a space of about 0.30 metres and the rear ends may have a 0.60 metres of space. This situation is illustrated in Figure 5.10.



(Source: Author)

Figure 5.10 Stacking forty-foot containers

In most of container terminals, the export containers are usually stacked and moved according to the containerships' arrival patterns, container dimensions, weight category, destination, *etc.* Therefore, export containers are stacked and loaded with a minimum re-handling effort. It has been observed that export containers stay a shorter duration of time in a terminal (dwell-time) waiting to be loaded than import containers (Bonsall, 2001). Import containers are generally transferred and stacked in the order that they have been discharged from the ships. Thus, when they are to be delivered to the road carriers where they arrive at the terminal on a random basis, access to the designated containers is a serious operational problem. Watanabe (2001) has introduced the index of accessibility of the stacked containers to analyse the access problem. Container accessibility and the number of re-handles are interrelated and consume a lot of time and effort and impede the fast retrieval of containers. The index of accessibility is simply the rule of productivity. The number of re-handling efforts can be calculated from the probabilistic equations proposed by the author (Appendix 1). The index of accessibility gives a value of one to every container to be stacked (input). It measures the amount of re-handling required to access a designated container (output). Where the height of stacking cranes is sufficiently tall enough to retrieve a container, the value of productivity (S_{con}) would be 1.0 for all top containers. That is, input is one and the output is one. Therefore, the system would be 100% productive. However, the lower and the remoter containers would have a lesser value of output. This is due to the fact that to have an access to a target container underneath, more re-handling and relocation of the blocking containers would be required. The value of 'S_{con}' therefore, will depend on the number of re-handles required to access such a container. In this concept, the higher the value of productivity becomes the easier the accessibility and retrievability will be. This indicates that stacking too high and having the cranes limited in their vertical stacking ability will result in a less accessibility of containers. Therefore, the number of container tiers to be stacked by a yard gantry crane should be worked out considering its value of accessibility. Watanabe (2001) has stated that the export, transhipment and empty containers can be issued a value of productivity of S_{con} = 0.65 to 0.75 whereas, import containers may be assigned 0.50 to 0.65. If the gantry cranes were capable of stacking 7 containers high (1 over 6), the proposed stacking height for an export stack would be 4.55 (7 x 0.65) to 5.25 (7 x 0.75) tiers.

Table 5.4 Proposed average stacking tiers for a maximum capacity

Type of Yard Crane	Number of stacking tiers				
	Import Containers (S_{con} = 0.65)	Export Containers (S_{con} = 0.75)	Transhipment Containers (S_{con} = 0.75)	Gate and Rail Buffers (S_{con} = 0.75)	Empty Containers (S_{con} = 0.85)
SC (1 over 2)	2.00	2.25	2.25	2.25	2.55
SC (1 over 3)	2.60	3.00	3.00	3.00	3.40
SC (1 over 4)	3.25	3.75	3.75	3.75	4.25
SC (1 over 5)	4.00	4.50	4.50	4.50	5.10
RTG (1 over 4)	3.25	3.75	3.75	3.75	4.25
RTG (1 over 5)	4.00	4.50	4.50	4.50	5.10
RTG (1 over 6)	4.55	5.25	5.25	5.25	5.95
RMG (1 over 4)	3.25	3.75	3.75	3.75	4.25
RMG (1 over 5)	4.00	4.50	4.50	4.50	5.10
RMG (1 over 6)	4.55	5.25	5.25	5.25	5.95
RMG (1 over 7)	5.20	6.00	6.00	6.00	6.80

(Source: Author)

The proposed average stacking heights to be used are listed in Table 5.4 for different stacking systems. The values of 'S_{con}' are derived from the studies proposed by Watanabe (1991 and 2001). It should be mentioned that stacking height for a terminal employing FLs and Reach Stackers (RSs) should be taken by having considered the probable number of re-handles to un-stack containers, time and effort required, weather conditions and the effect of the wind, Custom considerations, *etc.*

Usually, a one TEU import or export container occupies one TEU of ground slot in the stack-yard, while a one TEU transhipment container usually occupies 2 TEUs of ground slot (Watanabe, 1991). This is exercised to facilitate an easy access and a swift transfer operation of containers which is required for transhipment terminals. In this context, a Hub Port (HP) container terminal or a Pivot Port (PP) will require a larger transhipment ratio and therefore will need a larger area for transhipment containers than an Origin-Destination (OD) container terminal. This may be the case even when both types of the container terminals have the same capacity throughput for import and export containers. Watanabe (1991) has defined a hub centre container terminal as a terminal having a transhipment ratio of more than 50%, whereas, an OD type of container terminal has a transhipment ratio less than 40%. Amongst other things, he has stated that container terminals having a transhipment ratio between 40% and 50% are passing through a transition period towards a HP container terminal type.

- **Container dwell-times**

Containers stay in the terminals for a duration of time waiting to be exported or collected by their customers. The duration of time they stay is referred to as 'dwell-time' and will differ from port to port. Export containers have shorter dwell-times than import containers. On the other hand transhipment containers seem to have shorter dwell-times than both the import and export containers. This is due to the fact that the movements of transhipment containers are entirely under the control of the shipping lines. Table 5.5 shows the average dwell-times for some major container terminals. It illustrates that the average dwell-times for import containers range from 3 to 12 days, export containers from 3 to 5 days and transhipment containers 3 to 7 days. An experimental study carried out in BACT showed that the average dwell-times of import containers might range from 5 to 21 days.

Table 5.5 Average dwell-times and transhipment ratios of some container ports

Terminal	Dwell-days			Transhipment Ratio (%)
	Exports	Imports	Transhipments	
Port Island (Kobe, Japan)	4-5	4-5	3-7	50
Kaohsiung (Taiwan)	3-5	3-7	4-6	60
Tianjin (China)	3-5	3-7	3-5	70
Shanghai (China)	3-5	6-10	3-5	50
Hong Kong	3-5	3-7	2-3	70
Rotterdam (Netherlands)	4-5	7-11	5-7	60
Amsterdam (Netherlands)	3-5	7-12	5-7	60
Felixstowe (UK)	-	3-11	3-4	50
Thamesport (UK)	4-5	5-12	-	<50

(Source: Compiled by author from various sources including UNCTAD, Containerisation International and World Port Development International from 1990 to 2005)

- **Exponential distribution of the dwell-days**

The occurrence of a sequence of discrete events over specific time intervals such as arrival of containers to a terminal has been generally accepted to follow a Poisson distribution. Poisson distribution applies when the average number of containers 'N' to arrive is large and the probability of 'N' containers to arrive, 'P(N)' is small. The Poisson distribution implies that occurrence of events such as container arrivals is randomly distributed over a specified time interval. In the sequence of arrivals, the probability distribution of the time for the next arrival events would be the same regardless of how much service-time has already elapsed since the preceding arrival event. This is because of the independency of arrival-times from the service-times in a Poisson distribution process.

It should be noted that the queuing systems frequently have a degree of variability in their inter arrival-time / service-time or rate that falls somewhere between the high variability of exponential distributions and zero variability of degenerate distributions. Therefore, the degree of variability of arrivals is a determining factor when a queuing formula is used. To decide which queuing algorithm is more appropriate for a system, one must ascertain the degree of variability. For the study of the vessels' arrival, queuing and services in a port an Erlang distribution is widely used. In this distribution, the shape parameter 'k' is calculated first. When 'k = 1', the Erlang distribution reduces to the exponential distribution patterns. Whereas, '$K \rightarrow \infty$', then the Erlang distribution approaches to a degenerate distribution which has a zero variability.

However, the probability 'P(N)' for export and import containers to be stored in a terminal within a specified period of time may be defined as an exponential distribution as follows (Dally and Maquire, 1983 and Watanabe, 2001):

$$P(N) = \frac{(N)^{e} e^{-N}}{n!} \qquad 5.1$$

where:

N = Average number of container' arrivals per day over a long period of time.

n = Number of containers to arrive within a specified time period.

The above statement is equivalent to assuming that the distribution of the time intervals 't' between successive arrivals is a negative exponential phenomenon. The probability P(t) may be defined as follows:

$$P(t) = e^{-t/T} \qquad 5.2$$

where:

T = Average of time intervals over a large period of time.

t = Service-time period.

On the above basis, an exponential distribution concept may be used to model the number of random arrivals of import and export containers and to find a coefficient for the required container capacity where their receiving and delivery patterns are concentrated within two or three days before or after the ships' call days (Dally and Maquire, 1983). Such a coefficient may be defined as:

$$\rho = \frac{e^{-d/T_{dwell}}}{T_{dwell}} \qquad 5.3$$

where:

d = 0, 1, 2, 3,..., D, the number of days before the ship's call.

T_{dwell} = Average number of dwell-days of containers in the terminal.

However, the nature of container movements and their distribution patterns in a container terminal can be considered as having static and dynamic natures. Therefore, two approaches can be made to formulate and estimate the movement of containers in a container terminal.

i) Static approach

In a static approach the daily percentages of container movements associated with a particular vessel must be estimated (Frankel and Liu, 1979). For this purpose, the past voyages of a containership and the statistics of containers arrived by rail and road must be used to calculate the percentage (ρ_i) of the total export container arrivals, on day 'i' prior to the vessel's departure. The following equation may provide such a percentage:

$$\rho_i = \frac{N_i}{\sum_{i=0}^{d} D_i} \qquad 5.4$$

where:

N_i = Number of container arrivals on day 'i'.

D_i = Total number of days remaining to a vessel's departure.

In this instance, the derived model represents a probability density function that expresses the conditional probability ($P_i[x = i \mid 0 \leq i \leq d]$) that a container will arrive on day 'i' given the model horizon of 'd' days before the scheduled voyage date. A similar approach can be used to calculate the percentage of import container departures after the vessel's arrival. Multiplying the estimated probabilities with the total expected number of exports (N_E) in TEUs would provide the estimate (e_i) in TEUs for the required daily GSs prior to vessel's arrival. Thus:

$$e_i = \rho_i \times N_E \qquad 5.5$$

Similar estimate can be obtained after the vessel's departure, based on the total expected number of imports (N_I). The results of all voyages for import and export containers may provide the expected daily container movements within a terminal.

ii) Dynamic approach

Dynamic movement of containers may take advantage of a real time information that may be available to a terminal after it starts its normal operation. For any day of operation, all the gate movements should be recorded and tallied in full details. Therefore, by inquiring the inventory for a specific voyage it would be possible to estimate the number of export containers that have not yet entered the port to be stored (R_i), on day 'i' before the vessel arrival (Frankel and Liu, 1979). On day 'i', the total number of containers associated with a particular voyage that have already arrived at the terminal (A_i) may be defined as the sum of containers arriving each day 'a_n', with $i < n \leq d$ as follows:

$$R_i = N_E - A_i \qquad 5.6$$

where:

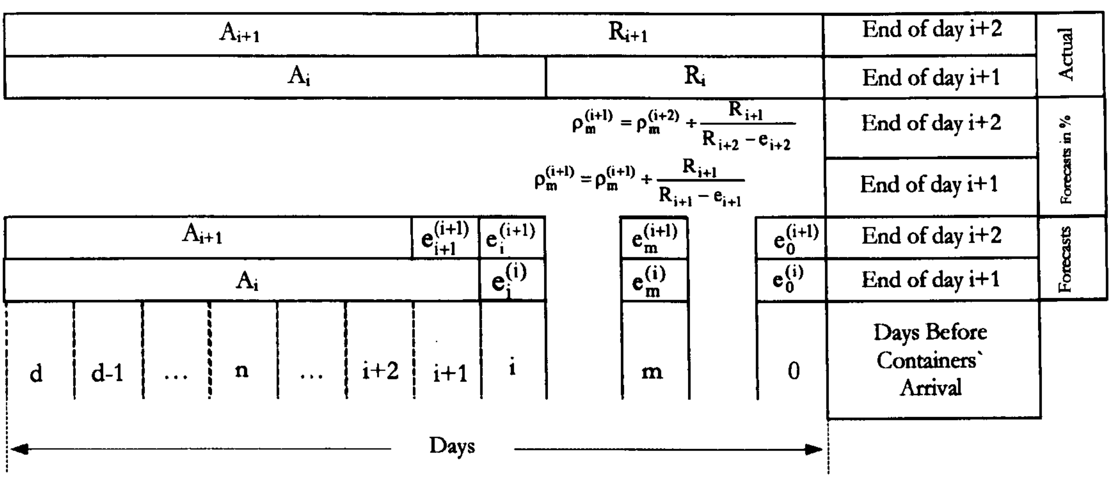
$$A_i = \sum_{n=i+1}^{d} a_n \qquad 5.7$$

a_n = Number of arrived containers on the day 'n'.

On the above basis, the estimated proportions of export containers (ρ_m) that will arrive each day (m) where $0 \leq m \leq i$ may be readjusted to account for the actual arrivals recorded of the previous days.

Table 5.6 illustrates this concept. The bottom part of the table shows the time horizon for export containers in days. Predictions can be made for 'd' days prior to the arrival of the vessel that occurs on day 0. The top part of the table shows the actual number of containers that have arrived (A_i) and or those that have not arrived yet (R_i) at the end of day i+1. The forecast in percentages in the middle part of the table shows how the estimated proportions of export containers that should be adjusted at the end of each day to account for actual container arrivals into the terminal. For example, at the end of day i+1, the number of actual container arrivals (R_i) that may occur over the remaining 'i' days is N_E - A_i would be exactly known. The same number can only be predicted for the day before (i+2) since at that point there would be no record of container arrivals that occurred on day i+1. This prediction may be equal to R_{i+1} - e_{i+1}. The proportions of export containers that are expected to arrive on each day 'm', as they have been estimated at the end of day i+2, may be denoted as e_m^{i+1}.

Table 5.6 Dynamic estimation of container arrivals



The proportions obtained in this way may be adjusted by multiplying them with the ratio of actual container arrivals to the predicted arrivals at the end of day i+1. The adjusted proportions may be multiplied by the total expected number of export containers (N_E) to estimate the required daily GSs. The lower part of the table shows the forecasts and indicates the estimated daily GSs. For example, $e_m^{(i)}$ is the expected GSs for the day 'm' as it is estimated at the end of day i+1. A similar approach can be used for import containers.

5.2.6 Stacking policy

The selection of a proper stacking policy will help the terminal operators to optimally maximise the use of the spaces of their container terminal and facilitate a smooth operation of its yard and transfer cranes. The stacking policy will clarify which block, row and even a slot has to be selected for stacking of a target container that will help to produce the highest storage capacity, quicker and easier transfer operation with a minimum number of re-handling moves at the end of the operation. Inaccurate and incomplete data coupled with the scattering of containers around may result in a longer cycle-time of the stacking cranes and the transfer vehicles. Steenken *et al.* (2004) have stated that at European terminals about 30% to 40% of the export containers that arrive at the container terminals lack accurate data respective to vessel, port of destination, or weight which is necessary to help to make an appropriate stacking decision. Amongst other things, Bonsall (2001) has stated that generally two main treatments may be exercised for export and import containers. Export and import containers can be stacked statically or dynamically. In a static situation, import containers are preferably stacked into the inland blocks where they stay in the same location until they are delivered to the inland carriers. The export containers may also be stacked in the same way. In the case of export containers however, practically it is difficult to keep the containers in their original locations. In a dynamic condition, containers are allowed to be relocated into the new slots to facilitate the availability of the other containers beneath or to move the containers close to the export storages near the quayside and the transhipment areas. Four stacking policies may be derived from these basic concepts for import, export and transhipment containers as follows:

1) Dedicated storage and facility

In some container terminals such as Hong Kong International Terminals (HIT), Pasir Panjang in Singapore and Rotterdam, a block or a portion of stacking area, and in some occasion, some of the terminal facility is dedicated to a particular shipping line or a container vessel. In this case, a number of slots are reserved for the export and the import containers. When a containership leaves the port and the storage becomes vacant, the available spaces may be used for another vessel to call at port. This policy is called the rotating strategy (Bonsall, 2001). The export containers may be sorted according to their destination, weight and sized to satisfy the vessel loading plans, her safety and stability requirements.

2) Segregating policy

In some terminals, a portion of a block on the inland side together with the appropriate stacking and transfer facilities are deployed to import containers prior to arrival of a container vessel. Containers are landed randomly but segregated from other containers in the other stacks. The oversize (non-standard), reefer and dangerous containers may be transferred to a special stack. The Less than full

Container Load (LCL) boxes may be transferred to the CFS depots directly when they are being discharged from the vessel or perhaps in the later stages (see the definitions given for LCL, FCL and CFS in Section 1.8 in Chapter 1). The segregation policy is basically exercised for export containers where a portion of a block or a row close to the quayside is reserved for a particular ship to call at port. The containers received from the trucks and railheads are sorted according to their type, weight and size and according to the ship loading plans. The terminal information systems are further capable of segregating containers according to their port of call sequence by stacking heavier containers on the front rows and on the top of other tiers to help containerships achieve an acceptable level of stability. The transhipment stacks in some terminals are provided very close to the quayside. The segregation policy may also be exercised in the transhipment stacks.

However, the dedicating and segregating strategies may provide an acceptable level of speed but may not provide an acceptable level of space utilisation required for automated operations and be a cost effective policy.

3) Non-segregating policy

Traditionally, export and import containers were stored on a non-segregate basis. The non-segregating strategy is not seen as a poor stacking system anymore due to the effective automatic container identification and positioning systems employed in container terminals. The import containers are stacked into the available slots in the import stacks ideally at the inland side of terminals. As the stack becomes denser, some un-desirable re-handling moves may be required to retrieve the designated containers to be delivered to the rail or road haulers. Export containers are also stacked on the available slots preferably into the landside rows. The landside rows are the container rows which are away from the quayside. The difficulty will lie on the effort to be made to sort the export containers according to the sequence of their port of calls, weight and size. Although the containers may be identified and located efficiently, retrieval of the target containers stacked in the lower tiers may consume a considerable time that may be in contradiction with the policy of shortening of the vessels' turnaround-time and Just In Time (JIT) deliveries. A combination of non-segregating and segregating strategies may be employed for import and export containers respectively.

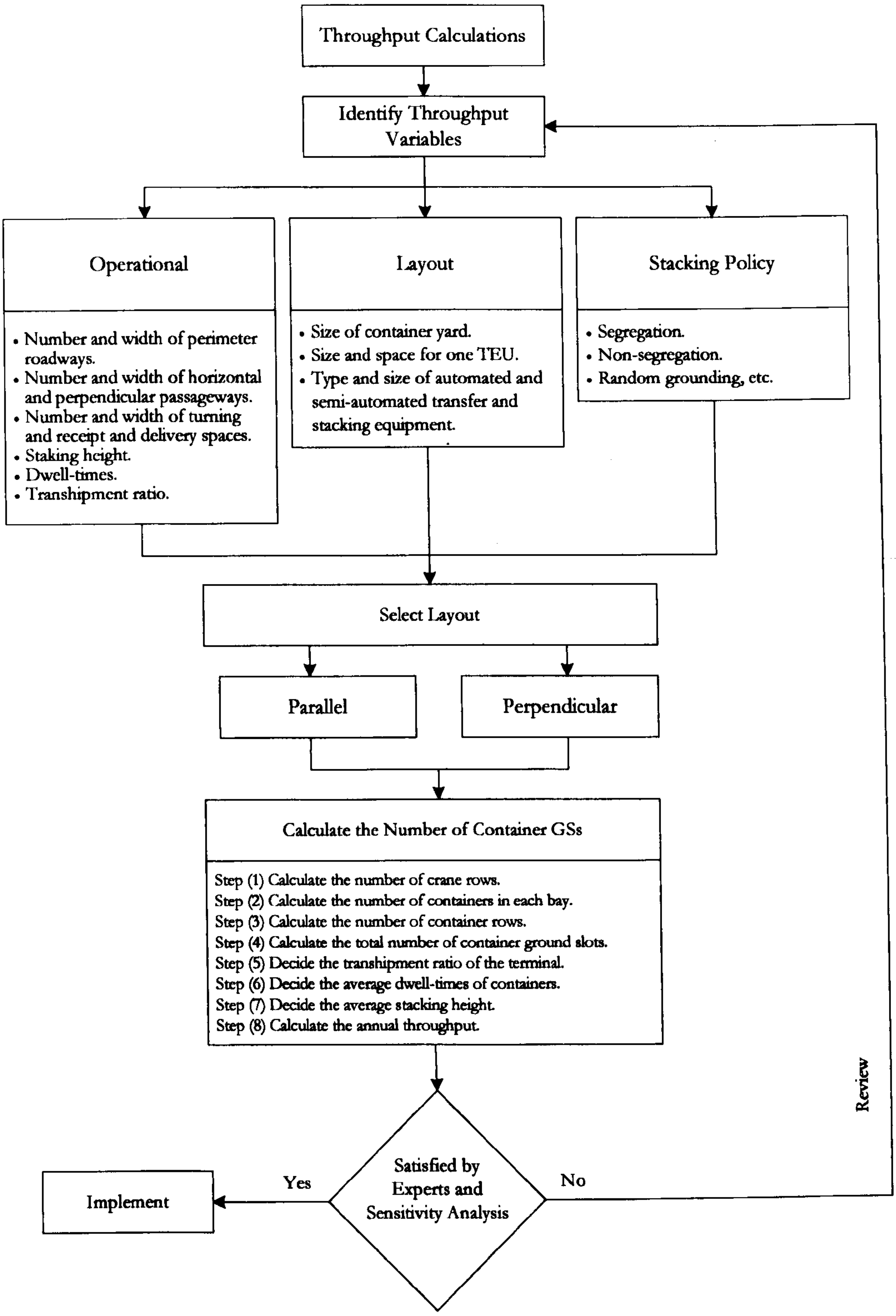
3) Random grounding

The productivity of a stacking area can be maximised in some terminals through a random grounding strategy. Random grounding may also improve the distribution of containers in the terminal, and minimise the housekeeping moves to a minimum and reduce the number of re-handling moves. This in turn will make stacking operations more flexible and may ease-up the gate operations. Although a random grounding strategy may be applicable to RTG and SC operating systems, it is very suitable for container terminals with RMG operating systems. In the random grounding, export containers for the same destination and or a containership are randomly stacked into a particular stack in a row. A row may accommodate individual stacks for several vessels in a static manner (Bonsall, 2001). In Thamesport it has been observed that export containers are stacked to a general storage area randomly into the available slots when they arrive into the terminal. Later and before the arrival of the designated vessel, all containers related to that ship are identified by the terminal information system and are re-moved into the export storage (magazine in the case of the Thamesport Container Terminal) where containers are stacked to a maximum allowable height in the normal rows. The containers may be stacked in the sequence of port calls, weight and size *etc.* On the arrival of the containership, the automated RMG cranes are remotely activated and containers are quickly transferred to the shipside. The import containers however, may be stacked on a segregating basis.

Random grounding differs from non-segregating strategy, namely, where an entire row (or rows) is devoted for stacking export containers whereas, in the non-segregating policy export containers are stacked to any available slot in the present stacked rows.

5.3 Throughput modelling

To determine the annual throughput of a terminal, this study identifies different static and dynamic key variable factors and proposes the following methodology illustrated in Figure 5.11 for calculating the annual throughput of a container terminal. The method proposed in Figure 5.11 for calculation of container ground slots has used the important factors such as, dimension of one TEU container, and size of the stack-yard, number and size of road and passage-ways, under span of the appropriate cranes and spaces required by Customs and spaces required for safe operation of containers which are clearly recognised in the literature particularly in the studies conducted by Frankel and Liu (1979), Dally (1983), Dally and Maquire (1983), Hoffman (1985), the UNCTAD (1985), Frankel (1987), Dharmalingam (1987) Puertos and Enriquez (1991) Watanabe (1991, 1995 and 2001) Dekker and Davis (1992) Friedman (1992) Agerschou (2004). The method proposed in this study has additionally considered the dynamic and size of modern stacking and un-stacking cranes in calculation of container ground slots that have not been incorporated in the analysis offered in the literature. Further, this study has introduced the index of container accessibility in determining the different stacking heights effectively for calculation of total container throughput that has not been considered before.



(Source: Author)

Figure 5.11 Throughput modelling process

5.3.1 Model variables

The following areas and associated variables have been identified and classified as the determining parameters that should be considered and used to formulate the expected annual throughput for a container terminal:

1) Layout factors:

   1.1) Size of the container yard:

   - Width of the container yard.
   - Depth of container yard.

   1.2) Size and space required for a one TEU container:

   - Width and / or the length of one TEU container.
   - Space required between the containers when placed door-to-door (or end-to-end) considering the Forty-foot Equivalent Units (FEUs) and over size containers and Custom requirements.
   - Space required between the containers for the operational considerations.

   1.3) Type and size of the semi-automated SC and RTG and automated and semi-automated RMG stacking and transfer cranes:

   - Maximum width of the under span of the stacking crane including the width required for traffic lanes used for the appropriate transfer vehicle.
   - Number and size of the stacking and transfer equipment track-ways.

2) Operational factors:

   - Number and width of the perimeter roadways.
   - Number and width of the horizontal and perpendicular passageways.
   - Space required between the track-ways or railways of two transfer vehicles passing side by side.

- Number and width of turning areas and space required for receipt and delivery for a particular stacking system.

- Number of container tiers that a particular yard crane is able to stack vertically, the export, import, transhipment, empty, *etc.* containers.

- Average number of dwell-days of the export, import, transhipment, empty, *etc.* containers.

- Transhipment ratio.

3) Stacking policy to be implemented to maximise the highest utilisation of the spaces available for export, import and transhipment containers (for example, segregation, non-segregation or random grounding).

5.3.2 Ground slot modelling

When a terminal is of a rectangular shape, it is easier to calculate the total number of GSs in TEUs. This can be done by calculating the total number of containers in each row and multiplying the results by the number of rows in the container yard. The calculations can be formulated for a container terminal with perpendicular and parallel layouts in the following process:

5.3.2.1 Number of container GSs in a parallel layout

Step 1: Number of crane rows

$$N_C^R = \frac{D_{CY}(W_{PWS}^H \times H_{PWS})}{(W_C + W_T + W_{SWS})} \qquad 5.8$$

where:

N_C^R = Total number of crane rows.

D_{CY} = Total depth of container yard in metres.

W_{PWS}^H = Width of the horizontal passageways in metres.

H_{PWS} = Number of the horizontal passageways.

W_C = Maximum width of crane in metres.

W_T = Width required for crane track-ways in metres.

W_{SWS} = Width of safety working space required between two adjacent rows when two handling equipment work side by side on two adjacent rows at the same time in metres.

Step 2: Number of container GSs in each bay

$$N^{B}_{TEU} = \frac{W_{CY}[(2 \times W_{RWS}) + (W^{P}_{PWS} \times P_{PWS}) + W_{S}]}{L_{TEU} + L_{CRS}} \quad 5.9$$

where:

N^{B}_{TEU} = Number of container ground slots in every bay in TEUs.

W_{CY} = Net width of container yard in metres.

2 x W_{RWS} = Number and width of perimeter roadways in metres.

W^{P}_{PWS} = Width of perpendicular passageways in metres.

P_{PWS} = Number of perpendicular passageways.

W_{S} = Total extra width required between the containers for gears of special needs such as refrigerated containers, *etc.* in metres.

L_{TEU} = Maximum length of one TEU container (6.058 metres).

L_{CRS} = Average length required by some Customs to place containers end-to-end in metres.

Step 3: Number of container rows

$$N_{R} = N^{R}_{C} \times N^{S}_{C} \quad 5.10$$

where:

N_{R} = Number of container rows.

N^{S}_{C} = Total number of rows under the span of the crane.

Step 4: Total number of container ground slots for a container yard

$$N_{TEU} = (N^{B}_{TEU} \times N_{R}) - IA_{TEU} \quad 5.11$$

where:

N_{TEU} = Total container ground slots in the container yard.

IA_{TEU} = Number of TEUs space required for interchange area in a SC system.

5.3.2.2 Number of container GSs in a perpendicular layout

Step 1: Number of crane rows

$$N_C^R = \frac{W_{CY}[(2 \times W_{RWS}) + (W_{PWS}^P \times P_{PWS})]}{(W_C + W_T + W_{SWS})} \tag{5.12}$$

Step 2: Number of containers in each bay

$$N_{TEU}^B = \frac{D_{CY}[(W_{PWS}^H \times H_{PWS}) + W_S]}{L_{TEU} + L_{CRS}} \tag{5.13}$$

Step 3 and Step 4: These steps for a perpendicular layout are the same as Step 3 and Step 4 for a parallel layout.

After selecting a perpendicular or a parallel planning strategy and completing Steps 1 to 4, the planner must proceed with Steps 5 to 8 as follows:

Step 5: Deciding the transhipment ratio of the terminal

Table 3.5 has provided the transhipment ratio (ω) for some major ports. The terminal designer must decide the average value of 'ω' for his / her terminal. One must consider that a HP may have a 'ω' of more than 50% whereas an OD port may have a 'ω' less than 40%. A port under a transition from an OD to HP may be given a value of 'ω' between 40% and 50% (Watanabe, 1991). Most container ports are likely to have a transhipment ratio between 40% to 60%. This study analyses ports with transhipment ratios of 40%, 50% and 60%.

Step 6: Deciding the average dwell-times of containers

As discussed previously, the dwell-times of export containers are shorter than import containers. On the other hand, the transhipment containers usually have dwell-times less than both the import and export containers. This study considers average dwell-times of 3, 5, 7 and 10 days for terminals.

Step 7: Deciding the average stacking height for different stacks

The average stacking heights (Table 5.4) for export, import, transhipment, empty, gate buffer and reefer stacks are considered in this study. A fraction for the index of accessibility, S_{con}, is considered.

Step 8: Annual throughput of a terminal

The annual throughput of a container terminal may be defined as the number of container GSs obtained from the above 7 steps multiplied by the number of working days in a year (365 days), multiplied by 2 assuming that the terminal will receive almost equal amount of import and export containers, divided by the average number of dwell-days in which the ratio of transhipment and stacking height of containers are considered (Watanabe, 2001). This study modifies the equation suggested by Watanabe (2001) but includes the empty, gate and rail buffer containers into consideration too. Therefore, the annual throughput may be more accurately defined as follows:

$$C_Y = \frac{365 \times 2 \times N_{TEU}}{T_{dwell} \times \left[(1-\omega) \times \left(\frac{1}{H^{Export}} + \frac{1}{H^{Import}} + \frac{1}{H^{G\&R}} + \frac{1}{H^{Empty}} \right) + \frac{\omega}{H^{Trans}} \right]} \qquad 5.14$$

where:

C_Y = Annual throughput of the terminal.

T_{dwell} = Average dwell-times of containers in a terminal is equal to the average of transhipment, export, import, gate and rail buffers and the empty containers respectively.

ω = Average transhipment ratio.

H^{Trans}, H^{Export}, H^{Import}, $H^{G\&R}$ and H^{Empty} = The average stacking height of the transhipment, export, import, gate and rail buffers and empty containers respectively.

The required parameters for calculation of annual throughput therefore would be GSs, average stacking height, average number of dwell-days and the average transhipment ratio.

5.4 Test case

This section of the study provides different assumptions and values for variables before running a test case for evaluating the applicability of the proposed model for container terminals using any of SC, RTG or RMG systems. The assumptions take into account the terminal layouts discussed previously, characteristics of the operating vehicle and the required area of land. It also considers the influence of the container average dwell-times, stacking height and transhipment ratio in determining the number of container ground slots for a given terminal. The following values for variables and assumptions are made:

a) Quay lengths that correspond to container yard widths of 300, 320, 350 metres (for a single-berth terminal), 600 and 700 metres (a double-berth terminal) to be considered.
b) Container yards with depths of 300 and 400 metres (for a single-berth terminal), 500 and 600 metres (for a double-berth terminal) to be considered in the analysis.
c) Width of the perimeter roadways for SC = 5 metres.
d) Width of the perimeter roadways for RTG systems = 22 metres.
e) Width of the perimeter roadways for RMG systems = 22 metres.
f) Number and width of the passageways for SCs to be 1 x 20 metres for single-berth and 3 x 20 metres for double-berth terminals respectively.
g) Number and width of the turning area and passageways for RTG systems to be 2 x 11= 22 metres for the turning area and passageways for a single-berth and 2 x 11 metres for turning area and passageways + 30 metres (a main passageway in the middle) = 52 metres for double-berth terminals respectively.
h) Number and width of the passageways for RMG systems to be 1 x 30 metres for single-berth and 2 x 30 metres for the width of the passageways for double-berth terminals respectively.
i) SCs to be considered to have a capability of lifting and stacking 3 containers (1 over 2), 4 containers (1 over 3) and 5 containers (1 over 4).
j) RTG cranes with portal spans of five container rows plus one traffic lane (5+1) and six container rows plus one traffic lane (6+1) capable of stacking and un-stacking of 1 over 4 and 1 over 5 containers to be considered in the analysis.
k) RMG (bridge cranes) with under portal spans of 11 container rows plus two traffic lanes (11+2) at one side of the crane and RMG with under portal span of 12 containers row plus two traffic lanes (12+2) at one side, where, the cranes are capable of stacking containers up to six and seven tiers high (1 over 5 and 1 over 6) respectively to be analysed.
l) Average length of space required by Customs for inspection to be 0.30 metres for SC, RTG and RMG systems.

m) Width required for special needs such as gears required for refrigerated containers, truck parks, *etc.*, to be 0.30 metres for SC, RTG and RMG systems.
n) Length of one TEU container = 6.058 metres.
o) Width required for SCs track-ways = 1.5 metres.
p) Width required for RTGs track-ways = 2.0 metres.
q) Width required for RMGs track-ways = 2 x 0.150 = 0.300 metres.
r) Width of the safety working space between two adjacent RMG cranes = 1.0 metres and zero for SC and RTG systems.
s) Width of a SC vehicle = 3.0 metres.
t) Number of TEUs space required for interchange area for one berth SC terminal = 60 TEUs and double-berth terminal = 120 TEUs, (zero for RMG and RTG systems).
u) Width of an RTG crane = 20 metres for under portal span of 5+1 and = 23.5 metres for 6+1.
v) Width of an RMG crane = 41 metres for under portal span of 11 TEUs and = 44 metres for 12 TEUs.
w) Transhipment, empty and rail and gate storages are considered to be included in the main stacks calculated in this study.

The following numerical example may help to demonstrate how the values for different steps are obtained for three cases of SC, RTG and RMG systems for a parallel layout. Steps 1 to 4 are given in Table 5.7 and Step 5 to Step 8 are explained thereafter.

Table 5.7 Summary of Step 1 to Step 4

Step	SC, (D_{CY}=300 metres and W_{CY}=300 metres)	RTG 6+1, (D_{CY}=400 metres and W_{CY}=350 metres)	RMG 12+2, (D_{CY}=600 metres and W_{CY}=600 metres)
Step 1	$N^{R}_{SC} = \frac{300-20}{3.0+1.5+0} = 62.220$ rows	$N^{R}_{RTG} = \frac{400-22}{23.5+2.0+0} = 14.820$ rows	$N^{R}_{RMG} = \frac{600-60}{44.0+0.3+1} = 11.920$ rows
Step 2	$N^{B}_{TEU} = \frac{300 \quad (2\times5+20+0.3)}{6.058+0.3} = 42.419$ TEUs	$N^{B}_{TEU} = \frac{350 \quad (2\times22+22+0.3)}{6.058+0.3} = 44.621$ TEUs	$N^{B}_{TEU} = \frac{600 \quad (2\times22+60+0.3)}{6.058+0.3} = 77.965$ TEUs
Step 3	$N_R = 62.220\times1 = 62.220$ rows	$N_R = 14.820\times6 = 88.920$ rows	$N_R = 11.920\times12 = 143.040$ rows
Step 4	$N_{TEU} = (42.419\times62.220) - 60 \approx 2{,}579.310$ TEUs	$N_{TEU} = (44.621\times88.920) - 0 \approx 3{,}967.700$ TEUs	$N_{TEU} = (77.965\times143.040) - 0 \approx 11{,}152.114$ TEUs

By substituting the parameters described in Section 5.4 into Equations 5.8 to 5.11, similar to the test case, it will result in the values illustrated in Table 5.8. The results for terminals with sizes of 300m x 300m (9 hectares), 350m x 400m (14 hectares), 600m x 600m (36 hectares) and 700m x 600m (42 hectares) illustrate that as the dimension of the container terminals increases, the number of GSs for SC system declines from the first best in 300m x 300m (9 hectares) to the least values in 700m x 600m (42 hectares) terminals.

Table 5.8 Comparison of the yard size and the number of GSs in TEUs for different stacking systems

	W_{CY}	Type of Yard Crane	Depth of Container Yard (D_{CY}) / metres							
			Single Berth Terminal				Double Berth Terminal			
			300		400		500		600	
			Total Number of GSs	TEUs / ha	Total Number of GSs	TEUs / ha	Total Number of GSs	TEUs / ha	Total Number of GSs	TEUs / ha
Single-Berth Terminal	300	SC	2579.31	286.59	3521.86	293.49	4087.73	272.52	5030.28	279.46
		RTG (5+1)	2323.04	258.12	3157.43	263.12	3741.86	249.46	4578.08	254.34
		RTG (6+1)	2403.91	267.10	3268.43	272.37	3874.92	258.33	4739.45	263.30
		RMG (11+2)	2491.32	276.81	3416.78	284.73	4061.09	270.74	4986.54	277.03
		RMG (12+2)	2538.89	282.10	3480.32	290.03	4136.34	275.76	5077.78	282.10
	320	SC	2775.05	289.07	3787.51	295.90	4395.35	274.71	5407.80	281.66
		RTG (5+1)	2521.81	262.69	3427.58	267.78	4062.02	253.88	4969.79	258.84
		RTG (6+1)	2609.59	271.83	3548.09	277.19	4206.47	262.90	5144.96	267.97
		RMG (11+2)	2712.04	282.50	3719.49	290.59	4420.87	276.30	5428.32	282.73
		RMG (12+2)	2763.82	287.90	3788.66	295.99	4502.80	281.43	5527.64	287.90
	350	SC	3068.61	292.25	4185.90	298.99	4856.67	277.52	5973.96	284.47
		RTG (5+1)	2820.05	268.58	3832.94	273.78	4542.42	259.57	5557.55	264.65
		RTG (6+1)	2918.21	277.92	3967.70	283.41	4703.95	268.80	5753.43	273.97
		RMG (11+2)	3043.22	289.83	4173.69	298.12	4960.73	283.47	6091.20	290.06
		RMG (12+2)	3101.32	295.36	4251.31	303.67	5052.66	288.72	6202.64	295.36
Double-Berth Terminal	600	SC	5063.67	281.32	6914.87	288.12	8026.25	267.54	9877.44	274.37
		RTG (5+1)	5006.89	278.16	6805.26	283.55	8064.90	268.83	9867.22	274.09
		RTG (6+1)	5181.18	287.84	7044.51	293.52	8351.69	278.39	10215.01	283.75
		RMG (11+2)	5471.58	303.98	7504.13	312.67	8919.20	297.31	10951.74	304.22
		RMG (12+2)	5576.06	309.78	7643.69	318.49	9084.48	302.82	11152.11	309.78
	700	SC	6042.33	287.73	8243.02	294.39	9564.23	273.26	11764.92	280.12
		RTG (5+1)	6000.90	285.76	8156.29	291.30	9666.01	276.17	11826.15	281.58
		RTG (6+1)	6209.80	295.70	8443.04	301.54	10009.73	285.99	12242.98	291.50
		RMG (11+2)	6575.37	313.11	9017.95	322.07	10718.48	306.24	13161.06	313.36
		RMG (12+2)	6700.92	319.09	9185.66	328.06	10917.11	311.92	13401.85	319.09

Table 5.8 provides the total number of container ground slots together with the number of TEUs ground slots per one hectare of land for each system.

The analysis reveals that as the width of container yards increases, the number of GSs for SC system loses its first best position and is replaced with RMG (11+2) system. The total number of GSs decreases in order of RMG (12+2), SC, RMG (11+1), RTG (6+1) and RTG (5+1) systems for single-berth terminals (see Appendix 3). The analysis indicates that as the width and depth of container terminals increase and the terminal manages to service two or more containerships, the number of GSs for SC system gradually decrease from the second best position and becomes overtaken by RTG (5+1) system in the largest terminal analysed in this study (see Appendix 3). This implies that in terminals with two or more berths, where the width and depth of container yards increase, the productivity of SC systems in terms of the number of GSs diminishes and gets overtaken by both RMG and RTG systems.

Table 5.9 Maximum land utilisation of the yard operating systems, m² / TEUs

Terminal	W_{CY}	Type of Operating System	Depth of Container Yard (D_{CY}) / metres							
			Single Berth Terminal				Double Berth Terminal			
			300		400		500		600	
			TEUs / ha	m² / TEU	TEUs / ha	m² / TEU	TEUs / ha	m² / TEU	TEUs / ha	m² / TEU
Single-Berth Terminal	300	SC	286.59	34.89	293.49	34.07	272.52	36.69	279.46	35.78
		RTG (5+1)	258.12	38.74	263.12	38.01	249.46	40.09	254.34	39.32
		RTG (6+1)	267.10	37.44	272.37	36.71	258.33	38.71	263.30	37.98
		RMG (11+2)	276.81	36.13	284.73	35.12	270.74	36.94	277.03	36.10
		RMG (12+2)	282.10	35.45	290.03	34.48	275.76	36.26	282.10	35.45
	320	SC	289.07	34.59	295.90	33.80	274.71	36.40	281.66	35.50
		RTG (5+1)	262.69	38.07	267.78	37.34	253.88	39.39	258.84	38.63
		RTG (6+1)	271.83	36.79	277.19	36.08	262.90	38.04	267.97	37.32
		RMG (11+2)	282.50	35.40	290.59	34.41	276.30	36.19	282.73	35.37
		RMG (12+2)	287.90	34.73	295.99	33.78	281.43	35.53	287.90	34.73
	350	SC	292.25	34.22	298.99	33.45	277.52	36.03	284.47	35.15
		RTG (5+1)	268.58	37.23	273.78	36.53	259.57	38.53	264.65	37.79
		RTG (6+1)	277.92	35.98	283.41	35.28	268.80	37.20	273.97	36.50
		RMG (11+2)	289.83	34.50	298.12	33.54	283.47	35.28	290.06	34.48
		RMG (12+2)	295.36	33.86	303.67	32.93	288.72	34.64	295.36	33.86
Double-Berth Terminal	600	SC	281.32	35.55	288.12	34.71	267.54	37.38	274.37	36.45
		RTG (5+1)	278.16	35.95	283.55	35.27	268.83	37.20	274.09	36.48
		RTG (6+1)	287.84	34.74	293.52	34.07	278.39	35.92	283.75	35.24
		RMG (11+2)	303.98	32.90	312.67	31.98	297.31	33.63	304.22	32.87
		RMG (12+2)	309.78	32.28	318.49	31.40	302.82	33.02	309.78	32.28
	700	SC	287.73	34.75	294.39	33.97	273.26	36.60	326.80	35.70
		RTG (5+1)	285.76	34.99	291.30	34.33	276.17	36.21	281.58	35.51
		RTG (6+1)	295.70	33.82	301.54	33.16	285.99	34.97	291.50	34.31
		RMG (11+2)	313.11	31.94	322.07	31.05	306.24	32.65	313.36	31.91
		RMG (12+2)	319.09	31.34	328.06	30.48	311.92	32.06	319.09	31.34

Table 5.9 provides the maximum utilisation factor for each system in terms of the area required to accommodate one TEU of ground slot for each system in m^2 / TEU. It indicates that a better utilisation of space (ground slot) / one TEU may be expressed as a smaller area used to accommodate a one TEU container. Therefore, the smaller the area becomes, the better utilisation of the space will be. The analysis shows that SC systems are more space efficient than RTG and RMG systems only in small size terminals. As the size of the terminal increases, a better utilisation is obtained from RMG and RTG systems than SC operating system. The analysis indicates that in overall the value of utilisation diminishes in order of RMG (12+2), RMG (11+2), RTG (6+1), RTG (5+1) and SC systems. These values can be used as the determining attributes for decision-making for the selection of stacking systems. They are simply calculated by dividing an area of 10,000 m^2 (one hectare) by the number of TEUs ground slots allowed in one hectare of land.

By knowing the number of GSs (Table 5.8), average stacking height (Section 5.2.3 and Table 5.4), average number of dwell-days and the average transhipment ratio (Table 5.5) and selecting a suitable system for stacking, it is possible to calculate the expected annual throughput for a container terminal. Excel spreadsheets are used to calculate the annual throughput of container yards having widths of (W_{CY}) of 300, 320, 350, 600 and 700 metres and depths (D_{CY}) of 300, 400, 500, and 600 metres. About 20 tables and 60 graphs were obtained. Due to the space limitation, some of the above tables and their corresponding graphs are randomly selected here and others are given in Appendix 3. The terminals are considered to be operating 365 days a year. The results for two types of terminals with 350m x 400m (14 hectares) and 600m x 500m (30 hectares) in size are shown in Tables 5.10 and 5.11. However, one can obtain the annual throughput for different combinations using the similar procedures offered in this chapter. The following procedures and considerations are taken for the analysis.

Step 5: Transhipment ratio

The transhipment ratios (ω) of 0.4, 0.5 and 0.6 are used in the analysis of this study.

Step 6: Average dwell-times of containers

The average dwell-times (T_{dwell}) of 3, 5, 7 and 10 days are considered for all types of containers.

Step 7: Average stacking height for different stacks

The average heights of the stacked containers are taken from Table 5.5 for the purpose of this study.

Step 8: Annual throughput

After calculating the required number of GSs, one can use different transhipment ratio, dwell-times and stacking heights for determining the annual throughput of his / her terminal. The following example explains how the annual throughput of a terminal can be calculated using Equation 5.14 (see Appendix 3).

In a test case (similar to the BACT) a terminal is considered to employ a SC system capable of stacking 1 over 4. The same terminal is considered to be 350 metres wide and 400 metres deep. Using the data calculated in Table 5.8, the number of GSs is about 4,185.90 TEUs. Therefore, an annual throughput for a SC capable of stacking 1 over 4 may be calculated as follows:

Straddle carrier 1 over 4:

where:

$\omega = 0.5$ (transhipment ratio)

$T_{dwell} = 3, 5, 7$ and 10 days (average dwell-days)

$H^{Tran} = 3.75$ TEUs

$H^{Export} = 3.75$ TEUs

$H^{Import} = 3.25$ TEUs

$H^{G\&R} = 3.75$ TEUs

$H^{Empty} = 4.25$ TEUs

The annual throughput of the terminal would be:

- $\mathbf{T_{dwell} = 3}$ **days**

$$C_Y = \frac{365 \times 2 \times 4185.90}{3 \times \left[(1-0.5) \times \left(\frac{1}{3.75} + \frac{1}{3.25} + \frac{1}{3.75} + \frac{1}{4.25} \right) + \frac{0.5}{3.75} \right]} \approx 1{,}516{,}872 \quad \text{TEUs}$$

- $\mathbf{T_{dwell} = 5}$ **days**

$$C_Y = \frac{365 \times 2 \times 4185.90}{5 \times \left[(1-0.5) \times \left(\frac{1}{3.75} + \frac{1}{3.25} + \frac{1}{3.75} + \frac{1}{4.25} \right) + \frac{0.5}{3.75} \right]} \approx 910{,}123 \quad \text{TEUs}$$

- $\mathbf{T_{dwell} = 7}$ **days**

$$C_Y = \frac{365 \times 2 \times 4185.90}{7 \times \left[(1-0.5) \times \left(\frac{1}{3.75} + \frac{1}{3.25} + \frac{1}{3.75} + \frac{1}{4.25} \right) + \frac{0.5}{3.75} \right]} \approx 650{,}088 \quad \text{TEUs}$$

- $\mathbf{T_{dwell} = 10}$ **days**

$$C_Y = \frac{365 \times 2 \times 4185.90}{10 \times \left[(1-0.5) \times \left(\frac{1}{3.75} + \frac{1}{3.25} + \frac{1}{3.75} + \frac{1}{4.25} \right) + \frac{0.5}{3.75} \right]} \approx 455{,}062 \quad \text{TEUs}$$

The same process has been carried out for terminals employing the following operation systems using different stacking heights, dwell-times and transhipment ratios:

i) SC system capable of stacking 1 over 2, 1 over 3 and 1 over 4 containers.

ii) 5+1 and 6+1 RTG systems capable of stacking 1 over 4 and 1 over 5 containers.

iii) 11+2 and 12+2 RMG systems capable of stacking of stacking 1 over 4 and 1 over 5 containers.

The results for two terminals of one single berth with a size similar to the BACT [350m x 400m (14 hectares)] and a double berth having a container yard dimension of 600m x 500m (30 hectares) have been reflected in this chapter and are summarised in Tables 5.10 and 5.11. Different tables for a combination of different terminal sizes were obtained out of which each table has generated 3 distinctive figures for each transhipment ratio and dwell-times. The results of calculations are given in Appendix 3. The analysis of the throughput shows an exponential representation of data. The results imply that an increase in the dwell-times will result in a sharp decrease in the annual throughputs. However, an increase in the transhipment ratio will result in a slight increase in the value of throughput for the terminals.

The analysis of this study demonstrates that the total annual throughput reduces in order of SC, RMG and RTG systems in single-berth terminals. However, the analysis demonstrates that for terminals with width of 600 metres and more and depths of 500 metres and more (double-berths and larger) the total annual throughput reduces in order of RMG, RTG and SC systems. From the tables it is evident that a SC system capable of stacking one over four containers produces a higher annual throughput than RMG and RTG systems capable of stacking the same height for a single-berth container terminal notably 300m x 300m (9 hectares). As the dimension of the terminal increases, the throughput for SC system decreases where it becomes approximately the same value as RTG (1+5) for a terminal of 600m x 600m (36 hectares) and becomes the smallest throughput in 700m x 600m (42 hectares) terminals. For example, in a similar size terminal to BACT [350m x 400m (14 hectares)] with a transhipment ratio of 0.4 and average dwell-time of 10 days where systems are capable of stacking 1 over 4 containers, the annual throughput would be about 406,097 TEUs for a SC system, 371,854 TEUs for a 5+1 RTG, 384,928 TEUs for a 6+1 RTG, 404,912 TEUs for a 11+2 RMG and 412,443 TEUs for a 12+2 RMG system.

It should be noted that the analysis shows that RMG systems with the higher spans and better stacking capabilities produce capacities that are more significant than RTG and SC systems.

Table 5.10 C_Y for systems with W_{CY} = 350 metres and D_{CY} = 400 metres

Average Transhipment Ratio	Average Dwell-days (T_{dwell})	SC			RTG				RMG			
					5 +1		6+1		11+2		12+2	
		1 over 2	1 over 3	1 over 4	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5
		H_{Trans}=2.25 H_{Export}=2.25 H_{Import}=2.00 $H_{G\&R}$=2.25 H_{Empty}=2.25	H_{Trans}=3.00 H_{Export}=3.00 H_{Import}=2.60 $H_{G\&R}$=3.00 H_{Empty}=3.40	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10
0.4	3	817206	1082924	1353655	1239513	1496596	1283093	1549214	1349707	1629644	1374808	1659951
	5	490324	649755	812193	743708	897958	769856	929528	809824	977786	824885	995971
	7	350231	464111	580138	531220	641398	549897	663949	578446	698419	589204	711408
	10	245162	324878	406097	371854	448979	384928	464764	404912	488893	412443	497986
0.5	3	915366	1213498	1516872	1388968	1676363	1437802	1735301	1512448	1825392	1540575	1859340
	5	549220	728099	910123	833381	1005818	862681	1041181	907469	1095236	924345	1115604
	7	392300	520071	650088	595272	718442	616201	743701	648192	782311	660247	796860
	10	274610	364050	455062	416691	502909	431341	520591	453735	547618	462173	557802
0.6	3	1040328	1379876	1724845	1579404	1905212	1634934	1972196	1719814	2074586	1751798	2113168
	5	624197	827926	1034907	947643	1143128	980960	1183318	1031889	1244752	1051079	1267901
	7	445855	591376	739220	676888	816520	700686	845227	737063	889109	750771	905644
	10	312099	413963	517454	473822	571564	490480	591659	515945	622376	525540	633951

Table 5.11 C_Y for systems with W_{CY} = 600 metres and D_{CY} = 500 metres

Average transshipment ratio	Average dwell days (T_{dwell})	SC			RTG				RMG			
					5 +1		6+1		11+2		12+2	
		1 over 2	1 over 3	1 over 4	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5
		H_{Trans}=2.25 H_{Export}=2.25 H_{Import}=2.00 $H_{G\&R}$=2.25 H_{Empty}=2.25	H_{Trans}=3.00 H_{Export}=3.00 H_{Import}=2.60 $H_{G\&R}$=3.00 H_{Empty}=3.40	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10
0.4	3	1899521	2517159	3146449	2957544	3570956	3061929	3696992	2507581	3027668	2594778	3132950
	5	1139712	1510296	1887870	1774527	2142574	1837158	2218195	1504548	1816601	1556867	1879770
	7	814080	1078783	1348478	1267519	1530410	1312255	1584425	1074677	1297572	1112048	1342693
	10	569856	755148	943935	887263	1071287	918579	1109098	752274	908300	778433	939885
0.5	3	2127686	2820666	3525832	3314150	3999891	3431122	4141065	2809932	3391344	2907643	3509272
	5	1276612	1692400	2115499	1988490	2399934	2058673	2484639	1685959	2034806	1744586	2105563
	7	911866	1208857	1511071	1420350	1714239	1470481	1774742	1204257	1453433	1246133	1503974
	10	638306	846200	1057750	994245	1199967	1029337	1242320	842980	1017403	872293	1052782
0.6	3	2418148	3207398	4009247	3768542	4545937	3901551	4706384	3195193	3854314	3306301	3988342
	5	1450889	1924439	2405548	2261125	2727562	2340931	2823830	1917116	2312588	1983780	2393005
	7	1036349	1374599	1718249	1615090	1948259	1672093	2017022	1369368	1651849	1416986	1709289
	10	725444	962219	1202774	1130563	1363781	1170465	1411915	958558	1156294	991890	1196503

5.5 Findings

This study has considered different determining factors to formulate the total GSs and the annual throughput of container terminals using the new generation of SC, RTG and RMG crane systems. It has discussed that container terminals should be designed according to the physical specification and capability of an operating system to be used in a terminal. It is has been found that the average dwell-times, transhipment ratio, stacking height of containers together with under span of the cranes which are effected by automation play a determining role on the number of GSs of a terminal. It has been found that as the dwell-times of the containers increase, the annual throughput of the terminal decrease sharply. However, it has been found that as the transhipment ratio of the terminal increases, the annual throughput of the terminal increases.

The study has demonstrated that in single-berth terminals and where the stacking height is limited to about four tiers the SC system produces higher GSs and therefore a higher annual throughput than the RMG and RTG systems having the same conditions, transhipment ratio and dwell-times (see Appendix 3). The analysis confirms that the RMG systems become more space efficient than the RTG and SC systems as the size of the container terminals increases. The analysis reveals that the size of container terminals, number and size of passageways, and the number and size of traffic lanes are the determining factors for the annual throughput of a container terminal. Tables 5.7, 5.8 and 5.9 demonstrate that as the width and depth of container terminals increase, a better land utilisation may be achieved from systems using cranes with larger spans, such as the RMGs and RTGs. It has also been found that in single-berth terminals, the annual throughput of a SC system capable of stacking 1 over 4 and higher overrides the RMG and RTG systems, but gradually this advantage decreases as the size of the terminal increases.

In the analysis it is evident that the maximum annual throughput may be obtained for a terminal employing a 12+2 RMG when the cranes are capable of stacking 1 over 5 (or more) containers than other systems. However, if a SC is capable of stacking the same height as RMG and RTG systems, then under the same conditions (dwell-times and transhipment ratio) such a system may provide even a higher number of GSs and therefore a higher annual throughput than RTG and RMG systems. The analysis has indicated that as the average dwell-times of the containers increase, the total annual throughput of the terminal decreases sharply. It has been found that when the type of container yard operating system changes, then annual throughput of a terminal increases by about 75%. The analysis also indicated that for a specific category of transhipment ratio and average dwell-days, the total annual throughput for a SC system can vary from 10% to 15% when compared with an RMG or an RTG system with the same stacking height. However, for different transhipment ratios but with the same dwell-times, the capacity does not change considerably.

A higher throughput of an RMG system over RTG and SC systems implies the desirable land saving and space efficient nature of such a system.

5.6 Conclusions and recommendations

The generic formulas derived in this study have calculated the maximum annual throughput for container terminals with different layouts and different operating systems. This study is a step forward in capacity planning since it has incorporated the average stacking height based on the size and capability, average dwell-times, transhipment ratio and under portal span of automated and semi-automated systems to calculate the annual throughput for the proposed terminals. The analysis has revealed that as the size of container terminal increases, the total number of GSs improves significantly for RMG and RTG systems. The analysis demonstrates that SC systems provide better land utilization, GSs and terminal throughput in small size container terminals. The total annual throughput reduces in order of the SC, RMG and RTG for single-berth and RMG, RTG and SC handling systems in the double-berth and larger size container terminals. The analysis has implied that as the size of the terminals increases beyond the dimensions stated in this study, the SC systems may produce the least annual throughput. This happens due to the limited vertical stacking capability of SC systems. The annual throughput can vary considerably because of different average dwell-times for specific cranes. Because of the large differences in the annual throughputs, a careful decision should be made when selecting a handling system for a container terminal since qualitative attributes and the costs involved are other determining attributes to be considered. In the design procedure and the selection of a suitable operating system for a terminal, it is crucial to adopt a crane system that satisfies the required terminal capacity.

The resulting annual throughputs from the proposed models are considered to be useful and helpful for the decision-makers to determine the most suitable operating system for their terminal at the planning stage. Although only the results with container yard widths of 300, 320, 350, 600 and 700 and container yard depths of 300, 400, 500 and 600 metres, dwell-times of 3, 5, 7 and 10 days, transhipment ratios of 0.4, 0.5 and 0.6 and stacking height of up to 1 over 6 containers are analysed in this study, one can easily interpolate to calculate the annual handling capacity for any combinations using the equations and procedures proposed in this study. This study has achieved the 4th objective presented in Chapter 1. Costs associated with container yard operations are considered as productivity factors for terminal operators. A further study is required to identify most important cost attributes and develop a cost-based model for the layout and throughput model of this chapter for final decision-making. The above issues would be discussed in Chapter 6.

Chapter 6

Cost Function Modelling for Semi-automated SC, RTG and Automated and Semi-automated RMG Operating Systems

Summary

This chapter analyses the concept of cost functions for container yard operating systems that were proposed in Chapter 5. It develops a generic cost-based model for pair-wise comparisons, analysis and evaluation of economic efficiency and effectiveness of yard equipment to be used for decision-making by terminal planners and designers. The cost function analysis of this study incorporates major cost attributes used in modern container terminal operations and discussed in the literature. They are considered to play a determining role over the total cost of advanced operating systems in a container terminal. The cost model in this study enables the planner and designer of container terminals to make a pair-wise comparison of handling systems to help determine the most appropriate container yard operating system for a port, based on the required technological capabilities and functions. The sensitivity analysis proposed in this study compares and demonstrates the magnitude and intensity of the selected attributes which determine preference of one system over another. The analysis assists a terminal planner in decision-making and selecting a container yard operating system with a minimum operating cost and a maximum annual throughput. The cost values are obtained from the Iranian port authorities to be used in the test cases of this thesis.

6.1 Introduction

The operation of advanced technologies including automated and semi-automated equipment in container terminals has reduced the costly time of transferring, stacking and un-stacking of containers in marshalling yards. The adoption of automated devices has increased the efficiency of the shipside, quayside, yard, gate and transfer operations. This in turn has reduced the loading and discharging time, dwell-time, cycle-time of container and transfer vehicle movements and consequently the total turnaround-time of containerships in ports. A variety of advanced systems such as semi-automated Straddle Carriers (SCs) capable of transferring and stacking containers to a height of 1 over 3 or more, Automated Guided Vehicles (AGVs) and shuttles capable of automatically transferring containers without human intervention have been involved in the operation of container terminals during the last two decades. At the stack-yard, semi-automated Rubber Tyred Gantry cranes (RTGs) and fully automated Rail Mounted Gantry cranes (RMGs) have been deployed for operation in today's modern container terminals.

Chapter 5 evaluated container terminals layouts and proposed throughput capacity models for semi-automated SC, RTG and RMG systems. This chapter identifies cost factors associated with the yard operation of the operating systems proposed and introduced in Chapter 5 and provides a method of measuring the cost effectiveness of the systems involved. Factors that determine the adoption and investment in any container yard operating system are the availability of land, initial cost of investment in any operating system, capacity of transfer and stack-yard operating system and the operational costs. The cost of transfer, the stacking capacity and the operation costs are directly dependent on the availability of the land and the type of equipment to be employed. In some container terminals particularly in the Asian ports, due to the difficulties in expanding the availability and the high cost of land, there has been an attempt to stack containers higher in order to increase the capacity of container terminals (Watanabe, 2001). RTG and RMG cranes have been the best candidates for new terminal developments owing to their high stacking capabilities. In some other terminals where there is always a piece of land available for expansion of the stack-yard, SC systems are more popular (Chen, 1998 and 1999 and Agerschou, 2004). Examples of these terminals are the Southampton Container Terminals and the Europe Combined container Terminals (ECT) in Rotterdam that have preferred to utilise the flexibility of SC systems even though their annual throughputs could be increased by employment of other systems. Some hub centres such as Medecentre Tauro in Italy and Hutchinson Freeport in Bahamas with a high capacity which are considered as the container terminals with a high transhipment ratio have successfully employed SC as their main transfer and stacking system (Avery, 1999). The SC system is preferred over other systems in many container terminals due to its versatility and relatively low purchasing cost per unit of equipment, smaller marshalling yard development and operation costs. However, there are some drawbacks with SC operating systems. The SC systems utilise less space in terms of m^2 / TEU in large terminals, lower stacking ability, require more area for receipt and delivery operations, require higher maintenance and greater down-times, not environmental friendly (Containerisation International, 1996) and are less suitable for automation. On the other hand, yard gantry cranes such as RTG and RMG cranes are more space efficient, more accurate and faster in operation and are more suitable for development and instalment of automated technologies (Watanabe, 2001). The yard gantry cranes however require a higher development and land preparation costs than SC systems due to their high wheel load and body weight. RTGs are more flexible and more economic to purchase and install, but more expensive to operate than RMGs (Containerisation International, 1996).

6.2 Analysis of cost parameters and variables

The productivity and efficiency of a container terminal is dependent on not only the effective automated and semi-automated container yard operating systems, but also on employing an efficient cost model. The basic parameters and variables that play a determining role in a cost function model for container terminal operating under the operating systems studied in Chapter 5 needs to be identified and analysed. Data for different cost parameters of this study have collectively been obtained from different sources such as the Bandar Abbas Container Terminals (BACT), Bandar Imam Container Terminals (BICT) and Chabahar Container Terminals (CCT), Containerisation International (1990-2005), World Port Development International (1990-2006), United Nations Conferences on Trade and Development (UNCTAD) (1990-2005), Bahrani (2004) and Watanabe (2001) and from different container terminals and equipment manufacturers. The average values of costs will be reflected in the appropriate tables in this study. The cost parameters and their individual variables are related to the direct cost of capital investment and indirect costs such as maintenance, repair and manning costs. Other cost concepts such as container yard management costs, cost associated with administration, management and processing of containers, internal yard equipment and external trucks that may be attributed to revenue are beyond the scope of this study. The parameters and variables may be categorised and defined into three groups as follows:

6.2.1 Container yard development and maintenance costs

For different ports situated in different geographical and political locations, there are different factors that may affect the volume of investment and consequently the development and maintenance of a purchased or leased land. These factors may range from subsidies, loans and borrowings to the physical features of a container terminal site such as costs involved in civil engineering, hydrography, topography, meteorological and oceanography influences, coastal hydraulics and environmental issues (UNCTAD, 1985). However, factors and issues such as those mentioned above are considered beyond the scope of this study. In this study, four major factors related to the land investment, development, maintenance and depreciations are considered. For almost all of the Iranian ports such as the BACT, BICT and CCT, the land within the port area has been retained as the property of government. Therefore, the initial cost of investment in land in the examples of the Iranian ports may differ significantly from European countries and many Asian countries such as Japan, Singapore and Hong Kong. This study includes the following factors in the proposed cost model:

- **Cost of investment in land**

The Port and Shipping Organisation of Iran (PSO) have leased out some part of the land in its port environment to private sectors operating the terminals. The values are approximate and are contracted for about 40 to 50 years. These values are stated in Table 6.1.

Table 6.1 Average annual cost of investment in land

- **Container yard development cost**

The cost of container yard development may vary from terminal to terminal due to the variations in the site construction and conditions. One may devote a considerable budget for preparation of the container yard surface, turning areas, road and passageway accesses, ducting and cable laying preparations, drainage, light stands, *etc.* It should be noted that the surface of the yard and its receipt and delivery areas, turning areas and the junctions of the road and passageways must be prepared to withstand loads of about 80-120 tonnes (Nahavandi, 1996). The terminal operator in BACT has considered a cost of £20 to £23 / m^2 in land preparation in 2004 for a SC operating system. In mid-2003 in BICT, an average of £52 / m^2 was spent on the preparation of stacking areas for the new modern 12+2 RMG system (Zahiri, 2005). This study considers a cost of £23 to £52 / m^2 which is used for the preparation of the container yard for CCT.

- **Container yard development depreciation cost**

The facilities used in the development of a container yard stated in the previous section will wear out over time. This may require the operator of container terminals to consider an annual depreciation cost for development of facilities in their calculations. This study uses the depreciation method recommended by UNCTAD and proposed by Constantinides (1990). Generally, the annual depreciation of a system is obtained by subtracting the salvage value of the equipment from the initial cost of investment and dividing the results by the expected project life of the system. In this study, a salvage value proportional to about 20% of the initial cost of investment in the container yard development is considered.

- **Container yard maintenance cost**

The annual maintenance cost of a container yard is usually taken as a percentage of its initial cost of investment in one square meter of land multiplied by total land area. UNCTAD (1985) has suggested a fraction of 0.1% to 0.5% of capital cost of container yard investment for a concrete yard, apron, roads, and asphalt surfaces. In BACT an extra fraction of 0.05% has been included for auxiliary facilities, lighting, ducts, pipes and cables, markings, drainage, insurance *etc.*, (Bahrani, 2004). In this study, a fraction of 0.15% of the initial cost of investment is considered for the analysis.

It should be noted that in calculating the maintenance costs of a system, one should consider the wear and tear of the assets (particularly equipment) which would increase over time. As the economic life of a container yard and equipment increases the annual maintenance cost increases at an exponential rate (Guthrie and Lemon, 2004). This implies that the annual maintenance cost of a system is minimum in year one and would be maximum at the end of its project life. For the purpose of this study, the Future Worth Factor (FWF) method recommended by

UNCTAD (Constantinides, 1990), Nahavandi (1996), UNCTAD (2002) and Guthrie and Lemon (2004) will be used for calculation of the annual maintenance costs for container yard development and yard cranes.

6.2.2 Crane investment, manning and maintenance costs

The costs and attributed factors related to the investment, operation and maintenance of a container yard operating system might be categorised as follows:

- **Crane procurement cost**

The purchasing price of container yard operating systems depends on factors such as:

i) Order time.

ii) Order size.

iii) Place and location of manufacturer from the purchaser.

iv) Equipment specification (type, capacity, size, degree of automation, safety features, crane lateral speed, number, type and speed of trolley and hoist, *etc.*).

v) Variations in market prices.

Table 6.2 provides purchase prices for some of the modern SC, RTG and RMG yard operating systems used in today's container terminals. The average prices for a total number of 76 SCs, 43 RTGs and 36 RMGs from different sources have been included in this study. The values include the cost of about 150 meters of rails and corresponding fittings per unit of equipment.

Table 6.2 Average procurement cost of yard operating systems, £ / equipment

Year	SC			RTG				RMG			
				5 +1		6+1		11+2		12+2	
	1 over 2	1 over 3	1 over 4	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5
1990-1994	175,300	190,550	-	217,250	228,570	230,350	247,500	522,320	566,320	587,140	604,450
1995-1999	191,750	212,310	-	321,200	330,240	385,870	407,760	612,550	633,540	609,240	614,250
2000-2004	232,450	260,870	290,780	394,200	419,150	440,400	471,550	640,100	667,140	610,320	623,200

(Source: Compiled by author based on information obtained from manufacturers together with UNCTAD and Containerisation International annual publications)

- **Annual cost of capital investment in cranes**

The cost of capital investment in any container yard operating system may depend on the number, procurement cost, average economic life of cranes and the average interest rate expected during such a period.

- **Economic life of cranes (t)**

The theoretical economic life of yard equipment is usually given by the manufacturer as the number of full cycles, movements and / or travels performed by the equipment. In practice, these values may differ from terminal to terminal under different operational and climatic conditions. The actual economic life of the equipment may, however, depend on the extent of utilisation, maintenance efficiency, skill of operators and the magnitude of hazards affecting the equipment. UNCTAD, (1990), Containerisation International, (1996) and some terminal operators have proposed different values of economic life. The average economic life of container yard operating systems has been compiled from different sources and tabulated in Table 6.3. The practical economic life of equipment for BACT may be considered shorter than the theoretical values recommended by UNCTAD. This is due to the fact that most Iranian ports are located in a tropical climate and are more vulnerable to corrosion, wear and tear.

Table 6.3 Average economic life of QSCs, SC, RTG and RMG cranes in years

Recommending Body	QSCs	SC	RTG	RMG
UNCTAD	10-12	6-10	15-18	-
Containerisation International	10-14	15-20	15-20	20-22
Manufacturers	12-15	10-16	12-16	18-22
Port Operators	12-15	10-15	12-15	15-20

(Source: Compiled by author)

- **Crane depreciation cost**

The depreciation of yard cranes may be considered as a process by which a container terminal gradually loses the fixed value of its investment in the equipment. The purpose of including crane depreciation cost is to spread the initial purchase price of the equipment over its useful life. It may be defined as the difference between the initial cost of investment and the salvage value of the equipment expressed as present values divided by its economic life. UNCTAD (1985) and Constantinides (1990) have proposed a fraction of about 20% of the initial cost of investment as a salvage value for SC, RTG and RMG systems after their economic lives are over. In this study, the fraction recommended by UNCTAD will be considered for yard cranes.

- **Crane maintenance costs**

The maintenance cost of SC, RTG and RMG systems is considered in this study. The maintenance cost varies from equipment to equipment depending on the mobility, speed, type of fuel, number of moves *etc.* The annual maintenance cost of yard cranes is normally taken as a percentage of the initial cost of investment over the economic life of the cranes. UNCTAD (1985) and Constantinides (1990) have proposed 1.0% to 1.2% and 1.8% of capital cost of investment for a SC system respectively. Their proposed percentage includes the cost of fuel, consumables such as lubricating oil, tyres, spare parts, *etc.* Watanabe (1995) has proposed 1.5% of initial investment and has included cost of fuel and spare parts too. One may consider about 0.2% extra for a SC operating under a direct system where, a direct system would require SCs to travel on longer routes than those operating under a relay system thus requiring higher maintenance. In a relay system cost associated with the extra number of vehicles fulfilling the transfer operation is required to be included. UNCTAD (1985) and Constantinides (1990) have suggested that about 1.0% of the initial cost of investment to be considered for RTG and RMG systems. In BACT, the maintenance cost of a SC system is about 0.8% whereas, in BICT the value for electrical power driven RMGs is between 0.3% to 0.4% and diesel RMGs is between 0.5% to 0.6% of the initial cost of investment (Bahrani, 2004). Wear and tear of the road and passageways for RTGs particularly at the junctions and turning areas may be more than that of a SC system therefore, it may be reasonable to consider a higher percentage for the cost of maintenance for an RTG system. Some terminals using RTG systems have used robust steel plates at the junctions and turning areas that may reduce the cost of tear and wear of the surface (Watanabe, 2001). This study uses the method proposed by UNCTAD (Constantinides, 1990) and Nahavandi (1996) for calculation of the equipment annual maintenance cost.

- **Inter-yard operation cost of cranes**

An attribute that may be used as a performance indicator between different systems is the average Cost Per Container (CPC) movement in a terminal. This value would be dependent on the annual throughput of a terminal. The annual capacity for container terminals with different sizes operating under SC, RTG and RMG systems with different container dwell-times, transhipment ratio and stacking height has been calculated and tabulated in Chapter 5, Section 5.3.2 and Table 5.9. These values are used in this study. The average value for a direct SC system in BACT is about £0.4 / move. The value for the electrically driven RMGs in BICT is about £0.2 / move and £0.3 / move for the diesel driven equipment (Bahrani, 2004). Conservatively, one may consider about £0.6 / move for an RTG system.

- **Crane manning cost and coordinating container yard foreman cost**

The minimum manpower required for each of the advanced SC, RTG and RMG cranes is about 3 operators per day that is one for every shift / day. In addition to the crane drivers, a coordinating foreman on each shift would be required to supervise the interactive and interdependent operation of the yard cranes, transfer vehicles (SC, AGVs, internal trucks, *etc.*) with the Quayside Cranes (QSCs). The manpower cost for other personnel who are not involved in the crane operation is left outside the scope of this study. The approximate salary of a competent crane driver and a container yard foreman including insurance, training, bonuses, incentives, *etc.* is about £13,440 / year (£1,120 / month) to £16,500 / year (£1,375 / month) (Bahrani, 2004).

6.2.3 Container transfer cost

The average annual cost of container transfer to and from the quayside to the stack-yard may be expressed as an average cost of handling operation fulfilled by AGVs in RMG or RTG systems, SCs in a SC direct system, internal trucks or Tractor-Trailers (T-Ts) in the SC relay system or other means of transferring and marshalling containers between the quayside and the stacking area. The calculated average cost may include the cost of fuel, maintenance, insurance, *etc.* In both BACT and BICT, the transfer operation has been contracted out to the private sector. A fixed cost has been agreed to be paid to the private operator according to the number of containers handled. A total amount of about £0.10, £0.20 and £0.25

/ container / move may be considered for SC, RTG and RMG systems respectively (Bahrani, 2004).

This study provides a cost model for the design model that was discussed in the previous study in Chapter 4 and compares the cost of the three operating systems based on the parameters and variables identified and analysed.

6.3 Cost function modelling

One of the most difficult decisions at the planning stage of the container terminals is to make a decision on the most suitable yard operating system for a terminal. Decisions should be made strategically for a long-term run of terminals. It is also difficult to indicate as to where and to what point in the time the terminal is going to stand in the future. Is the terminal going to develop the present Origin-Destination (O-D) stage into a Hub-Port (HP) status at some time in the future? Is it likely that land becomes less expensive and more available for future expansion of the terminal? What would be the cost of the development of a specific operating system in the terminal? There would be many questions that should be clearly answered before the final decision is made.

There are other cost related attributes, some of which are qualitatively expressed, that play a determining role and affect on the layout, design and final selection decision of yard equipment in a terminal. They can be categorised as follows:

- Land size, shape and condition.
- Calculated annual throughput.
- Under portal span and vertical lifting capacity of the yard equipment.
- Type, number and level of technology of yard equipment.
- Ease of maintenance and repair.
- Strength of the yard construction.
- Economic life of the equipment.
- Environmental and social considerations.

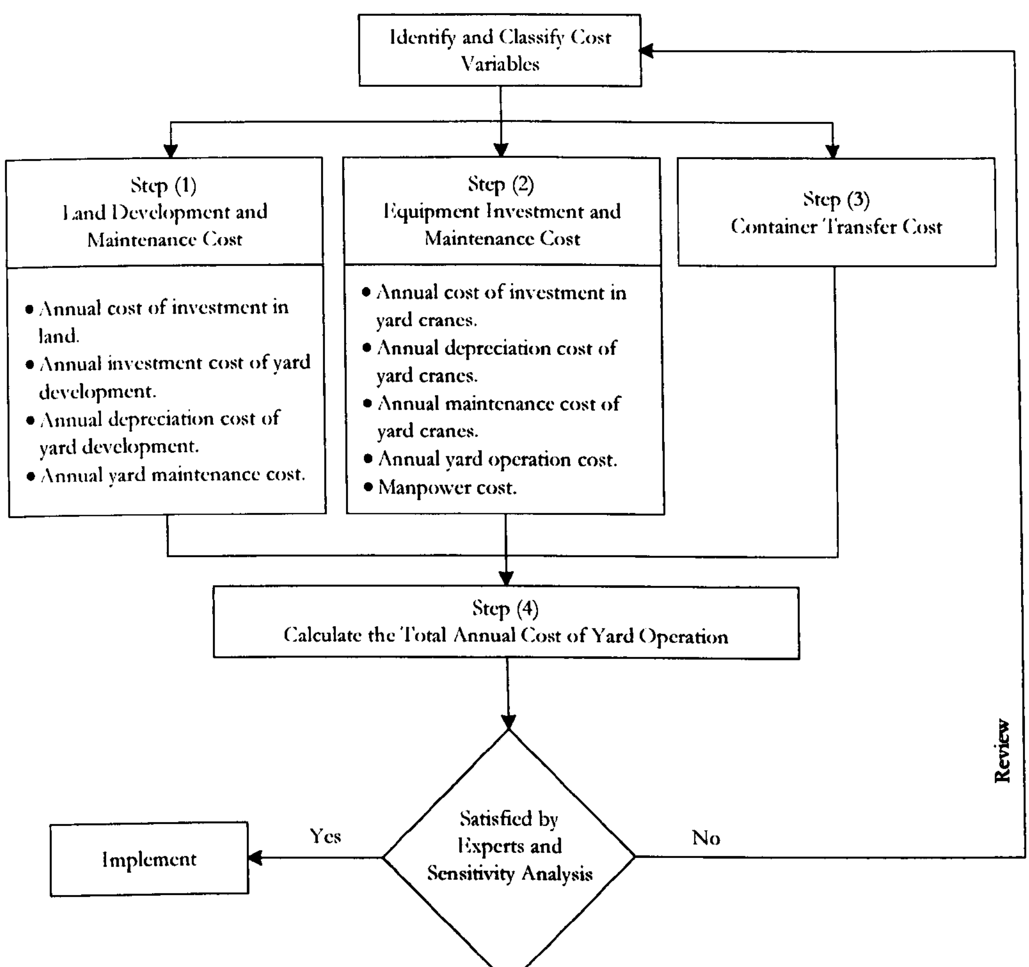
This study only considers SC, RTG and RMG systems. The cost model developed in this study comprises the following elements:

1) Land cost and container yard development and maintenance cost.

2) Cost of equipment, maintenance and manning for a specific container yard operating system.

3) Transfer cost.

There will be more cost elements such as administration costs, cost of inflation, possible rise in the price of land, fuel consumption, and spare parts *etc.*, which are out of the scope of this study. It should be noted that different container yard operating systems require different facility, preparation, installation and training costs *etc.* These may affect the total annual cost of the system. A trade-off can be made between the cost of land, equipment and operation costs for the container yard system to be employed. This study develops a cost-based methodology with the steps indicated in Figure 6.1 and the process as follows:



(Source: Author)

Figure 6.1 Cost function process

Step 1: Land development and maintenance costs

Steiner (1992), Thuesen and Fabrycky (1993), UNCTAD (2002) and Guthrie and Lemon (2004) have proposed applying a Capital Recovery Factor (CRF) to calculate the annual cost of investment for `t` years of a project life (see Appendix 4). The cost of land for a container yard operating under a specific operating system can be defined in the following process:

- **Annual cost of capital investment in land**

$$LC = CL \times AT \times CRF \qquad 6.1$$

where:

LC = Annual cost of investment in land in £ / year.

CL = Average cost of one square metre of land in £ / m^2.

AT = Total area of container terminal for a specific container yard operating system (including stack-yard + gate, CFS, workshop area, rail and transhipment buffers + Interchange area, if appropriate, roadways, *etc.*) in m^2.

CRF = Capital recovery factor which converts the initial investment into an equivalent average annual cost of equal series calculated as follows:

$$CRF = \frac{i \times (1+i)^t}{(1+i)^t - 1} \qquad 6.2$$

t = Economic life of the terminal in years.

i = Average annual interest rate.

- **Annual container yard development cost**

$$YDC = CD \times AT \times CRF \qquad 6.3$$

where:

YDC = Annual container yard development cost in £ / year.

CD = Development cost of one square metre of land for a specific container yard operating system in £ / m^2.

- **Annual depreciation cost of container yard development**

$$Y_{dep}C = \frac{(CD \times AT) - S_{yard}}{t} \qquad 6.4$$

where:

$Y_{dep}C$ = Annual depreciation cost of container yard development in £ / year.

S_{yard} = Salvage value of facilities in £.

- **Annual container yard maintenance cost**

This study uses the FWF method recommended by UNCTAD (Constantinides, 1990) and UNCTAD (2002) (see Appendix 4) as follows:

$$YMC = CYM \times FWF \qquad 6.5$$

where:

YMC = Annual cost of container yard maintenance in £ / year.

CYM = Average annual maintenance cost of a specific container yard operating system in £.

$FWF = (1+i)^{t-1}$

where:

t = Economic life of the terminal in years.

i = Average annual interest rate.

Step 2: Crane investment, manning and maintenance costs

This study assumes that only one type of operating system such as SC, RTG or RMG would be operating in the terminal. Although a combination of the above systems with other modes of operation is possible, the analysis of their effect is not considered in this study. The costs involved in any specific operating system may be defined in the following process:

- **Annual cost of investment in yard cranes**

$$IC = PC \times NC \times CRF \qquad 6.6$$

where:

IC = Annual cost of capital investment in container yard operating system in £ / year.

PC = Procurement cost of a yard crane in £.

NC = Average number of RMGs, RTGs or SCs defined in Chapter 3, Section 3.4.

- **Annual depreciation cost of yard cranes**

$$DC = \frac{PC - S_{crane}}{t} \qquad 6.7$$

where:

DC = Annual depreciation cost of yard cranes in £ / year.

S_{crane} = Salvage value of a specific container yard operating system.

t = Average economic life of the cranes in years.

- **Annual maintenance cost of yard cranes**

The cost of maintenance may include the cost to cover spare parts, repairs and fuel (energy), *etc.* It should be noted that as the economic life of the yard cranes increases, the cost of maintenance increases. This study uses the recommended method proposed by UNCTAD (Constantinides, 1990), Nahavandi (1996) and UNCTAD (2002). This can be formulated as:

$$MCC = PC \times FWF \qquad 6.8$$

where:

MCC = Annual maintenance cost of a container yard operating system in £ / year.

$FWF = (1+i)^{t-1}$

where:

t = Average economic life of the cranes in years.

i = Average annual interest rate.

- **In-yard operation cost**

$$OC = HC_{TEU} \times C_Y \times CRF \quad 6.9$$

where:

OC = Annual cost of in-yard-handling operation of containers in £ / year.

HC_{TEU} = Cost of handling of one container in £ / container (an average cost for one TEU and / or 2 x TEU may be taken).

C_Y = Annual throughput of a terminal in TEUs (calculated in Chapter 5, Section 5.3.2, e.g., Table, 5.9).

- **Manning cost**

Two types of workers are normally involved in the daily operation of a container yard. They are the yard gantry drivers and foremen who coordinate the operation of container transfer from the quayside to container stack-yard and *vice versa*. Where the container yard operation is fully automated, then there would not be such a work force. Instead, a few automation technicians would be available at all times to support yard cranes. The average salary of technicians is expected to be high in today's container terminals. The cost of the work force therefore can be defined as:

i) Crane operators cost

$$LC_{driver} = NL_{shift}^{driver} \times N_{shift} \times AS_{CD} \quad 6.10$$

where:

LC_{driver} = Annual cost of work force for all cranes (including stack-yards, gate, rail and transhipment buffers, empty and refer stacks, *etc.*) in £ / year.

NL_{shift}^{driver} = Number of crane divers in each shift.

N_{shift} = Number of shifts in 24 hours.

AS_{CD} = Average annual salary of a crane driver including taxes, insurance, incentives, *etc.* in £ / year / person.

ii) Coordinating foremen cost

$$LC_{YFM} = NYF_{day} \times N_{shift} \times AS_{YF} \quad 6.11$$

where:

LC_{YFM} = Annual cost of all container yard foremen in £ / year.

NYF_{day} = Number of container yard foremen for the coordination of the QSCs and yard cranes in each day.

AS_{YF} = Average annual salary of a container yard foreman including taxes and all other benefits in £ / year / person.

Step 3: Container transfer cost

Depending on the type of a container yard system employed in a terminal, the transfer of containers between the quayside and the container yard, and *vice versa*, may be carried out by a SCs, T-Ts, AGVs, *etc.* The cost of container transfer by SC relay system and other modes of transfer such as AGV, lift trucks, T-Ts *etc.*, may be higher than a SC direct system. The total cost of container transfer excluding the costs of transfer equipment such as maintenance, depreciation and cost of investment can be defined as:

$$C_{transfer} = C_{TEU} \times C_Y \times N_{moves} \quad 6.12$$

where:

$C_{transfer}$ = Annual cost of container transfer operation in £ / year.

C_{TEU} = Average cost of handling one container in £ / container.

C_Y = Annual throughput of the corresponding container terminal in TEUs.

N_{moves} = Average number of moves per container performed by a specific transfer vehicle within the terminal (at least 2 moves are usually considered for import and export jobs).

Step 4: Total container yard operation cost

The Total Cost (TC) of a container yard operating system will be the summation of all costs involved in Steps 1 to 3. The equation can therefore be defined as follows:

$$TC = LC+YDC+Y_{dep}C+YMC+IC+DC+MCC+OC+LC_{driver}+LC_{YFM}+C_{transfer} \quad 6.13$$

This study introduces the concept of a 'cost comparison indicator' that will help a port designer to measure the percentage of cost effectiveness of one container yard operating system over another.

6.4 Sensitivity analysis

To help the terminal operator in making decisions, this study introduces the concept of a cost comparison process for the sensitivity analysis. The 'cost comparison indicator' analyses the cost effectiveness of one-yard operating system over another in terms of investment, maintenance, operation, depreciation, *etc.* The 'Variable Intensity Factor' (VIF) method analyses the cost effectiveness of the selected parameters by demonstrating the magnitudes of the parameters with each other.

6.4.1 Cost comparison indicator

The selection of a cost effective operating system may be done by comparison of similar cost parameters, for example, the annual costs obtained for each container yard operating system (TCY) in Step 4. Where the annual cost of a system is considered as a criterion, a semi-automated SC operating system may be preferred over a semi-automated RTG or an automated RMG system from a cost effective standpoint when $TCY_{SC}<TCY_{RTG}$ and $TCY_{SC}<TCY_{RMG}$. A semi-automated RTG system may be preferred over a SC or an automated RMG system when $TCY_{RTG}<TCY_{SC}$ and $TCY_{RTG}<TCY_{RMG}$. This study denotes variables 'j', 'k' and 'm' to represent semi-automated SC, semi-automated RTG and automated RMG systems respectively. Therefore, the cost comparison indicator to compare the cost effectiveness of a SC over an RTG and RMG and on RMG over an RTG system may be defined as follows:

$$R_{j/k} = \frac{TCY_j}{TCY_k} \quad 6.14$$

$$R_{j/m} = \frac{TCY_j}{TCY_m}$$ 6.15

$$R_{m/k} = \frac{TCY_m}{TCY_k}$$ 6.16

Other combinations are possible. In this process and under the lowest-cost-preference policy, for example, if $R_{j/k} < 1$ the 'j' container yard operating system is preferred over 'k' system. There would be of course no preference of a system over another if $R_{k/j} = 1$. Therefore, a sensitivity analysis would be required to indicate each case comparison by indicating the value of $R_{j/k} = 1$ as a benchmark to help better indicate such a relation.

6.4.2 Variable Intensity Factor (VIF)

The variables and parameters identified in the development of the cost model may vary significantly from each other, from port to port and from time to time. Therefore, a further sensitivity analysis is required to represent the magnitude of a preference of a container yard operating system over another by taking the individual cost parameter in the analysis. A terminal designer and or a port operator may vary the value of any of the cost parameters and keep others unchanged to observe the impact of cost changes under the new condition. The operator may consider one or more particular cost parameters as the important and / or governing cost factors to be analysed. For example, a terminal planner may be interested in purchasing a SC rather than a semi-automated RTG system or switching from a SC to a semi-automated RTG system. Therefore, the operator can calculate the magnitude of his / her preference of SC over RTG using specific cost parameters, cost intensity factor (R) and Variable Intensity Factor (VIF). Hee and Wijbrands (1988) have defined the VIF as:

$$VIF_{j/k} = \frac{CP_j \times R_{j/k}}{CP_k - CP_j}$$ 6.17

where:

$VIF_{j/k}$ = Variable intensity factor of 'j' operating system over 'k'

$R_{j/k}$ = Comparison indicator of 'j' operating system over 'k'.

CP_k = Value of cost parameter 'k'.

CP_j = Value of cost parameter 'j'.

$CP_k \neq CP_j$

The value of 'VIF' will indicate the relative degree of preference of one system over another. The higher the positive value becomes the higher the desire to employ a system will be. When the value of 'VIF' of a system, for example 'j' system over 'k' system, becomes negative, that is to say $VIF_{j/k} < 0$, it may indicate that 'j' system is no longer desirable over 'k' system. This undesirability of course will be based on the specific cost component considered in the analysis. Depending on the magnitude and the sign of the value (being of a positive or a negative value) calculated for different combinations of cost factors, it may be argued that 'j' system may or may not be considered preferable over 'k' system. When the value of $VIF_{j/k}$ becomes negative, it is valid to assume that the 'k' system possesses more preferability over 'j'. In this case the value of $VIF_{k/j}$ may not be equal to the $VIF_{j/k}$ value even with a different sign and polarity. This means that the exact value of $VIF_{k/j}$ requires to be calculated in the same way. It should be noted that when the values of CP_k and CP_j are close to each other, then the VIF result produced may be very high and therefore unreliable. To avoid uncertainties in calculating the value of VIF, it would be better to select cost factors with unequal values and preferably with a high difference between the values of the pairs.

6.5 Test case

The Port and Shipping Organisation of Iran that owns most of the active ports in Iran is transforming the former Kalantary Port in Chabahar into a modern automated container terminal to facilitate the transfer of containers through land modes of transport to Europe *via* Turkey at a lower cost than sea transport from the Suez Canal. The data from the CCT and BACT are used for evaluation of test cases since they represent a typical terminal of the Persian Gulf and many others in the region. The example container yard is considered to accommodate one post-Panamax containership. This study uses the cost model and different variables developed to evaluate the viability of the proposed model. The majority of cost values are from Iranian and other ports in the Persian Gulf region obtained from the BACT and the port operators (Bahrani, 2004) and are converted to Pound Sterling equivalent for the purpose of this study. The following assumptions are made:

a) Size of the container yard is assumed 350m x 400m (14 hectares) similar to the BACT.

b) Average interest rate of about 8% to be considered.

c) An estimated cost of £38 / m^2 for a long-time rent (usually 50 years for Iranian ports and renewable) for land investment has been assumed.

d) Cost of development of about £23, £38 and £52 / m^2 for SC, RTG and RMG systems has been considered respectively (Section 6.2.1).

e) Container yard maintenance cost of about £7,980 [0.15% x £38 x 350m x 400m (14 hectares)] for SC, RTG and RMG systems to be considered.

f) The economic life (t) of container terminal is about 50 years.

g) Procurement cost of SC (1 over 3) = £260,870 / equipment, RTG 6+1 (1 over 5) = £471,550 / crane and RMG 12+2 (1 over 5) = £623,200 / crane.

h) Number of container yard facilities calculated in Chapter 5, Section 5.2.5 is about 63 for SC, 30 (2 RTG x 15 blocks) for RTG and 24 RMG (2 RMG x 12 blocks) for RMG systems.

i) Average economic life (t) of a SC = 15 years, RTG = 15 years and RMG = 20 years.

j) This study considers about 20% of the initial investment cost of container yard development and 10%, 20% and 30% of the initial investment cost of SC, RTG and RMG cranes as salvage values in Iran after their economic life is over.

k) An average of 1.0%, 0.8% and 0.4% of the initial procurement cost of SC, RTG and RMG would be considered for the annual maintenance cost of the cranes respectively. Therefore, the average annual maintenance cost of yard cranes would be as follows:

- SC = £260,870 x 63 x 1.0% ≈ £164,348
- RTG = £471,550 x 30 x 0.8% = £113,172

- RMG = £623,200 x 24 x 0.4% ≈ £59,827

l) In-yard operation cost of containers is assumed £0.4 / container for SC, £0.5 / container for RTG and £0.3 / container for any RMG systems (Section 6.2.2).

m) Maximum annual throughput of SC (1 over 3) = 1,379,876 TEUs / year, RTG 6+1 (1 over 5) = 1,972,196 TEUs / year and RMG 12 +2 (1 over 5) = 2,113,168 TEUs / year (Chapter 5, Section 5.3.2, Table, 5.9).

n) Average salary of a competent driver and a container yard foreman is considered about £15,000 and £17,500 / year respectively. There would be 3 shifts a day where the terminal is considered to be operating 24 hours / day and 365 days a year.

o) Number of crane drivers in each shift is assumed 40 persons for SC, 20 persons for RTG and 15 persons for RMG systems (Equation 5.12).

p) Number of container yard foremen for SC = 4, RTG = 3 and RMG = 2 persons.

q) Transfer costs of about of £0.10, £0.20 and £0.25 / container are considered for SC, RTG and RMG systems respectively. Transfer vehicles are considered to perform at least two continuous moves in each job assignment.

The calculation of the values and a summary of the parameters are illustrated in Tables 6.4 and 6.5. In addition to the cost parameters stated in this study, a Cost Per Container (CPC) parameter which indicates the cost efficiency of one system over other is also included. CPC is found by dividing the Total Cost (TC) of a particular system by the annual throughput (C_Y) of the corresponding container terminal.

Table 6.4 Average annual values of parameters of the cost model, £

	Cost Parameter	SC (1 over 3)	RTG 6+1 (1 over 5)	RMG 12 +2 (1 over 5)
Step 1	LC	$38 \times (350 \times 400) \times \frac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$	$38 \times (350 \times 400) \times \frac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$	$38 \times (350 \times 400) \times \frac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$
	YDC	$23 \times (350 \times 400) \times \frac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 263{,}212$	$38 \times (350 \times 400) \times \frac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$	$52 \times (350 \times 400) \times \frac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 595{,}088$
	$Y_{dep}C$	$\frac{23 \times (350 \times 400) - 0.2 \times 23 \times (350 \times 400)}{50} = 51{,}520$	$\frac{38 \times (350 \times 400) - 0.2 \times 23 \times (350 \times 400)}{50} = 85{,}120$	$\frac{52 \times (350 \times 400) - 0.2 \times 23 \times (350 \times 400)}{50} = 116{,}480$
Step 2	YMC	$7{,}980 \times (1+0.08)^{50-1} \approx 346{,}551$	$7{,}980 \times (1+0.08)^{50-1} \approx 346{,}551$	$7{,}980 \times (1+0.08)^{50-1} \approx 346{,}551$
	IC	$260{,}870 \times 63 \times \frac{0.08 \times (1+0.08)^{15}}{(1+0.08)^{15} - 1} = 1{,}920{,}071$	$471{,}550 \times 30 \times \frac{0.08 \times (1+0.08)^{15}}{(1+0.08)^{15} - 1} = 1{,}652{,}729$	$623{,}200 \times 24 \times \frac{0.08 \times (1+0.08)^{20}}{(1+0.08)^{20} - 1} = 1{,}523{,}383$
	DC	$\frac{63 \times (260{,}870 - 0.1 \times 260{,}870)}{15} \approx 986{,}089$	$\frac{30 \times (471{,}550 - 0.2 \times 471{,}550)}{15} = 754{,}480$	$\frac{24 \times (623{,}200 - 0.3 \times 753{,}200)}{20} = 523{,}488$
	MCC	$164{,}348 \times (1+0.08)^{14} = 482{,}722$	$113{,}172 \times (1+0.08)^{14} = 332{,}408$	$59{,}827 \times (1+0.08)^{19} \approx 258{,}195$
	OC	$0.4 \times 1{,}379{,}876 \approx 551{,}950$	$0.5 \times 1{,}972{,}196 = 986{,}098$	$0.3 \times 2{,}113{,}158 \approx 633{,}947$
	LC_{driver}	$40 \times 3 \times 15{,}000 = 1{,}800{,}000$	$20 \times 3 \times 15{,}000 = 900{,}000$	$15 \times 3 \times 15{,}000 = 775{,}000$
	LC_{YFM}	$4 \times 3 \times 17{,}500 = 210{,}000$	$3 \times 3 \times 17{,}500 = 157{,}000$	$2 \times 3 \times 17{,}500 = 105{,}000$
Step 3	$C_{transfer}$	$0.1 \times 1{,}379{,}876 \times 2 \approx 275{,}975$	$0.2 \times 1{,}972{,}196 \times 2 = 788{,}878$	$0.25 \times 2{,}113{,}158 \times 2 = 1{,}056{,}579$

Table 6.5 Summary of the cost parameters

Step	Cost Parameter	SC (1 over 3) / £	RTG 6+1 (1 over 5) / £	RMG 12 +2 (1 over 5) / £
	'CP'	'j'	'k'	'm'
Step 1	LC	434,872	434,872	434,872
	YDC	263,212	434,872	595,088
	$Y_{dep}C$	51,520	85,120	116,480
	YMC	346,551	346,551	346,551
Step 2	IC	1,920,071	1,652,729	1,523,383
	DC	986,089	754,480	523,488
	MCC	482,722	332,408	258,195
	OC	551,950	986,098	633,947
	LC_{driver}	1,800,000	900,000	675,000
	LC_{YFM}	210,000	157,500	105,000
Step 3	$C_{transfer}$	275,975	788,878	1,056,579
Step 4, TC		7,322,962	6,873,508	6,268,583
Cost Per Container (CPC)		5.3	3.5	3.0

6.5.1 Cost comparison and sensitivity analysis using 'R' values

The values of cost comparison indicator (R) for different parameters are calculated and summarised in the second, third and fourth columns in Table 6.6. The attributed cost factors indicated in the table show that from a minimum cost policy standpoint, a SC system may be preferred over a semi-automated RTG system where it produces a lower value of 'R' (R<1) for cost factors such as '$C_{transfer}$', 'OC', '$Y_{dep}C$' and 'YDC'. In cases where the value of 'R= 1', then there would be no preference of one system over another. For R>1 values such as 'LC_{driver}', 'CPC', 'MCC', 'TC', 'DC' and 'IC', a SC system is no longer preferred over an RTG system. A SC may be preferred over an automated RMG system only where the cost parameters such as '$C_{transfer}$', 'YDC', 'OC' and '$Y_{dep}C$' have produced a lower 'R' value than '1'. However, the comparison indicator implies that for the rest of cost parameters such as 'LC_{driver}', 'CPC', 'LC_{YFM}', 'TC', 'MCC', 'DC', and 'IC' and except 'LC' and 'YMC' an automated RMG may be preferred over a SC system. The cost comparison indicator shows that for most of the cost parameters except '$C_{transfer}$', 'YDC' and '$Y_{dep}C$', the other parameters promise a lower cost ratio to prefer an automated RMG to a semi-automated RTG system. There is no preference of one system over another in 'LC' and 'YMC' cost parameters.

For an easier concept, the results of the three columns are illustrated in Figures 6.2, 6.3 and 6.4. The horizontal line drawn at `R = 1` indicates an indifference level above / below which other systems may be preferred.

Table 6.6 Cost comparison indicator

Cost Parameter	$R_{SC/RTG}$	$R_{SC/RMG}$	$R_{RMG/RTG}$
LC	1.000	1.000	1.000
YDC	0.605	0.442	1.368
$Y_{dep}C$	0.605	0.442	1.368
YMC	1.000	1.000	1.000
IC	1.162	1.260	0.922
DC	1.307	1.884	0.694
MCC	1.452	1.870	0.777
OC	0.560	0.871	0.643
LC_{driver}	2.000	2.667	0.750
LC_{YFM}	1.333	2.000	0.667
$C_{transfer}$	0.350	0.261	1.339
TC	1.065	1.168	0.912
CPC	1.523	1.789	0.851

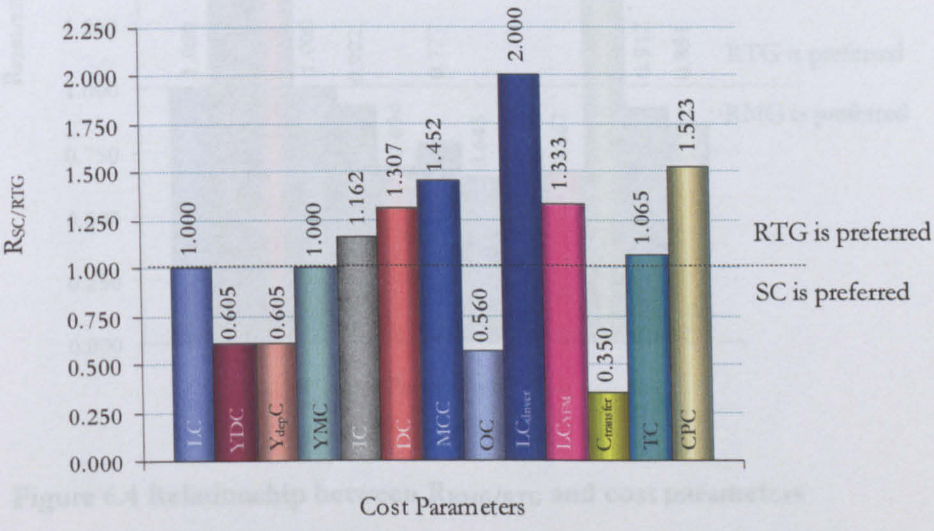


Figure 6.2 Relationships between $R_{SC/RTG}$ and cost parameters

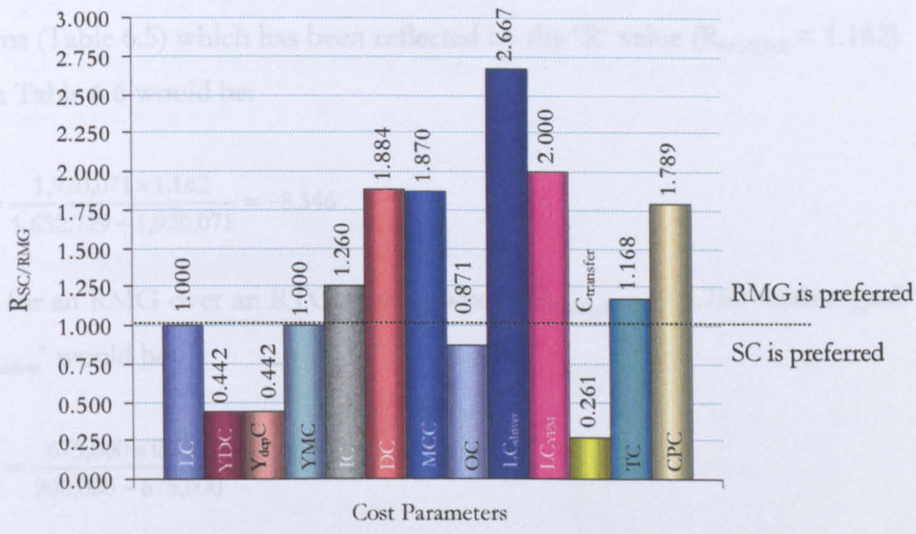


Figure 6.3 Relationship between $R_{SC/RMG}$ and cost parameters

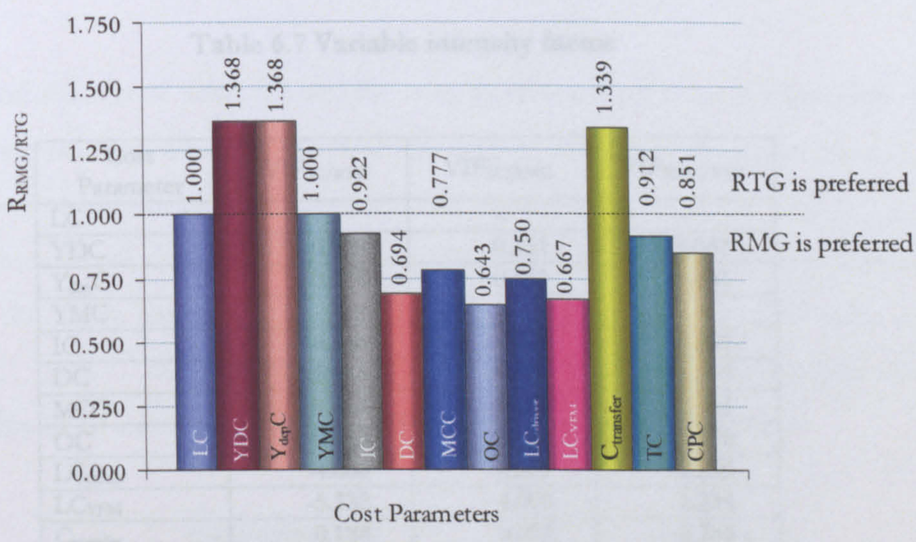


Figure 6.4 Relationship between $R_{RMG/RTG}$ and cost parameters

6.5.2 Cost comparison and sensitivity analysis using `VIF` values

The values of cost comparison indicator, `R`, given in Table 6.6 have been used for calculation of `VIF` in this study. The following example demonstrates how the value of the variable intensity factors that favour a SC system over a semi-automated RTG system for different cost parameters, has been obtained. Consider that the initial cost of yard equipment, `IC`, is the cost parameter that has been chosen as a preference attribute of comparison by a port operator. Then the `VIF` for a SC system over an RTG system with regard to the annual investment cost of both systems (Table 6.5) which has been reflected by the 'R' value ($R_{SC/RTG} = 1.162$) obtained in Table 6.6 would be:

$$VIF_{SC/RTG} = \frac{1{,}920{,}071 \times 1.162}{1{,}652{,}729 - 1{,}920{,}071} = -8.346$$

The 'VIF' for an RMG over an RTG system, where '$R_{RMG/RTG} = 0.750$' with regard to the 'LC_{driver}' would be:

$$VIF_{RMG/RTG} = \frac{675{,}000 \times 0.750}{900{,}000 - 675{,}000} = 2.250$$

The 'VIF' values for the SC over the semi automated RTG, the SC over the automated RMG and the automated RMG over the semi automated RTG have been calculated and summarised in Table 6.7.

Table 6.7 Variable intensity factor

Cost Parameter	$VIF_{SC/RTG}$	$VIF_{SC/RMG}$	$VIF_{RMG/RTG}$
LC	-	-	-
YDC	0.928	0.351	-5.081
$Y_{dep}C$	0.928	0.351	-5.081
YMC	-	-	-
IC	-8.346	-6.099	9.859
DC	-5.565	-5.401	1.573
MCC	-4.663	-4.020	2.703
OC	0.712	5.863	1.158
LC_{driver}	-4.000	-4.267	2.250
LC_{YFM}	-5.332	-4.000	1.334
$C_{transfer}$	0.188	0.092	-5.285
TC	-8.352	-8.112	9.451
CPC	-4.484	-4.122	5.106

Table 6.7 illustrates the 'VIF' values of the systems discussed with the same sequence of preferences as indicated in 'R' values. In the second column of the table, the $VIF_{SC/RTG}$ where a SC is considered to be preferred over a semi-automated RTG system with regards to the 'R' value and different cost parameters, it is evident that cost parameters for SC system such as 'IC', 'DC', 'TC', 'LC_{driver}', 'LC_{YFM}', 'MCC' and 'CPC' produce negative and the least values of 'VIF'. They imply that a semi-automated RTG may be preferred over a SC system. In contrast 'YDC', '$Y_{dep}C$', 'OC' and '$C_{transfer}$' cost factors have produced positive values that may indicate the preferability and magnitude of 'VIF' of a SC system over an RTG system. Figure 6.5 demonstrates the above statement where a SC system has not

gained sufficient positive `VIF` values to override or even balance the negative values of `VIF` that imply the preference of an RTG over a SC system when the whole scenario is considered.

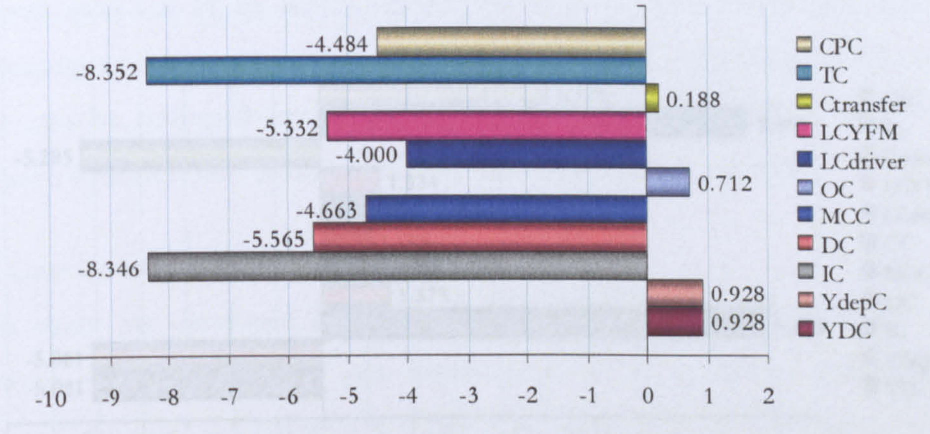


Figure 6.5 Magnitude of $VIF_{SC/RTG}$

In the third column of Table 6.7 and the corresponding illustration in Figure 6.6, it is demonstrated that `OC` has provided the highest positive `VIF` value for a SC system over an automated RMG system. Even though `YDC`, `$Y_{dep}C$` and `$C_{transfer}$` attributes have also provided additional positive values but the total positive value of the above parameters does not balance the total negative `VIF` value of `IC`, `DC`, `MCC`, `$LC_{driver}$`, `$LC_{YFM}$`, `TC` and `CPC` parameters. This implies the preferability of an automated RMG over SC system in this particular case.

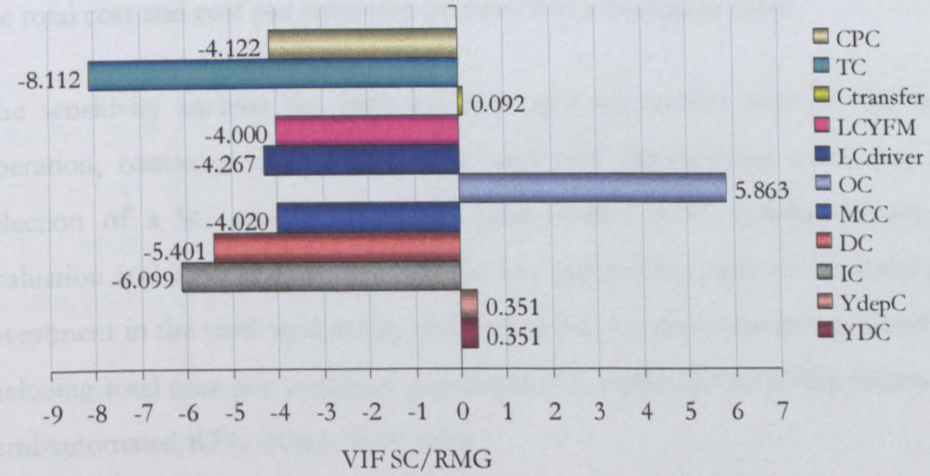


Figure 6.6 Magnitude of $VIF_{SC/RMG}$

From the forth column of Table 6.7 and the produced graph in Figure 6.7, it is evident that an automated RMG system has gained high positive `VIF` values in `TC`, `IC`, `CPC`, `$LC_{driver}$`, `MCC`, `$LC_{YFM}$`, `DC` and `OC` to favour an automated RMG over a semi-automated RTG operating system..

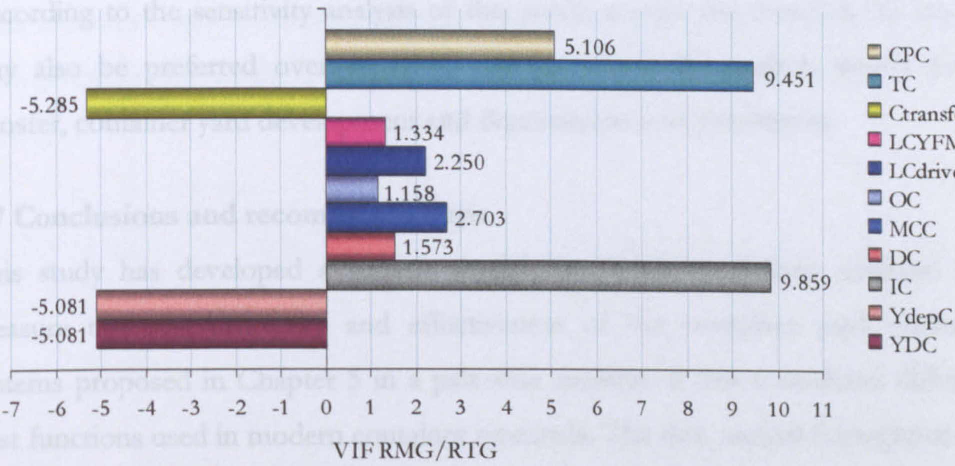


Figure 6.7 Magnitude of $VIF_{RMG/RTG}$

6.6 Findings

This study has developed a conceptual cost function model for the design and capacity of container terminals that were discussed in Chapter 5. The analysis of the test case has revealed that the size of a container yard, total containers to be processed, type, number and size of stacking cranes and transfer fleet and the costs associated with the procurement and maintenance of the cranes play a major role in the total cost and cost per container processed in a container yard.

The sensitivity analysis has indicated that cost parameters such as the transfer, operation, container yard development and yard depreciation costs may favour selection of a SC system over a semi-automated RTG system. However, the evaluation and analysis have shown that cost parameters such as the initial cost of investment in the yard equipment, equipment depreciation, maintenance and labour including total cost per container processed in a terminal favour the selection of a semi-automated RTG over a SC system.

It has also been found that cost parameters such as container yard operation, development and depreciation and transfer costs are the only factors that may favour selection of a SC over an automated RMG system The pair-wise comparison implies that most of the cost attributes evaluated such as initial cost of investment, total cost, cost per container, crane depreciation, operation and maintenance cost of yard cranes together with crane manning and container yard foremen costs strongly support selection of an automated RMG over a semi-automated RTG system. According to the sensitivity analysis of this study, a semi-automated RTG system may also be preferred over an RMG system where the analysis shows lower transfer, container yard development and depreciation cost parameters.

6.7 Conclusions and recommendations

This study has developed a generic model that helps to analyse, evaluate and measure the cost efficiency and effectiveness of the container yard operating systems proposed in Chapter 5 in a pair-wise manner. It has considered different cost functions used in modern container terminals. The size, annual throughput and mode of operation, the size and stacking height of yard equipment together with cost parameters such as land cost, container yard development, maintenance, operation, depreciation and procurement costs of yard equipment and transfer vehicles and labour costs which are normally affected by automation technologies have been incorporated in the model. The model developed may enable the designer, planner and operator of a container terminal to set-up a comparison analysis platform for decision-making and to measure the impact of different cost parameters involved on the total cost of container yard operating systems. This study has proposed a sensitivity analysis tool using a cost comparison indicator and cost intensity factors for the analysis of cost efficiency in container terminals. The cost-based model of this study provides the basis for pair-wise comparisons of container yard operating systems which is the main contribution of this chapter. Using a case study, the sensitivity analysis has demonstrated that an automated RMG system promises a lower cost per container, crane procurement and maintenance and container yard total costs than both RTG and SC systems.

The model proposed in this study has helped to achieve the 5th objective presented in Chapter 1. The model developed has a generic nature and may be used as a tool to set-up the basis for pair-wise comparisons of cost efficiency and effectiveness of equipment in other industries. Some of the parameters defined and the results obtained from the model will be used as the important attributes for decision-making in Chapter 7 and may provide confidence grounds to select or reject equipment or a system to be employed. This study has developed a cost-based model only. Further studies may be required to evaluate the benefits gained in terms of revenue generated from the equipment or operating systems. It should be noted that similar to the managers in the port industries, the managers and operators of other industries may resist revealing costs they have or are experiencing since high costs generally indicate the inefficiency and reduced productivity of systems.

Chapter 7

Multiple Attribute Decision-Making (MADM) and Analytical Hierarchy Process (AHP) for Selecting the Best Container Yard Operating System

Summary

This chapter evaluates the important parameters of container yard operating systems examined in Chapters 5 and 6 and sets up the basis for decision-making to select the best scenario amongst alternatives. It examines the important attributes determined using a Multiple Attribute Decision-Making (MADM) method. The MADM methods often study complex problems and allow the consideration of qualitative attributes expressed in linguistics terms and quantitative attributes illustrated in financial and throughput measures in the container terminals. An Analytical Hierarchy Process (AHP) technique is employed for solving the MADM problems. The AHP and the principal eigenvector weighting techniques have been proposed in this study as the weighting tools since they allow decomposition of a decision problem into a hierarchical order and enable a pair-wise comparison of the attributes with an acceptable level of consistency. The analysis assures that both qualitative and quantitative aspects of the decision are incorporated in the process. The results of the AHP analysis develop the basis for pair-wise comparison, judgement and selection of the best alternative for the purpose of this study. For the first time, this chapter proposes application of MADM and AHP for selection decisions in container terminals.

7.1 Introduction

The evolution of automation technologies has enabled simultaneous cost reduction along with output and quality improvements in services offered in the operation of today's modern container terminals. The container port industry today is very competitive and users such as shipping lines, agents and individual users select a port based on the criteria offered such as low tariffs, safety, ease of access, minimum turnaround, waiting, dwell and administration times to deal with the processing of their containerships and cargoes. On the other hand, it is natural for port owners (and operators) to expect high efficiency and productivity with a minimum cost from the operating systems in their terminals. Development of decision-support frameworks based on the conflicting objectives with different weights and preferences emanating from the quantitative and the qualitative nature of attributes is often difficult and requires a comprehensive decision-making technique. Before a designer or an operator of a container terminal selects a decision-making methodology, it is essential to identify measure and evaluate the value of the most determining attributes that have a role in selection of the most suitable container yard operating system.

The purpose of the study in this chapter is to introduce the concept of the MADM technique by using the AHP additive weighting method for selection of the best container yard operating system amongst three alternatives, namely, semi-automated Straddle Carriers (SCs), Rubber Tyred Gantry cranes (RTGs) and automated and semi-automated Rail Mounted Gantry cranes (RMGs) by integrating the quantitative and the qualitative decision attributes into a hierarchical process. The AHP method has originally been developed by Saaty (1977 and 1980) to solve decision problems with a complex nature. This study proposes an AHP method as a decision-support tool for the designers and planners of container terminals to enable a pair-wise comparison between quantitative and qualitative attributes to assess the relative importance of each criterion for decision-making. Using experts' knowledge, the study provides scores for a selection of attributes for each container yard operating system alternative equal to the weighted sum of its cardinal evaluation / preference ratings. The resulting scores for each alternative may be used to rank, screen or select an alternative as the desired container yard operating system.

7.2 Elements of the MADM method

Decision-support systems incorporating the MADM methods analyse problems in which the decision-maker is required to select or rank a finite number of alternatives which are measured by a number of relevant and often conflicting criteria and attributes with heterogeneous natures (Saaty, 1990). Five common elements can be distinguished in all of the MADM techniques that make the method ideal for the purpose of this study to help draw decisions on the resulting priorities. These elements are:

1) Finite set of alternatives

The MADM and the Multiple Objective Decision-Making (MODM) methods are the categories of the Multiple Criteria Decision-Making (MCDM) problems. Generally they attempt to analyse a finite and small set of discrete and known alternatives or options. The MODM and the MADM problems involve the optimisation and selection of the best alternatives by allowing trade-offs within a set of interacting design and selection constraints (Zahedi, 1986). Selection of the best container yard operating system amongst a variety of attractive alternatives may be considered as a MADM problem.

2) Trade-offs between attributes

The analysis of the MADM problems particularly the elements discussed in this thesis may require certain trade-offs to be exercised amongst some attributes if no single alternative demonstrates the highest value of preferences for all attributes. An example may be the trade-off that is required to be made between a low and undesirable flexibility and a high transfer cost of a container yard operating system.

3) Heterogeneity of qualitative and quantitative attributes

Attributes measured in container terminal operating systems are not homogeneous in nature and therefore are not always measurable in the same unit. They are sometimes impractical, impossible or even too costly to measure. For example, the costs associated with procurement, operation, maintenance and manning of the container yard operating systems are quantifiable in monetary terms, the throughput and capacity of the container yards are measured in terms of container Twenty-foot Equivalent Units (TEUs) processed in units of time or area, the waiting and dwell-times are expressed numerically, whilst issues such as flexibility, efficiency, versatility of the systems and their social acceptability are often expressed in linguistic terms.

4) Matrix of Pair-wise Comparison (MPC)

Decision-makers often find it difficult to accurately determine the corresponding weights for a set of attributes simultaneously. An AHP helps the decision-makers to derive relative values using their judgements or data from a standard scale. The professional's and expert's judgements are normally tabulated in a matrix often called as the 'Matrix of Pair-wise Comparison' (MPC). In a MPC the decision-maker specifies a judgement by inserting the entry 'a_{ij}' ($0 < a_{ij} \leq 9$) stating how much more important attribute 'i' is than attribute 'j' (Anderson *et al.*, 2003). To simplify the analysis of a MADM problem, the experts' judgements in an AHP are reflected in a MPC. These judgments are generally expressed in cardinal values rather than ordinal numerals. A MPC can be defined as:

$$A = (a_{ij}) = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \qquad 7.1$$

where:

a_{ij} = Relative importance of attributes 'i' and 'j'.

In this respect the MPC would be a square (n x n) matrix, 'A', embracing 'n' number of attributes whose relative weights are '$w_1, \dots, w_n$' respectively. In this matrix the weights of all attributes are measured with respect to each other in terms of multiples of that unit. The comparison of the values is expressed in Equation 7.2.

$$a_{ij} = \frac{w_i}{w_j} \qquad 7.2$$

where:

i, j = 1,2, …, n.

5) The decision matrix

The results of a MADM problem using the AHP techniques are often given in a decision matrix which represents both alternatives and attributes in order to make the final selection from amongst alternatives. A decision matrix is usually illustrated in a table format and consists of rows corresponding to the alternatives and columns corresponding to the main attributes representing the weighted value of their corresponding sub-attributes. All of the attributes and their corresponding sub-attributes are required to be weighted consistently with a common weighting technique. The weights of the sub-attributes are required to be normalised by multiplying their values by the priority ratios of their main attributes on the upper levels of hierarchy immediately above them (Dyer and Forman, 1992). The normalised weights are multiplied by a set of 'performance scores' defined by the decision-maker with respect to each individual alternative. The row-sum of this operation may represent the overall ranking of the alternatives.

7.3 The AHP technique

The AHP is categorised as an 'additive weighting method'. The method proposed in this study involves the 'principal eigenvector' weighting technique that utilises the experts' opinions for both qualitative and qualitative attributes. The AHP may provide a framework for a pair-wise comparison environment for the analysis of this study by using the quantitative data and the experts' judgements obtained in the previous chapters conducted in this research. In the process of the analysis, the basic logic of the 'additive weighting methods' and hence the AHP is characterised and distinguished by the following principles:

7.3.1 Hierarchy of the problem

The first logic of every AHP analysis is to define the structure of hierarchy of the study. A hierarchy is defined as:

> "*... an abstraction of the structure of a system to study the functional interactions of its components and their impacts upon the entire system*" (Saaty, 1980 and 2004).

The structuring of a MADM hierarchy to solve the selection of the best container yard operating system through the AHP method may be defined as the division of the series of levels of attributes in which each attribute represents a number of small sets of inter-related sub-attributes. The overall goal of the AHP analysis is positioned at the end of the hierarchy and will be indicated as the first level. At the last level of the hierarchy the leaf attributes are positioned. In the AHP problems, the alternatives are scored and compared with respect to the leaf attributes.

7.3.2 Weighting the attributes

Additive weighting methods consider cardinal numerical values that characterise the overall preference of each defined alternative. In this context, the linguistics judgements of the pair of qualitative or quantitative attributes may require ordinal values to be translated into equivalent cardinal numbers. Saaty (2004) has recommended equivalent scores from 1 to 9 as shown in Table 7.1 that will be used in this study. A preference of 1 indicates equality between two attributes while a preference of 9 indicates that one attribute is 9 times larger or more important than the one to which it is being compared with.

Table 7.1 Comparison scale for the MPC in the AHP method

Relative Importance of Attribute (Scale)	Definition
1	Equal importance.
3	Moderate importance of one over another.
5	Essential or strong importance.
7	Very strong importance.
9	Extreme importance.
2,4,6,8	Intermediate values between the two adjacent judgements.
Reciprocals	When activity 'i' compared with 'j' is assigned one of the above numbers, then activity 'j' compared with 'i' is assigned its reciprocal.

(Source: Saaty, 1990)

7.3.2.1 Principal eigenvector approach for calculating the relative weights

The relative weighting vector for each attribute of comparison matrix is required to be calculated. The weights of attributes are calculated in the process of averaging over the normalised columns.

- **Weight vector calculation**

The priority matrix representing the estimation of the eigenvalues of the matrix is required to provide the 'best fit' for the attributes in order to make the sum of the weights equal to '1'. This can be achieved by dividing the relative weights of each individual attribute by the column-sum of the obtained weights. This approach is called the 'Division by Sum' (DBS) method. A 'DBS' is used in the AHP analysis when selection of the highest ranked alternative is the goal of the analysis (Saaty, 1990). Other combinations such as 'Division by Maximum' (DBM) and 'Division by Average' (DBA) may also be applicable. It should be noted that different weighting methods may lead to the selection of different alternatives. Therefore, only one method should be employed throughout the analysis. Equation 7.3 defines the process of averaging over normalised columns using the 'DBS' approach for 'w_1' (Pillay and Wang, 2003).

$$w_1 = \frac{1}{n}\left[\left(\frac{a_{11}}{\sum_{i=1}^{n} a_{i1}}\right) + \left(\frac{a_{12}}{\sum_{i=1}^{n} a_{i2}}\right) +, \ldots, \left(\frac{a_{1n}}{\sum_{i=1}^{n} a_{in}}\right)\right] \qquad 7.3$$

where:

n = Size of the comparison matrix.

In general terms, the weights (priority vectors) for w_1, w_2, w_3, ..., w_n can be calculated using the following equation (Pillay and Wang, 2003):

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right) \qquad 7.4$$

where:

k = 1, 2, …, n.

- **The problem of consistency**

A decision-maker may require to make trade-offs within the attribute values in a compensatory way if the inconsistencies calculated exceed 10% (Saaty, 1980 and 1988). This is possible when the values of the attributes to be traded-off are numerically comparable with all of the attributes assigned to a particular alternative. In a perfectly consistent matrix, it is assumed that the rule of transitivity and reciprocity stated in Equation 7.5 is complied with.

$$a_{ji} = \frac{1}{a_{ij}} \qquad 7.5$$

where:

i, j = 1, 2, …, n.

The calculated priorities are plausible only if the comparison matrices are consistent or nearly consistent. It should be noted that for high order matrices, consistency may be difficult to reach because the number of transitive rules to be satisfied increase in a quadratic manner. In this case the inconsistency of a matrix could be improved around 10% by making trade-offs. For each MPC to be evaluated in this study, the consistency would be checked.

The approximate ratio of consistency can be obtained using Equation 7.6

$$CR = \frac{CI}{RI} \qquad 7.6$$

where:

CR = Consistency ratio.

CI = Consistency index.

RI = Random index for the matrix size, 'n'.

The value of 'RI' would depend on the number of attributes under comparison. This can be taken from Table 7.2 given by Saaty (1980). The consistency index, 'CI', may be calculated from the following Equation:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad 7.7$$

where:

λ_{max} = The principal eigenvalue of an 'n x n' comparison matrix 'A'.

In a perfectly consistent matrix, λ_{max} is equal to 'n' (Saaty, 1980). When the value of λ_{max} becomes closer to 'n', the error in judgement of the decision-maker would become smaller thus the results would be more accurate. To estimate λ_{max}, first the comparison matrix is multiplied by the priority vector calculated from Equation 7.5. Then every element of the resulting matrix (A') is divided by the corresponding element of the matrix of the priority vectors to obtain a new matrix (A''). The λ_{max} will be the vector with the maximum eigenvalue (Karlsson and Ryan, 1997). The procedure for estimating the λ_{max} for the main attributes is shown in Section 7.5.

Table 7.2 Average random index (RI) values

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

(Source: Saaty, 1990)

7.4 Performance scores

In order to obtain the final priority scores, first it is necessary to obtain the performance values for each attribute. This will require bringing the qualitative values defined in the linguistic forms and the quantitative values obtained in the previous chapters such as Table 6.5 into a common denominator. The performance scores can be derived from the important parameters identified in the study and be assigned equivalent values using professional and experts' judgements. Alternatively (or jointly) they can be achieved by defining a value function for each attribute that translates the corresponding parameter to a performance value. In this context, the values are assigned on the scale from '0' to '9'. Value '0' is assigned to the least and '9' to the most favourable calculated value amongst all. The decision-maker may exercise some trade-offs between the values. The conversion of the parameter values is accomplished using the equality function proposed by Spasovic (2004).

$$\frac{y_{max} - y_0}{y_i - y_0} = \frac{x_b - x_w}{x_i - x_w} \qquad 7.8$$

where:

y_i = Value of performance measure for parameter 'i'.

y_0 = Lowest score on the scale for an attribute.

y_{max} = Highest score on the scale for an attribute.

x_i = Calculated value of parameter 'i'.

x_w = Highest value of a parameter.

x_b = Lowest value of a parameter.

Therefore, 'y_i' can be re-written as:

$$y_i = y_0 + \frac{(y_{max} - y_0)(x_i - x_w)}{x_b - x_w} \qquad 7.9$$

When the performance values are calculated, they are rounded up to a single digit and divided by the maximum value of the measuring scale (9 in this case) to obtain the final performance scores. A trade-off between the values of attribute may be exercised by the decision-maker.

7.5 Application of the AHP to select the best yard operating system

An AHP may be applied to find the best container yard operating system amongst the semi-automated SC and RTG and automated and semi-automated RMG systems analysed in the previous chapters. This study examines the applicability of the AHP method using the following steps:

Step 1: Identify, classify and select attributes of the decision tree in a hierarchical structure.

Step 2: Calculate the performance scores.

Step 3: Set-up the MPC and define the relative priorities of the main and sub-attributes over others using series of pair-wise comparisons.

Step 4: Calculate the weighting vectors (vector of priorities) using the principal eigenvector approach.

Step 5: Check for inconsistency and exercise necessary trade-offs if 'CR' appears greater than an acceptable level (i.e. 10%).

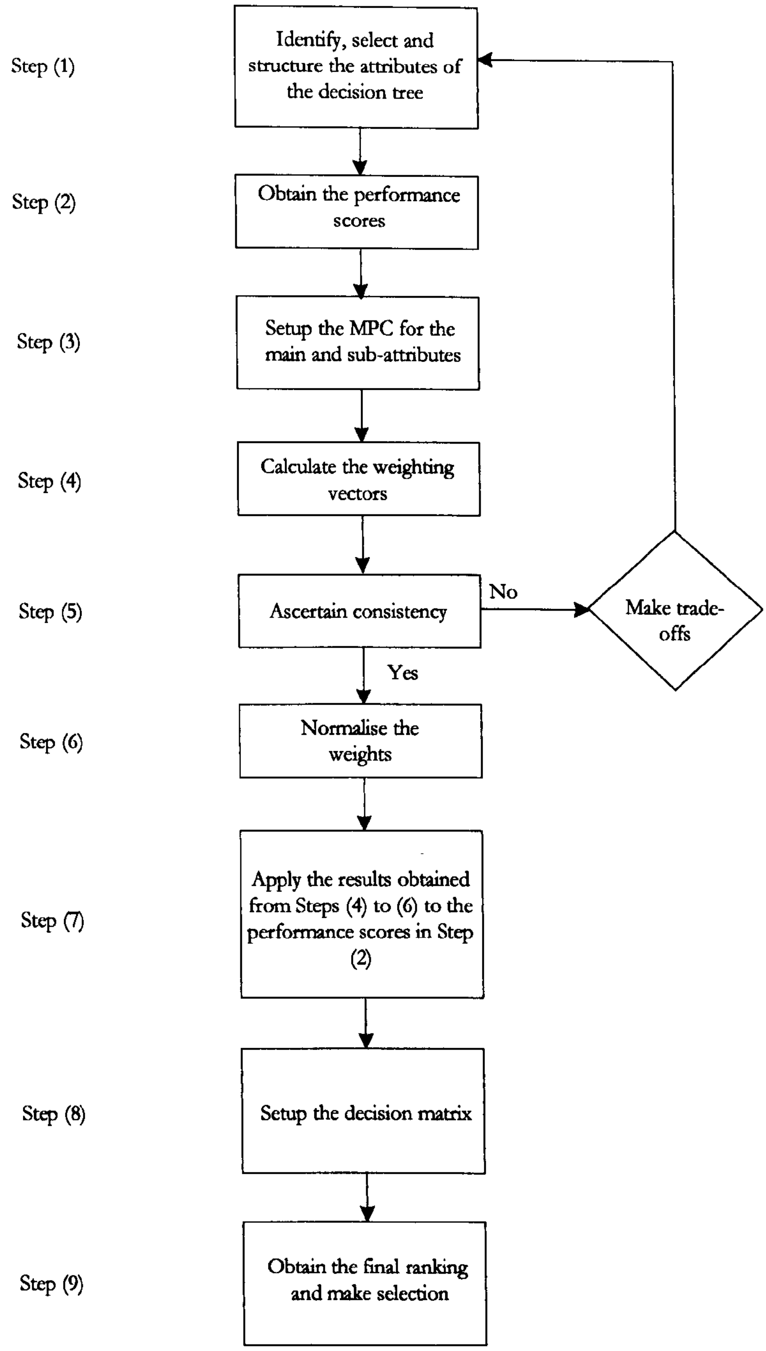
Step 6: Normalise the weights through multiplying the weights of sub-attributes by the corresponding weighting vector of their main attributes obtained in Step 4.

Step 7: Apply the results obtained in Steps 4 to 6 to the 'performance scores' obtained in Step 2.

Step 8: Set-up a decision matrix representing the results obtained in Step 7. Sum-up the values of all sub-attributes in each row corresponding to each alternative.

Step 9: Obtain the final ranking and select an alternative with the highest ranking order.

The above steps can be illustrated in the flowchart in Figure 7.1.



(Source: Author)

Figure 7.1 Flowchart of the AHP application

7.6 Test case

The performance scores and values given to attributes in the analysis of this study are based on the studies conducted on the planning, design and cost modelling presented in the previous chapters and on the experts' opinions. A stepwise procedure defined in Section 7.4 and in Figure 7.1 is used to examine the applicability of the AHP to a case derived from the analysis of the previous chapters in this thesis.

Step 1:

For the MADM analysis in this study, the selection of the best container yard operating system is identified in this research and will be based on the following important criteria defined by the author:

- **Automation.** The attributes related to automation technology (hence 'automation') which are directly impacted by container yard capacity, stacking height, economic life and level of technology are considered.

- **Cost.** The cost attributes in terms of procurement, maintenance, operation, transfer and cost per container processed are included in the analysis.

- **Operations.** Operational attributes referred to as 'operations' in terms of flexibility, applicability of random grounding as the best stacking strategy, re-handling management and environmental and social acceptability are included.

The above attributes together with their corresponding sub-attributes (summarised in Table 7.3) have been identified as the important criteria throughout this research. All of the attributes are required to be weighted by the decision-maker before any selection decision is made. In this context, some elements of the analysis such as 'level of technology' and all of the elements of operational attributes that are expressed in linguistics terms would be translated into a common language and scale consistent with the scales of analysis of the whole system. A combination of other attributes and sub-attributes with different values and characteristics is possible using the generic AHP method proposed in this study.

Table 7.3 Related decision attributes for selection of a container yard operating system

Attribute	Sub-attribute
Automation	Container yard throughput (C_Y)
	Stacking height advantage (SH)
	Economic life (t)
	Level of automation (LA)
Cost	Procurement cost (PC)
	Maintenance cost of cranes (MCC)
	Container yard operation cost (OC)
	Transfer operation cost ($C_{transfer}$)
	Cost per container (CPC)
Operations	Flexibility (FL)
	Random grounding applicability (RGA)
	Re-handling management (RM)
	Environmental and social acceptability (ESA)

(Source: Author)

The importance of comparison criteria for the main attributes in Table 7.3 is assessed as follows using the experts' knowledge and the comparison scales given in Table 7.1:

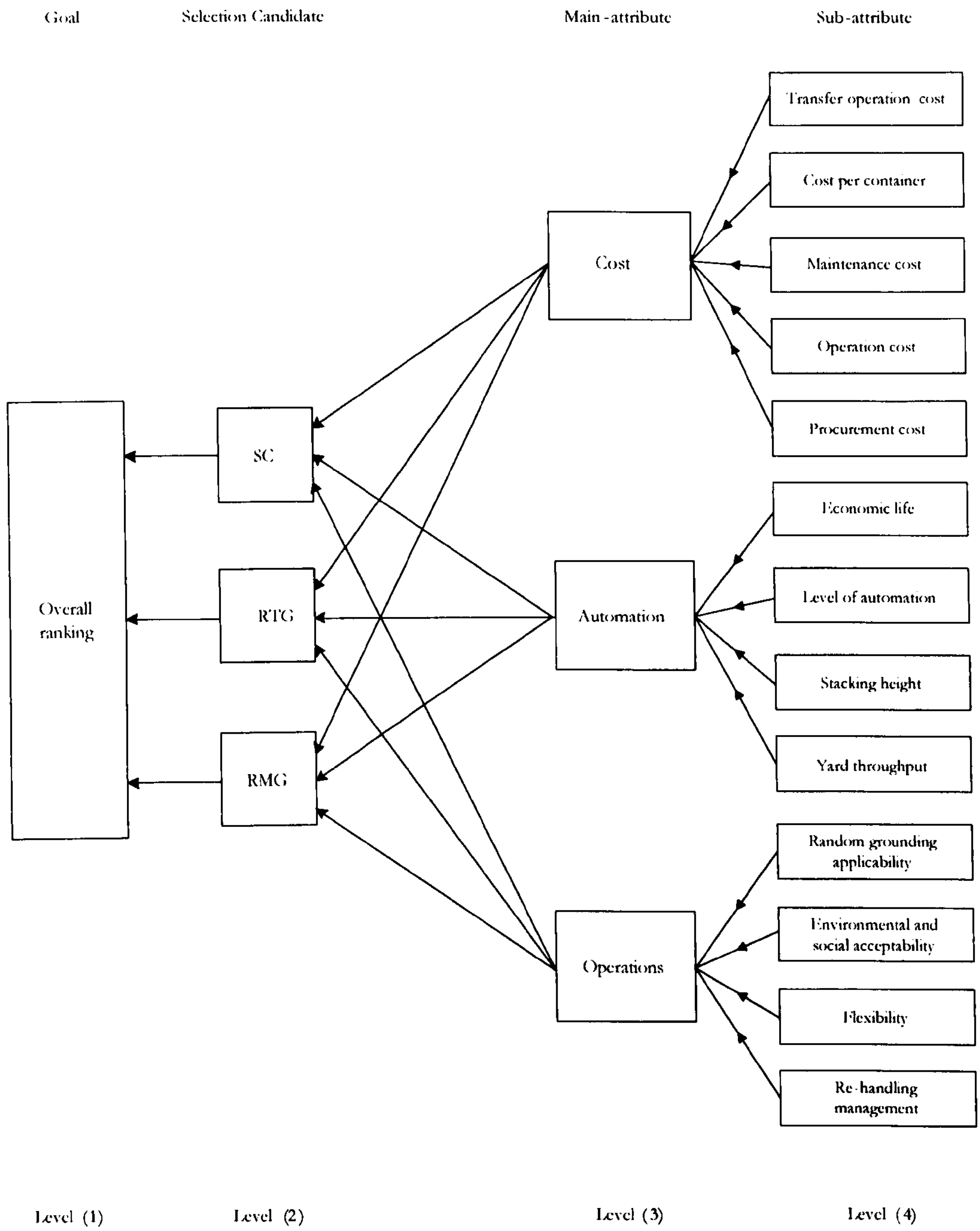
Operations = Moderate.

Cost = Essential or strong.

Automation = Extreme.

- **Structure of container yard operating system decision tree in the AHP framework**

Figure 7.2 illustrates a simple AHP decision tree for the goal of this study leading towards the selection of the best container yard operating system amongst semi-automated SC and RTG and automated and semi-automated RMG systems. It shows the AHP structure for this study which is defined in four levels. It shows three alternatives and three main attributes and their corresponding sub-attributes. The study will analyse and measure the weights of each attribute and its corresponding sub-attributes with respect to each alternative to obtain the final rankings.



(Source: Author)

Figure 7.2 Container yard handling system decision tree

Step 2:

The final performance scores are obtained using experts' judgements and jointly using Equation 7.9. The performance values obtained from Equation 7.9 are divided by 9 to ensure that the maximum score for a particular attribute does not exceed 1. In some cases, the performance measures are given higher (or lower) values than the calculated scores on the basis of experts' judgement and experience. The following examples illustrate how the performance scores of attributes 'MCC' in an RTG system and RMG systems have been calculated:

$$y_i = y_{MCC,RMG} = 0 + \frac{(9-0)(258{,}195 - 482{,}722)}{258{,}195 - 482{,}722} = 9$$

The performance score for 'MCC' attribute in RMG system $= \frac{9}{9} = 1.0000$

$$y_i = y_{MCC,RTG} = 0 + \frac{(9-0)(332{,}408 - 482{,}722)}{258{,}195 - 482{,}722} \approx 7$$

The performance score for 'MCC' attribute in RTG system $= \frac{7}{9} \approx 0.7778$

The performance scores are obtained jointly using Equation 7.9 and experts' judgement obtained in Appendix 5. The values are assigned to the attributes and corresponding alternatives by the author on the above basis and are given in Tables 7.4, 7.5 and 7.6.

Table 7.4 Performance scores of the cost attributes

	$C_{transfer}$	CPC	MCC	OC	PC
SC	6/9 = 0.6667	3/9 = 0.3333	5/9 = 0.5556	8/9 = 0.8889	2/9 = 0.2222
RTG	4/9 = 0.4444	6/9 = 0.6667	7/9 = 0.7778	4/9 = 0.4444	5/9 = 0.5556
RMG	2/9 = 0.2222	9/9 = 1.0000	9/9 = 1.0000	6/9 = 0.6667	7/9 = 0.7778

Table 7.5 Performance scores of the automation attributes

	t	LA	SH	C_Y
SC	5/9 = 0.5556	2/9 = 0.2222	1/9 = 0.1111	7/9 = 0.7778
RTG	7/9 = 0.7778	5/9 = 0.5556	3/9 = 0.3333	8/9 = 0.8889
RMG	8/9 = 0.8889	7/9 = 0.7778	8/9 = 0.8889	9/9 = 1.0000

Table 7.6 Performance scores of the operations attributes

	RGA	ESA	FL	RM
SC	2/9 = 0.2222	4/9 = 0.4444	9/9 = 1.0000	7/9 = 0.7778
RTG	3/9 = 0.3333	4/9 = 0.4444	7/9 = 0.7778	5/9 = 0.5556
RMG	6/9 = 0.6667	5/9 = 0.5556	4/9 = 0.4444	3/9 = 0.3333

Steps 3 to 6:

A) Main attributes:

The matrix of pair-wise comparison for the main attributes is defined by the decision-makers as shown in Table 7.7.

Table 7.7 MPC for the main attributes

	Operations	Cost	Automation
Operations	1	1/5	1/9
Cost	5	1	1/2
Automation	9	2	1

The MPC for the main attributes can be shown in the following matrix:

$$\text{MPC for the main attributes} = \begin{bmatrix} 1.0000 & 0.2000 & 0.1111 \\ 5.0000 & 1.0000 & 0.5000 \\ 9.0000 & 2.0000 & 1.0000 \end{bmatrix}$$

According to the proposed 'DBS' method, the weight of each main attribute would be calculated in the following process:

$$\begin{bmatrix} \text{Operations} & = 1/(1.0000 + 5.0000 + 9.0000) = 0.0667 \\ \text{Cost} & = 1/(0.2000 + 1.0000 + 2.0000) = 0.3125 \\ \text{Automation} & = 1/(0.1111 + 0.5000 + 1.0000) = 0.6208 \end{bmatrix}$$

Having 'RI' equal to 0.58 (Table 7.2), λ_{max} and the consistency ratio, 'CR', can be calculated from the following process proposed by Karlsson and Ryan (1997):

$$A' = \begin{bmatrix} 1.0000 & 0.2000 & 0.1111 \\ 5.0000 & 1.0000 & 0.5000 \\ 9.0000 & 2.0000 & 1.0000 \end{bmatrix} \times \begin{bmatrix} 0.0667 \\ 0.3125 \\ 0.6208 \end{bmatrix}$$

$$A' = \begin{bmatrix} (0.0667 \times 1.0000) + (0.3125 \times 0.2000) + (0.6208 \times 0.1111) \\ (0.0667 \times 5.0000) + (0.3125 \times 1.0000) + (0.6208 \times 0.5000) \\ (0.0667 \times 9.0000) + (0.3125 \times 2.0000) + (0.6208 \times 1.0000) \end{bmatrix} = \begin{bmatrix} 0.1982 \\ 0.9564 \\ 1.8461 \end{bmatrix}$$

$$A'' = \begin{bmatrix} 0.1982 \\ 0.9564 \\ 1.8461 \end{bmatrix} \div \begin{bmatrix} 0.0667 \\ 0.3125 \\ 0.6208 \end{bmatrix} = \begin{bmatrix} 2.9715 \\ 3.0605 \\ 2.9737 \end{bmatrix}$$

$\lambda_{max} = 3.0605$

RI = 0.58

Therefore, $CI = \frac{3.0605 - 3}{3 - 1} = 3.0 \times 10^{-2}$

The consistency ratio for the above matrix is:

$$CR = \frac{3.0 \times 10^{-2}}{0.58} = 5.0 \times 10^{-2}$$

Since 'CR' is < 10%, the pair-wise comparison in this matrix is consistent and no trade-offs would be needed. The same approach is used to calculate the 'CR' for all of the sub-attributes. The detailed procedure of calculations is not given in this study due to the space limitation.

Steps 3 to 6:

B) Sub-attributes:

The MPCs for the cost, automation and operations attributes are defined by the author using data from Tables A.5.3 to A.5.5 (Appendix 5) and are reflected in Tables 7.8, 7.9 and 7.10.

Table 7.8 MPC of the cost attributes

	$C_{transfer}$	CPC	MCC	OC	PC
$C_{transfer}$	1	1/5	1/7	1/4	1/9
CPC	5	1	5/7	5/4	5/9
MCC	7	7/5	1	7/4	7/9
OC	4	4/5	4/7	1	4/9
PC	9	9/5	9/7	9/4	1

The MPC, weighting vectors and normalised weights for all sub-attributes are calculated in the following process:

- **Cost:**

$$\text{MPC of the cost attributes} = \begin{bmatrix} 1.0000 & 0.2000 & 0.1429 & 0.2500 & 0.1111 \\ 5.0000 & 1.0000 & 0.7143 & 1.2500 & 0.5556 \\ 7.0000 & 1.4000 & 1.0000 & 1.7500 & 0.7778 \\ 4.0000 & 0.8000 & 0.5714 & 1.0000 & 0.4444 \\ 9.0000 & 1.8000 & 1.2857 & 2.2500 & 1.0000 \end{bmatrix}$$

$$\text{Weighting vectors of the cost attributes} = \begin{bmatrix} 0.0385 \\ 0.1923 \\ 0.2692 \\ 0.1538 \\ 0.3462 \end{bmatrix}$$

$\lambda_{max} = 5.0020, \text{RI} = 1.12, \text{CI} = 5.0\times10^{-4}$, therefore, $\text{CR} = 4.5\times10^{-4} < 10\%$

$$\text{Normalised weights of the cost attributes} = \begin{bmatrix} 0.0385\times0.3125 = 0.0120 \\ 0.0601 \\ 0.0841 \\ 0.0481 \\ 0.1082 \end{bmatrix}$$

- **Automation:**

Table 7.9 MPC of the automation attributes

	t	LA	SH	C_Y
t	1	1/3	1/5	1/9
LA	3	1	3/5	1/3
SH	5	5/3	1	5/9
C_Y	9	3	9/5	1

$$\text{MPC of the automation attributes} = \begin{bmatrix} 1.0000 & 0.3333 & 0.2000 & 0.1111 \\ 3.0000 & 1.0000 & 0.6000 & 0.3333 \\ 5.0000 & 1.6667 & 1.0000 & 0.5556 \\ 9.0000 & 3.0000 & 1.8000 & 1.0000 \end{bmatrix}$$

$$\text{Weighting vectors of the automation attributes} = \begin{bmatrix} 0.0555 \\ 0.1667 \\ 0.2778 \\ 0.5000 \end{bmatrix}$$

$\lambda_{max} = 4.0036, \text{RI} = 0.9, \text{CI} = 1.2\times10^{-3}$, therefore, $\text{CI} = 1.3\times10^{-3} < 10\%$

$$\text{Normalised weights of the automation attributes} = \begin{bmatrix} 0.0555 \times 0.6208 = 0.0345 \\ 0.1035 \\ 0.1724 \\ 0.3104 \end{bmatrix}$$

- **Operations:**

Table 7.10 MPC of the operations attributes

	RGA	ESA	FL	RM
RGA	1	1	1/7	1/8
ESA	1	1	1/7	1/8
FL	7	7	1	7/8
RM	8	8	8/7	1

$$\text{MPC of the operations attributes} = \begin{bmatrix} 1.0000 & 1.0000 & 0.1429 & 0.1250 \\ 1.0000 & 1.0000 & 0.1429 & 0.1250 \\ 7.0000 & 7.0000 & 1.0000 & 0.8750 \\ 8.0000 & 8.0000 & 1.1429 & 1.0000 \end{bmatrix}$$

$$\text{Weighting vectors of the operations attributes} = \begin{bmatrix} 0.0588 \\ 0.0588 \\ 0.4117 \\ 0.4707 \end{bmatrix}$$

$\lambda_{max} = 4.0017, \mathrm{RI} = 0.9,\ \mathrm{CI} = 5.7 \times 10^{-4}$, therefore, $\mathrm{CR} = 6.3 \times 10^{-4} < 10\%$

$$\text{Normalised weights of the operations attributes} = \begin{bmatrix} 0.0588 \times 0.0667 = 0.0039 \\ 0.0039 \\ 0.0275 \\ 0.0314 \end{bmatrix}$$

Steps 7 and 8:

The summary of the performance scores is given in Table 7.11. The weighting vectors of all the sub-attributes at level (4) are obtained. The weights are then normalised through multiplying their values by the priority ratio of their corresponding main attributes at level (3). The normalised weights are multiplied by their corresponding 'performance scores' and the results are summed-up and indicated in the decision matrix in Table 7.12. The final priority rankings are obtained by calculating the row-sum of the results for each individual alternative. The above process is illustrated in Figures 7.3, 7.4 and 7.5.

Table 7.11 Summary of the performance scores

	Cost					Automation				Operations			
	$C_{transfer}$	CPC	MCC	OC	PC	t	LA	SH	C_Y	RGA	ESA	FL	RM
SC	0.6667	0.3333	0.5556	0.8889	0.2222	0.5556	0.2222	0.1111	0.7778	0.2222	0.4444	1.0000	0.7778
RTG	0.4444	0.6667	0.7778	0.4444	0.5556	0.7778	0.5556	0.3333	0.8889	0.3333	0.4444	0.7778	0.5556
RMG	0.2222	1.0000	1.0000	0.6667	0.7778	0.8889	0.7778	0.8889	1.0000	0.6667	0.5556	0.4444	0.3333

Table 7.12 The decision matrix

	Cost (0.3125)					Automation (0.6208)				Operations (0.0667)				Sum	Final Priority
	$C_{transfer}$ (0.0120)	CPC (0.0601)	MCC (0.0841)	OC (0.0481)	PC (0.1082)	t (0.0345)	LA (0.1035)	SH (0.1724)	C_Y (0.3104)	RGA (0.0039)	ESA (0.0039)	FL (0.0275)	RM (0.0314)		
SC	0.0080	0.0200	0.0467	0.0428	0.0240	0.0192	0.0230	0.0192	0.2414	0.0009	0.0017	0.0275	0.0244	0.4988	0.2474
RTG	0.0053	0.0401	0.0654	0.0214	0.0601	0.0268	0.0575	0.0575	0.2759	0.0013	0.0017	0.0214	0.0174	0.6519	0.3233
RMG	0.0027	0.0601	0.0841	0.0321	0.0842	0.0307	0.0805	0.1532	0.3104	0.0026	0.0022	0.0122	0.0105	0.8654	0.4293
													Total	2.0161	1.0000

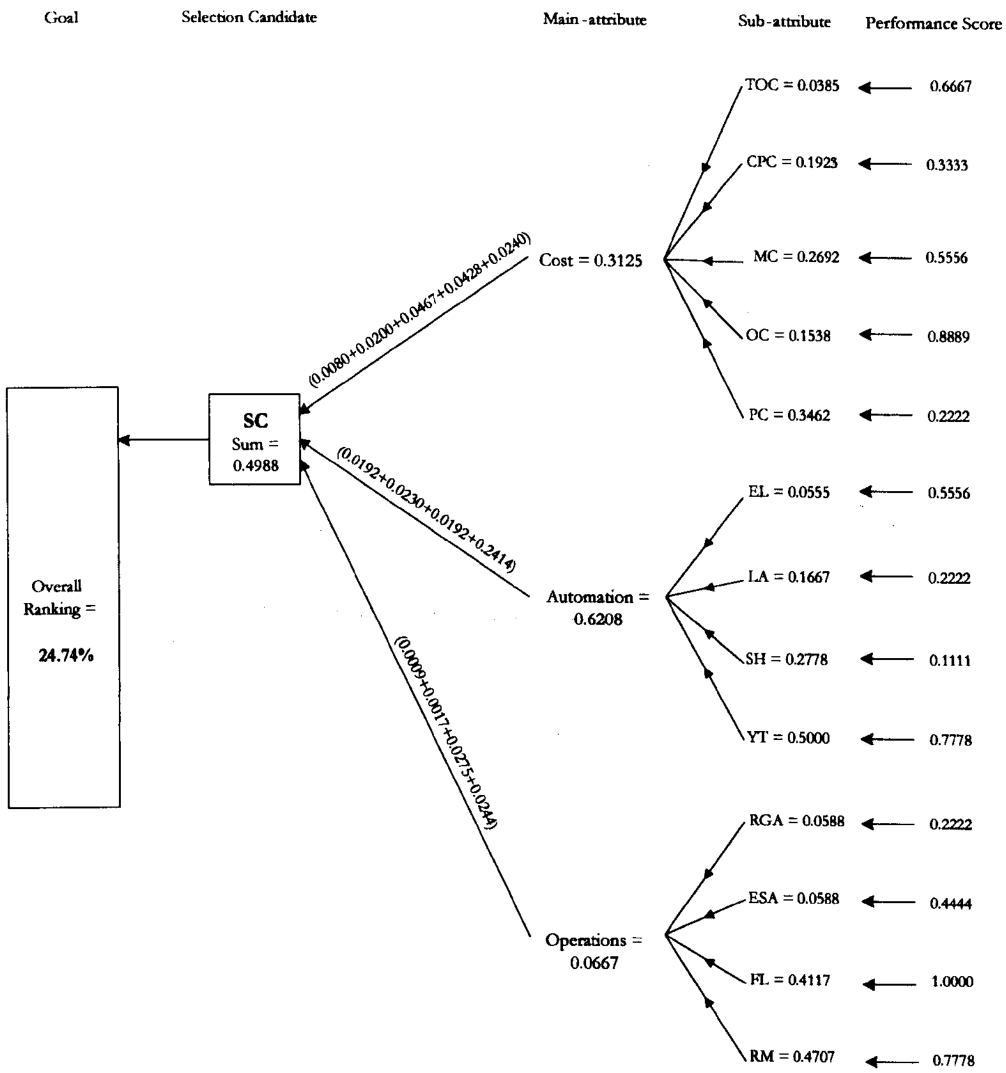


Figure 7.3 The AHP value tree for SC (1 over 3)

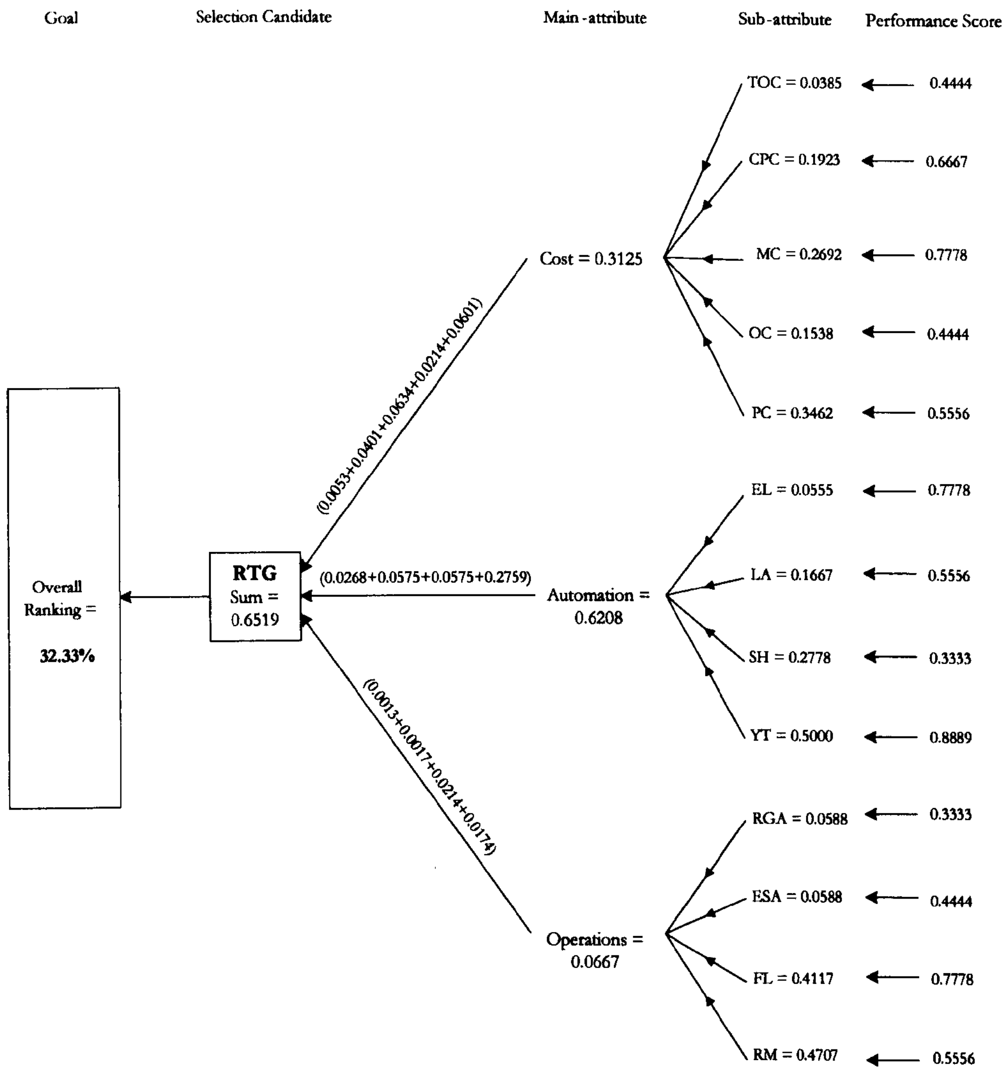


Figure 7.4 The AHP value tree for RTG 6 + 1 (1 over 5)

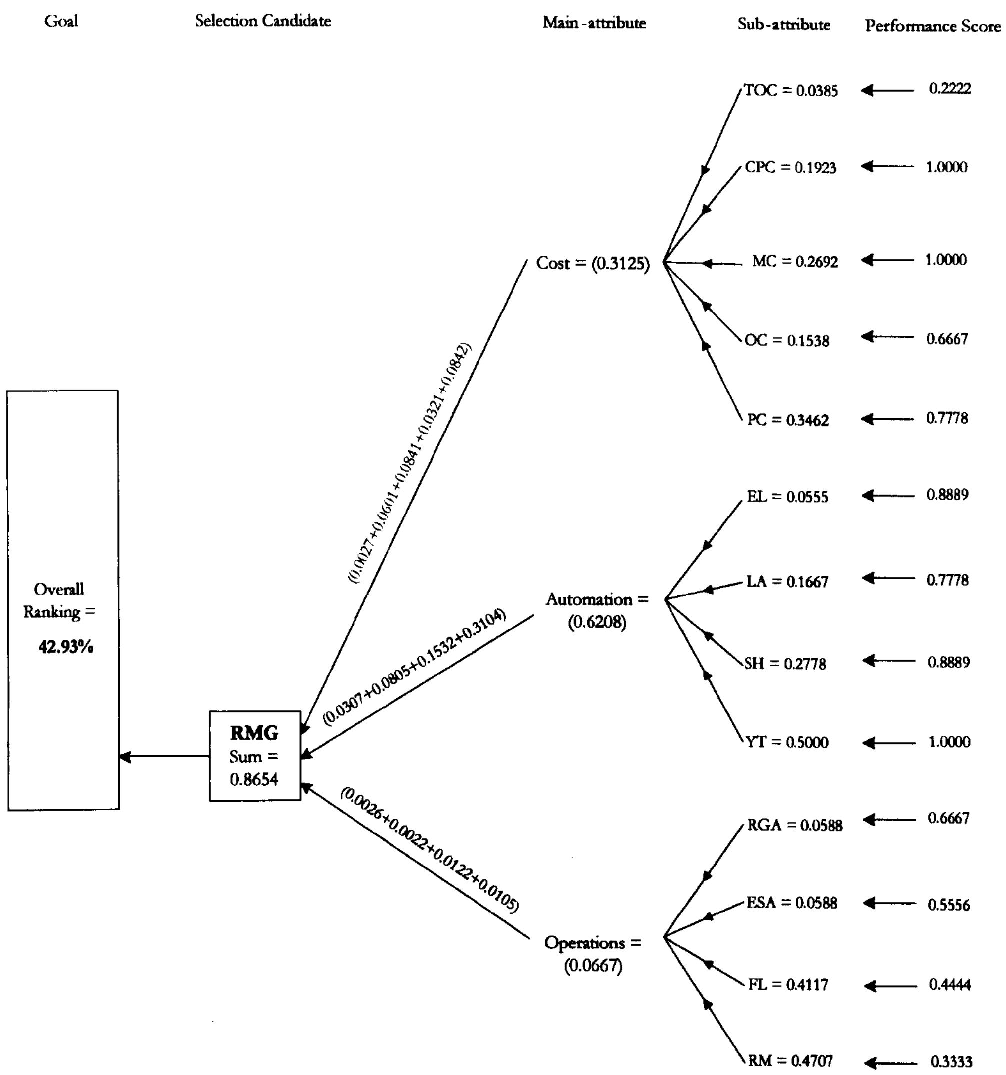


Figure 7.5 The AHP value tree for RMG 12 + 2 (1 over 5)

Step 9:

The final ranking and selection is obtained as follows:

1) RMG 12 + 2 (1 over 5) = $\dfrac{0.8654}{2.0161} = 42.93\%$

2) RTG 6 +1 (1 over 5) = $\dfrac{0.6519}{2.0161} = 32.33\%$

3) SC (1 over 3) = $\dfrac{0.4988}{2.0161} = 24.74\%$

The AHP analysis in this study has shown that the RMG system with an under portal span of 12 + 2 container rows and capable of stacking 6 containers high (1 over 5) has obtained the highest priority ratio of 42.93%. The second best alternative is the RTG system with a span of 6 + 1 container rows, capable of stacking 6 containers high (1 over 5) which has gained a priority of 32.33%. The final and least priority is given to the SC system capable of stacking 4 containers high (1 over 3). The SC system has gained only 24.74% of the priority ratio. The AHP analysis implies that the RMG system examined in this study is the most desirable container yard operating system amongst the three alternatives. The priority of RMG container yard operating systems over others can be seen in many pioneered container terminals (Saanen and Verbraeck, 2006, Sisson, 2005). Such examples include the Thamesport Container Terminals (UK), Shanghai (China), Kaohsiung, (Taiwan), Euromax, (Netherlands), Hong Kong International Terminals (HIT), ECT (Rotterdam), and Sea Port in Dubai who have employed automated and semi-automated devices in their container yard operations (Saanen and Valkengoed, 2005).

It should be noted that the generic AHP method proposed in this study has analysed the performance scores and the matrices of pair-wise comparisons given by experts and decision-makers for this study. The judgement of the decision-makers and experts are based on the quantitative and the qualitative data obtained in this thesis. Changes in the values of the performance scores and weights of attributes for different container terminals may produce different ranking orders which may lead to the selection of a different container yard operating system.

7.7 Conclusions and recommendations

This chapter has developed a generic decision-support model for the important elements and attributes analysed in Chapters 5 and 6. The study has proposed MADM technique and employed an AHP method that has enabled the decision-maker to incorporate qualitative attributes as well as quantitative values for decision problems in the container yard operations. Selection of qualitative attributes together with the quantitative attributes for comparison and decision-making is the main advantage of this system over others. The MADM technique and AHP method have not been applied to the selection decisions in container terminals before. The study has illustrated that an RMG system evaluated in this thesis has gained the highest ranking compared with the RTG and SC container yard operating systems. Therefore, the AHP analysis prioritises RMG, RTG and SC systems in a ranking manner. Theoretically, the AHP may be considered as a sound methodology that container terminals can easily adopt as a decision-support tool for decision-making at the strategic and operational levels. Particularly it can be used for selection decisions of automation technologies in a container terminal operation. The analysis of this chapter has helped in achieving the final objective of this research. It would be worthwhile investigating the applicability of the AHP in the process of planning and design and or re-design of container terminals to meet the needs of the port operators and users.

Chapter 8

Conclusions and Discussions

Summary

The analysis and results of the research conducted to examine and measure the impact of automation on the efficiency and cost effectiveness of the Quayside Cranes (QSCs), Straddle Carrier (SC), Rubber Tyred Gantry (RTG) and Rail Mounted Gantry (RMG) yard cranes are concluded in this chapter. This chapter briefly explains the methodologies used and the evaluation models generated and outlines the results and the contributions that every individual study has made. It also discusses the limitations incurred during the study. Further, it discusses and recommends the areas that are required to be examined in the future studies.

8.1 Conclusions of this study

The first and second objectives of this research stated in Section 1.3 were examined in Chapter 3. A novel cycle-time model was developed to analyse and examine the manual and the automatic cycle-times obtained from experimental work conducted on post-Panamax QSCs. The cycle-time analysis of QSCs has provided the following implications:

1) Employment of automatic devices on the conventional QSCs substantially reduces the loading and discharging time of containerships.

2) The total percentage of saving of the entire QSC time even under conservative assumptions may be substantial. The assumptions may be considered conservatively since there exists uncertainties about capabilities of different automated systems offered by different manufacturers, drivers' skills, extent of time-savings, possible rise or falls in the prices of the cranes, interest rates, inflation, subsidies, future developments in the quayside cranes and the frequency, number and size of the containerships calling at the ports, etc.

3) Upon the proper utilisation of the QSC productive time, the cost of investment in automatic devices is recoverable within a few months. The sensitivity analysis has revealed that even under the least desirable assumption there will be an acceptable rate of return on investment.

4) There may be intangible benefits obtained from a safer operation of the QSCs, reduction in human errors, optimised and integrated operation of the QSCs. The benefits may be obtained using advanced safety switches, fault monitoring and detection, trolley collision controllers, smart spreaders capable of automatic identification and positioning of containers, sway dampening and optimum path generator systems installed on post-Panamax QSCs. The above benefits, however, may be difficult to quantify monetarily.

5) Enhancement of the QSCs' cycle-times through automation would produce a considerable benefit for port users such as shipping companies, their charter parties and individual users since it significantly reduces the turnaround-time of the containerships at ports.

The analysis and evaluations in Chapter 3 have discussed the probable benefits that may be accrued from automation of QSC under optimistic and ideal assumptions that there are always sufficient containerships available to be served by automated QSCs. The study in Chapter 4 has used queuing algorithms and has produced a break-even model to establish a balance between the cost of containership waiting-times and the cost of the probable berth idle (unproductive) times. The analysis has demonstrated that:

6) Automation of the QSCs significantly reduces the total turnaround-times of containerships.

7) The costly automated QSCs in some small to medium size container terminals remain idle and therefore unproductive for a considerable duration of time due to the automation being introduced without an appropriate increase in containerships' arrivals.

8) It has been argued that there should be balance between the cost of containership waiting-times and the cost of automated berth unproductive-times (idle-times). The study has proposed a break-even value model to establish such a balance.

9) The break-even model proposed in this thesis can be used to find a feasible level of automation in terms of the number of cycles that an automated QSC (considered as a server) should perform when compared with the actual rate of containership arrivals.

10) The case study examined in Chapter 4 has revealed that the port operators in some container terminals should review their port policies to attract more containerships to satisfy the requirements of a break-even value model. In some cases the investment in automation of QSCs may not be feasible and therefore it may not be considered a valid policy unless the excess capacity, which is wasted, is utilised by attracting more containerships.

Chapter 5 has proposed a generic formula to calculate the maximum annual throughput for container terminals with different layouts using semi-automated SC and RTG and automated and semi-automated RMG operating systems. It has incorporated most of the dynamic and static aspects of the container yard operations such as the average stacking height based on the size and capability, average dwell-times, transhipment ratio and under portal span of automated and semi-automated systems to calculate the annual throughput for the proposed terminal sizes. The analysis has concluded the following:

11) It has been found that as the size of container terminal increases, the total number of container Ground Slots (GSs) improves significantly for RMG and RTG systems.

12) The semi-automated SC system analysed in the study has provided a better land utilization, number of container GSs and terminal throughput than the semi-automated RTG and automated RMG systems only for single berth or small size container terminals.

13) The total annual throughput reduces in order of the SC, RMG and RTG for single-berth terminals. The total annual throughput reduces in order of the RMG, RTG and SC handling systems for double-berth and larger size container terminals.

14) The analysis has implied that as the size of the container terminals increase beyond the dimensions stated in Chapter 5, the semi-automated SC systems might produce the least annual throughput which may be considered as a significant disadvantage for this system. This has happened mainly due to the limited vertical stacking capability of the SC system compared with the RTG and the RMG systems.

15) The annual throughput of container terminals may vary considerably as the average dwell-times for specific cranes vary.

16) Due to a large difference in the annual throughputs obtained, a careful decision should be made when selecting a handling system for a container terminal.

17) In the design procedure and the selection of a suitable operating system for a container terminal, it is crucial to adopt a semi-automated or fully automated crane system that satisfies the required terminal capacity.

18) The resulting annual throughputs from the proposed model may be considered to be useful for decision-makers to determine the most suitable operating system for their terminal at the strategic stage.

Chapter 6 has proposed a generic model to analyse, evaluate and measure the cost efficiency and effectiveness of automated and semi-automated container yard operating systems over others. It has considered different but important cost functions and attributes used in modern container terminals. The size, annual throughput, mode of operation and the size and stacking height of yard equipment together with the important cost parameters are considered. The cost parameters include the land, container yard development, maintenance, operation, depreciation and procurement costs. It also includes the yard equipment, transfer vehicles and labour costs. The model developed enables the designer, planner and decision-makers of a container terminal to set-up a comparison analysis platform to measure the impact of different cost parameters involved on the selection of a system. Chapter 6 has proposed a sensitivity analysis tool to measure the relative magnitude and preferences of the systems and attributes and provided a basis for the pair-wise comparisons of container yard operating systems for decision-making. It has provided the following implications:

19) An automated RMG promises a lower cost per container processed than both of the semi-automated RTG and SC systems.

20) An automated and or semi-automated RMG system may be preferred over a semi-automated SC or a semi-automated RTG system in the majority of cost parameters evaluated.

21) The results obtained from the generic cost function model developed may be used to measure the performance scores and may be used as a tool to set-up the basis for a pair-wise comparison of cost efficiency and effectiveness of yard equipment. The results obtained from the model may provide confidence grounds to select or reject equipment or a system to be employed.

Chapter 7 has provided a decision-support model to analyse the most important attributes obtained in previous chapters. In Chapter 7 the concept of the Multiple Attribute Decision-Making (MADM) has been introduced. The proposed model has employed an Analytical Hierarch Process (AHP) method to solve decision-making problems to select the most desirable automated or semi-automated container yard operating system. In this process, a selection of quantitative attributes identified in the previous chapters together with qualitative attributes identified in the process of this research have been evaluated. The following statements have been concluded from Chapter 7:

22) The MADM and the AHP analysis may enable the decision-maker to effectively incorporate qualitative attributes as well as quantitative values for decision problems in the container yard operations.

23) The study has illustrated that an automated RMG system evaluated in this thesis has gained the highest ranking compared with the semi-automated RTG and SC container yard operating systems.

24) The AHP analysis has prioritised the RMG, RTG and SC systems in a ranking manner.

8.2 Limitations

The results of the manual and the automated QSCs analysis in Chapters 3 and 4 may appear different for ports with different operational environments, situated in different climate, economical and political regions. It should be noted that the cycle-times values of the QSCs may not be precise since the loading and discharging operations could have been impacted by the bowing effect of the QSC and ships movements such as yaw, roll, pitch, sway, surge and heave effects. These effects would result in the inaccuracy of the cycle-time measurements.

The cost-based evaluation in Chapter 4 has been difficult to establish because the terminal operators were reluctant and some times refused to cooperate and produce their cost data even for academic purposes. This is natural since a misuse and even misinterpretation of cost data may indicate that a particular container terminal entails an economical drain rather than a revenue generator.

Chapter 5 has considered the layout and procedures for calculating the annual throughputs for semi-automated SC and RTG and semi-automated and automated RMG systems. Only the results with container yard widths of 300, 320, 350, 600 and 700 and container yard depths of 300, 400, 500 and 600 metres, dwell-times of 3, 5, 7 and 10 days, transhipment ratios of 0.4, 0.5 and 0.6 and stacking height of up to 1 over 6 containers have been analysed. It might be necessary to calculate the annual handling capacity for other combinations and dimensions using the equations and procedures proposed in Chapter 5.

In the analysis of the cost attributes in Chapter 6 a similar problem in the study of Chapter 4 was faced. It was experienced that for the same reason the managers in the port industries were reluctant to provide cost values and parameters of their container yard operating systems. The Bandar Abbas Container Terminals (BACT) experience confirms that this is natural since high costs generally indicate the inefficiency and un-productivity of the systems and may indicate failures of decisions-makers in selecting the best strategy to some extent.

8.3 Discussion and recommendations for future works

QSCs cycle-times, container berth un-productive times and containerships' waiting-times have been analysed from the viewpoint of terminal operators and designers. This implies that the cost-benefit analysis of the QSCs cycle-times is viewed from the interest point of view of the port owners and operators. Additional studies may be worthwhile in order to evaluate and examine the benefits that may accrue for shipping companies and individual port users when the quayside facilities are automated. The cycle-time analysis and evaluations have been performed for containerships under the single-cycle mode of operation. Further studies may be required to measure the benefits of shortening the crane cycle-times operating under double and multi-task modes of operations.

The examination of the arrival rate of the containerships and service rate of the manual and the automated quayside facilities has been conducted to find a balance between the cost of containership waiting-times and the cost of automated berth idle (unproductive) times. A further study may be worthwhile to investigate the implications of the automation of yard cranes on the cycle-times and dwell-times of containers and the satisfaction (or dissatisfaction) of port users.

The layout and capacity of the semi-automated SC and RTG and semi-automated and automated RMG systems have been analysed and evaluated in this research. Further studies may be worthwhile to evaluate systems employing automated shuttle, automated overhead grid rails or other semi-automated and automated container yard operating systems using the Automated Guided Vehicles (AGVs). This study has developed a cost-based model to evaluate the cost efficiency of automated and semi-automated container yard operating systems. Further studies may be required to evaluate the benefits gained in terms of revenue generated from the automated equipment or operating systems.

The MADM and the AHP approaches proposed in this research may be recommended as a sound methodology that container terminals can easily adopt as decision-support tools at the strategic and operational levels. The proposed methodology may be used for the selection decisions of automation technologies in a container terminal operation. It would be worthwhile investigating the applicability of AHP in the process of planning and design and or re-design of container terminals to meet the needs of the port operators and users. Further studies may be worthwhile to compare the manual and the automated ports using the MADM and AHP methods.

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Appendices

Appendix 1 Publications arising from the research

- **Refereed articles published or submitted for publication.**

1. Kiani, M., Wang, J., Bonsall, S. and Wall, A. (2006-a) An Experimental Evaluation of the Economic Feasibility of Automated Quayside Cranes, *Journal of Marine Technology Society*, Spring Edition, No. 40, (Issue 1), pp. 24-34.

2. Kiani, M., Bonsall, S., Wang, J. and Wall, A. (2006-b) Container Re-handling Minimisation as a Prerequisite for Container Terminal Automation, *Journal of Euroship*, June, No. 13, pp. 9-14.

3. Kiani, M., Bonsall, S., Wang, J. and Wall, A. (2006-c) A Break-even Model for Evaluating the Cost of Containerships' Waiting-times and Berth Unproductive-Times in Automated Quayside Operations, *The WMU Journal of Maritime Affairs*, No. 5, (Issue 2), pp. 153-179.

4. Kiani, M., Bonsall, S., Wang, J. and Wall, A. (2007-a) Multiple Attribute Decision-Making and Analytical Hierarchy Process for Selecting the Best Yard Operating System, (*accepted for publication in the Journal of Marine Technology Society, Summer* 2007).

- **Refereed seminar publications and presentations.**

1. Kiani, M. (2004) Quayside Crane Cycle-time Analysis, *IRCE Seminar*, 5th July 2004, University of Manchester (UMIST), UK.

2. Kiani, M. (2005) Analysis of Containerships' Waiting-times and Berth Idle-times, *IRCE Seminar*, 2nd July 2005, University of Leeds, UK.

3. Kiani, M. (2007) Application of Multiple Attribute Decision-Making (MADM) and Analytical Hierarchy Process (AHP) in Container Terminal Operations, TRANS-NAV 2007, 20-22 June 2007, Gdynia, Poland.

- **Articles in hand.**

1. Kiani, M., Bonsall, S., Wang, J. and Wall, A. (2007-b) Cost Function Modelling for Automated Yard Crane Operations, (*under submission for publication in the Journal of Marine Technology Society*).

Appendix 2 Data for the manual and the automated quayside operations obtained from the BACT

Table A.2.1 Manual quayside operations

Jan-02

The Port of Bandar Abbas Container Terminals-Conventional Quayside Cranes

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2320	27.25	85.14	21.28
2	2715	32.50	83.54	20.88
3	3100	32.50	95.38	23.85
4	2450	28.25	86.73	21.68
5	1995	22.75	87.69	21.92
6	2450	30.25	80.99	20.25
7	2720	31.75	85.67	21.42
Total:	17750	205.25	–	–
Mean / Average:		29.32	86.45	21.61

Feb-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2250	23.50	95.74	23.94
2	2430	26.75	90.84	22.71
3	2090	21.00	99.52	24.88
4	2455	25.25	97.23	24.31
5	2310	23.50	98.30	24.57
6	1285	18.75	68.53	17.13
7	1355	19.25	70.39	17.60
8	2020	22.50	89.78	22.44
Total:	16195	180.50	–	–
Mean / Average:		22.56	88.79	22.20

Mar-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2445	26.25	93.14	23.29
2	2983	31.25	95.46	23.86
3	1235	17.50	70.57	17.64
4	3150	30.50	103.28	25.82
5	2216	22.75	97.41	24.35
6	2915	29.50	98.81	24.70
7	2335	24.50	95.31	23.83
8	1430	19.25	74.29	18.57
9	2728	27.25	100.11	25.03
10	2224	26.50	83.92	20.98
11	1875	23.00	81.52	20.38
Total:	25536	278.25	–	–
Mean / Average:		25.30	90.35	22.59

Apr-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2150	24.25	88.66	22.16
2	1110	17.75	62.54	15.63
3	2765	32.50	85.08	21.27
4	1880	22.75	82.64	20.66
5	2324	26.00	89.38	22.35
6	2727	29.50	92.44	23.11
7	3025	33.25	90.98	22.74
8	1966	25.75	76.35	19.09
9	2467	26.75	92.22	23.06
10	1655	23.00	71.96	17.99
11	2240	25.50	87.84	21.96
12	2115	22.75	92.97	23.24
13	2175	20.25	107.41	26.85
Total:	28599	330.00	–	–
Mean / Average:		25.38	86.19	21.55

May-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3345	36.50	91.64	22.91
2	2674	29.00	92.21	23.05
3	1583	19.75	80.15	20.04
4	2185	23.50	92.98	23.24
5	1740	21.50	80.93	20.23
6	2550	29.25	87.18	21.79
7	2121	22.75	93.23	23.31
8	1050	17.25	60.87	15.22
9	2465	26.00	94.81	23.70
10	2955	31.25	94.56	23.64
Total:	22668	256.75	–	–
Mean / Average:		25.68	86.86	21.71

Jun-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2650	29.25	90.60	22.65
2	1880	22.50	83.56	20.89
3	2345	26.75	87.66	21.92
4	3100	37.75	82.12	20.53
5	2767	31.50	87.84	21.96
6	2365	24.00	98.54	24.64
7	1985	23.00	86.30	21.58
8	2037	23.00	88.57	22.14
9	1210	18.75	64.53	16.13
10	2227	23.50	94.77	23.69
11	1694	20.75	81.64	20.41
Total:	24260	280.75	–	–
Mean / Average:		25.52	86.01	21.50

Jul-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	1250	14.50	86.21	21.55
2	2653	31.25	84.90	21.22
3	2385	26.25	90.86	22.71
4	3100	35.50	87.32	21.83
5	2785	30.25	92.07	23.02
6	2245	23.00	97.61	24.40
7	1950	22.50	86.67	21.67
8	2700	32.75	82.44	20.61
9	2527	29.25	86.39	21.60
10	3111	37.00	84.08	21.02
11	2655	31.75	83.62	20.91
12	2035	24.25	83.92	20.98
13	1935	22.00	87.95	21.99
14	2436	28.25	86.23	21.56
Total:	33767	388.50	–	–
Mean / Average:		27.75	87.16	21.79

Aug-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2725	33.25	81.95	20.49
2	1400	16.00	87.50	21.88
3	2325	26.00	89.42	22.36
4	2746	31.75	86.49	21.62
5	2075	24.75	83.84	20.96
6	3020	36.25	83.31	20.83
7	1086	13.00	83.54	20.88
8	1435	16.50	86.97	21.74
9	1364	15.25	89.44	22.36
10	2520	29.50	85.42	21.36
Total:	20696	242.25	–	–
Mean / Average:		24.23	85.79	21.45

Sep-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2210	25.25	87.52	21.88
2	1837	21.00	87.48	21.87
3	3055	37.75	80.93	20.23
4	2560	30.50	83.93	20.98
5	2325	27.00	86.11	21.53
6	1430	17.50	81.71	20.43
7	2663	33.25	80.09	20.02
8	2458	28.50	86.25	21.56
9	2230	25.00	89.20	22.30
10	1115	12.75	87.45	21.86
11	2636	32.50	81.11	20.28
12	1480	19.25	76.88	19.22
Total:	25999	310.25	–	–
Mean / Average:		25.85	84.06	21.01

Oct-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2245	26.25	85.52	21.38
2	2763	33.50	82.48	20.62
3	1700	20.75	81.93	20.48
4	3005	36.00	83.47	20.87
5	2765	32.25	85.74	21.43
6	2487	29.00	85.76	21.44
7	2216	25.50	86.90	21.73
8	2235	26.50	84.34	21.08
9	1955	24.25	80.62	20.15
10	3015	35.75	84.34	21.08
11	2940	35.75	82.24	20.56
12	2336	28.00	83.43	20.86
Total:	29662	353.50	–	–
Mean / Average:		29.46	83.90	20.97

Nov-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2653	32.00	82.91	20.73
2	2210	25.25	87.52	21.88
3	2785	34.50	80.72	20.18
4	3120	38.00	82.11	20.53
5	1650	20.50	80.49	20.12
6	2865	33.25	86.17	21.54
7	3012	36.50	82.52	20.63
8	2420	27.25	88.81	22.20
9	2268	26.00	87.23	21.81
10	1900	23.75	80.00	20.00
11	2175	25.25	86.14	21.53
12	2543	30.25	84.07	21.02
13	1300	15.75	82.54	20.63
Total:	30901	368.25	–	–
Mean / Average:		28.33	83.94	20.98

Dec-02

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	1985	24.00	82.71	20.68
2	2712	32.25	84.09	21.02
3	3055	36.50	83.70	20.92
4	2877	35.25	81.62	20.40
5	2534	29.75	85.18	21.29
6	2385	27.25	87.52	21.88
7	2240	25.50	87.84	21.96
8	1500	17.75	84.51	21.13
9	2396	28.50	84.07	21.02
10	3235	39.00	82.95	20.74
Total:	24919	295.75	–	–
Mean / Average:		29.58	84.42	21.10

Table A.2.2 Summary of the manual operations

No.	Total Number of Containerships	Total containers Handled	Total Berth Occupancy	Average Berth Occupancy	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
Jan-02	7	17750	205.25	29.32	86.45	21.61
Feb-02	8	16195	180.50	22.56	88.79	22.20
Mar-02	11	25536	278.25	25.30	90.35	22.59
Apr-02	13	28599	230.00	25.38	86.19	21.55
May-02	10	22668	256.75	25.68	86.86	21.71
Jun-02	11	24260	280.75	25.52	86.01	21.50
Jul-02	14	33767	388.50	27.75	87.16	21.79
Aug-02	10	20696	242.25	24.23	85.79	21.45
Sep-02	12	25999	310.25	25.85	84.06	21.01
Oct-02	12	29662	353.50	29.46	83.90	20.91
Nov-02	13	30901	368.25	28.33	83.94	20.98
Dec-02	10	24919	295.75	29.58	84.42	21.10
Total: (12 Months = 365 days)	131	300952	3390.00	–	–	–
Mean / Average:	10.92	25079.33	282.50	26.58	86.16	21.53
Standard Deviation	2.07			2.27		

Table A.2.3 Automated quayside operations

Jan-03

The Port of Bandar Abbas Container Terminals-post-Panamax
Automated Quayside Cranes

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2928	15.50	188.90	47.23
2	3296	14.25	231.30	57.82
3	2911	15.25	190.89	47.72
4	3209	17.00	188.76	47.19
5	3533	14.25	247.93	61.98
6	3608	14.75	244.61	61.15
7	3125	13.75	227.27	56.82
8	3105	13.75	225.82	56.45
9	3304	13.25	249.36	62.34
10	3050	16.25	187.69	46.92
11	3470	15.25	227.54	56.89
12	2790	15.75	177.14	44.29
13	3292	17.00	193.65	48.41
Total:	41621	196.00	–	–
Mean / Average:		15.08	213.91	53.48

Feb-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2745	13.25	207.17	51.79
2	2721	13.25	205.36	51.34
3	2641	12.25	215.59	53.90
4	2611	13.50	193.41	48.35
5	2817	14.25	197.68	49.42
6	2413	12.00	201.08	50.27
7	2510	13.25	189.43	47.36
8	2918	14.00	208.43	52.11
9	2798	14.25	196.35	49.09
10	2533	14.00	180.93	45.23
11	2698	14.50	186.07	46.52
12	2447	13.50	181.26	45.31
13	2614	13.00	201.08	50.27
14	2409	13.75	175.20	43.80
15	2406	12.25	196.41	49.10
Total:	39281	201.00	–	–
Mean / Average:		13.40	195.70	48.92

Mar-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3014	14.75	204.34	51.08
2	2722	15.25	178.49	44.62
3	3011	15.50	194.26	48.56
4	2188	14.50	150.90	37.72
5	2648	13.75	192.58	48.15
6	2884	14.00	206.00	51.50
7	2912	15.25	190.95	47.74
8	2012	13.50	149.04	37.26
9	3300	13.50	244.44	61.11
10	2767	14.50	190.83	47.71
11	2009	15.25	131.74	32.93
12	2155	13.50	159.63	39.91
Total:	31622	173.25	–	–
Mean / Average:		14.44	182.77	45.69

Apr-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3365	13.25	253.96	63.49
2	2923	13.00	224.85	56.21
3	3217	12.25	262.61	65.65
4	2845	12.50	227.60	56.90
5	2764	14.00	197.43	49.36
6	2983	14.75	202.24	50.56
7	3055	16.50	185.15	46.29
8	3238	16.25	199.26	49.82
9	3705	15.50	239.03	59.76
10	3343	16.50	202.61	50.65
11	2988	15.50	192.77	48.19
12	3112	16.50	188.61	47.15
13	2787	15.25	182.75	45.69
14	2934	14.75	198.92	49.73
15	3276	15.25	214.82	53.70
16	3314	14.50	228.55	57.14
Total:	49849	236.25	–	–
Mean / Average:		14.77	212.57	53.14

May-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3211	14.25	225.33	56.33
2	2798	13.00	215.23	53.81
3	2973	14.50	205.03	51.26
4	3124	13.75	227.20	56.80
5	2780	15.00	185.33	46.33
6	3066	14.25	215.16	53.79
7	2543	13.50	188.37	47.09
8	3421	14.75	231.93	57.98
9	3185	13.00	245.00	61.25
10	2814	14.75	190.78	47.69
11	2700	15.25	177.05	44.26
12	2997	13.50	222.00	55.50
13	3016	12.25	246.20	61.55
14	2871	15.25	188.26	47.07
15	2533	14.25	177.75	44.44
Total:	44032	211.25	–	–
Mean / Average:		14.08	209.38	52.34

Jun-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2714	14.00	193.86	48.46
2	2922	13.75	212.51	53.13
3	3116	13.00	239.69	59.92
4	3071	12.75	240.86	60.22
5	2875	12.75	225.49	56.37
6	2597	12.50	207.76	51.94
7	2663	13.25	200.98	50.25
8	2934	12.50	234.72	58.68
9	3246	13.75	236.07	59.02
10	2711	12.00	225.92	56.48
11	2478	14.50	170.90	42.72
12	3235	13.25	244.15	61.04
Total:	34562	158.00	–	–
Mean / Average:		13.17	219.41	54.85

Jul-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2713	12.50	217.04	54.26
2	2219	13.25	167.47	41.87
3	2773	13.00	213.31	53.33
4	2522	12.25	205.88	51.47
5	2365	13.00	181.92	45.48
6	2749	13.25	207.47	51.87
7	2355	11.00	214.09	53.52
8	3112	13.25	234.87	58.72
9	3048	13.25	230.04	57.51
10	2295	12.75	180.00	45.00
11	2715	13.00	208.85	52.21
12	2778	12.25	226.78	56.69
13	2678	12.50	214.24	53.56
14	2935	12.50	234.80	58.70
15	2405	11.25	213.78	53.44
16	2552	11.00	232.00	58.00
Total:	42214	200.00	–	–
Mean / Average:		12.50	211.41	52.85

Aug-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2200	10.75	204.65	51.16
2	3175	14.25	222.81	55.70
3	2645	13.25	199.62	49.91
4	2538	12.75	199.06	49.76
5	2317	14.00	165.50	41.38
6	2850	13.50	211.11	52.78
7	2685	13.50	198.89	49.72
8	2315	12.25	188.98	47.24
9	2814	11.75	239.49	59.87
10	2885	12.50	230.80	57.70
11	2725	13.25	205.66	51.42
12	2838	12.75	222.59	55.65
13	2719	11.75	231.40	57.85
14	3118	13.75	226.76	56.69
Total:	37824	180.00	–	–
Mean / Average:		12.86	210.52	52.63

Sep-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3130	14.50	215.86	53.97
2	2940	13.75	213.82	53.45
3	2525	13.75	183.64	45.91
4	3215	14.25	225.61	56.40
5	2745	13.50	203.33	50.83
6	3118	13.75	226.76	56.69
7	2865	13.75	208.36	52.09
8	2115	15.50	136.45	34.11
9	2844	13.75	206.84	51.71
10	1394	14.50	96.14	24.03
11	2563	12.75	201.02	50.25
12	2495	13.50	184.81	46.20
13	3235	14.25	227.02	56.75
14	2675	12.75	209.80	52.45
15	3335	13.75	242.55	60.64
Total:	41194	208.00	–	–
Mean / Average:		13.87	198.80	49.70

Oct-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3350	14.50	231.03	57.76
2	3820	16.50	231.52	57.88
3	3255	18.25	178.36	44.59
4	3765	15.75	239.05	59.76
5	3720	16.75	222.09	55.52
6	2013	9.50	211.89	52.97
7	3723	14.25	261.26	65.32
8	3221	17.25	186.72	46.68
9	4135	16.75	246.87	61.72
10	3872	16.25	238.28	59.57
11	3632	16.00	227.00	56.75
12	3232	15.75	205.21	51.30
Total:	41738	187.50	–	–
Mean / Average:		15.63	223.27	55.82

Nov-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3606	18.50	194.92	48.73
2	3726	16.75	222.45	55.61
3	3415	15.25	223.93	55.98
4	2918	14.25	204.77	51.19
5	2355	12.00	196.25	49.06
6	3150	13.75	229.09	57.27
7	1725	9.25	186.49	46.62
8	1265	7.5	168.67	42.17
9	2287	12.00	190.58	47.65
10	3350	14.25	235.09	58.77
11	2726	13.00	209.69	52.42
12	1475	8.25	178.79	44.70
13	2377	10.75	221.12	55.28
14	2868	13.50	212.44	53.11
15	2412	11.00	219.27	54.82
Total:	39655	190.00	–	–
Mean / Average:		12.67	206.24	51.56

Dec-03

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2830	13.25	213.58	53.40
2	2915	14.25	204.56	51.14
3	2713	14.00	193.79	48.45
4	3300	15.50	212.90	53.23
5	2578	13.75	187.49	46.87
6	2455	12.25	200.41	50.10
7	2612	13.75	189.96	47.49
8	2845	14.50	196.21	49.05
9	2483	13.75	180.58	45.15
10	2316	12.00	193.00	48.25
11	2709	14.25	190.11	47.53
12	3462	15.50	223.35	55.84
13	3604	15.25	236.33	59.08
Total:	36822	182.00	–	–
Mean / Average:		14.00	201.71	50.43

Jan-04

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2813	14.00	200.93	50.23
2	2525	13.50	187.04	46.76
3	2627	13.50	194.59	48.65
4	2355	12.25	192.24	48.06
5	2505	12.75	196.47	49.12
6	2456	12.50	196.48	49.12
7	2557	13.25	192.98	48.25
8	2780	13.75	202.18	50.55
9	2730	13.25	206.04	51.51
10	2650	12.25	216.33	54.08
11	2948	13.50	218.37	54.59
12	2615	13.25	197.36	49.34
13	2550	13.00	196.15	49.04
Total:	34111	170.75	–	–
Mean / Average:		13.13	199.78	49.95

Feb-04

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3125	13.75	227.27	56.82
2	3256	14.25	228.49	57.12
3	3087	14.75	209.29	52.32
4	3134	13.75	227.93	56.98
5	2745	15.50	177.10	44.27
6	2312	14.25	162.25	40.56
7	2632	13.00	202.46	50.62
8	2128	16.25	130.95	32.74
9	2814	15.50	181.55	45.39
10	3565	16.00	222.81	55.70
11	2746	16.25	168.98	42.25
Total:	31544	163.25	–	–
Mean / Average:		14.84	194.46	48.62

Mar-04

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	2437	13.50	180.52	45.13
2	2128	13.25	160.60	40.15
3	3395	15.50	219.03	54.76
4	3567	15.00	237.80	59.45
5	3565	14.75	241.69	60.42
6	2978	15.00	198.53	49.63
7	2435	13.75	177.09	44.27
8	3434	16.50	208.12	52.03
9	3607	17.25	209.10	52.28
10	3765	17.75	212.11	53.03
Total:	31311	152.25	–	–
Mean / Average:		15.23	204.46	51.12

Apr-04

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3335	16.50	202.12	50.53
2	3622	15.75	229.97	57.49
3	3825	16.25	235.38	58.85
4	2468	13.75	179.49	44.87
5	3543	16.00	221.44	55.36
6	3034	12.75	237.96	59.49
7	2966	12.50	237.28	59.32
8	2376	12.25	193.96	48.49
9	3110	13.50	230.37	57.59
10	2612	12.25	213.22	53.31
11	3550	15.00	236.67	59.17
12	3117	12.75	244.47	61.12
13	3251	13.25	245.36	61.34
14	3575	15.50	230.65	57.66
15	3840	18.00	213.33	53.33
Total:	48224	216.00	–	–
Mean / Average:		14.40	223.44	55.86

May-04

No.	Total Boxes Handled / Containership	Berth Hours / Containership	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
1	3545	14.50	244.48	61.12
2	3115	13.50	230.74	57.69
3	3524	16.00	220.25	55.06
4	2846	12.75	223.22	55.80
5	2968	13.00	228.31	57.08
6	3327	13.75	241.96	60.49
7	1275	9.75	130.77	32.69
8	2645	12.50	211.60	52.90
9	3455	15.25	226.56	56.64
10	2943	12.25	240.24	60.06
11	3712	15.75	235.68	58.92
12	1976	11.00	179.64	44.91
13	2534	12.25	206.86	51.71
14	2645	12.75	207.45	51.86
Total:	40510	185.00	–	–
Mean / Average:		13.21	216.27	54.07

Table A.2.4 Summary of the automated operations

No.	Total Number of Containerships	Total Containers Handled	Total Berth Occupancy	Average Berth Occupancy	Average Berth Productivity (Moves / Hour)	Average Crane Productivity (Moves / Hour)
Jan-03	13	41621	196.00	15.08	213.91	53.48
Feb-03	15	39281	201.00	13.40	195.70	48.92
Mar-03	12	31622	173.25	14.44	182.77	45.69
Apr-03	16	49849	236.25	14.77	212.57	53.14
May-03	15	44032	211.25	14.08	209.38	52.34
Jun-03	12	34562	158.00	13.17	219.41	54.85
Jul-03	16	42214	200.00	12.50	211.41	52.85
Aug-03	14	37824	180.00	12.86	210.52	52.63
Sep-03	15	41194	208.00	13.87	198.80	49.70
Oct-03	12	41738	187.50	15.63	223.27	55.82
Nov-03	15	39655	190.00	12.67	206.24	51.56
Dec-03	13	36822	182.00	14.00	201.71	50.43
Jan-04	13	34111	170.75	13.13	199.78	49.95
Feb-04	11	31544	163.25	14.84	194.46	48.62
Mar-04	10	31311	152.25	15.23	204.46	51.12
Apr-04	15	48224	216.00	14.40	223.44	55.86
May-04	14	40510	185.00	13.21	216.27	54.07
Total: (17 Months = 518 days)	231	666114	3211	–	–	–
Mean / Average:	13.59	39183.18	188.85	13.96	207.30	51.83
Standard Deviation	1.77			0.96		

Appendix 3 Results for a combination of different container yard sizes with different transhipment ratio and dwell-times

Figures A.3.1, A.3.2 and A.3.3 show the comparison of GSs for selected sizes. They illustrate that as the size of a terminal increases the ranking order of the container yard operating systems changes.

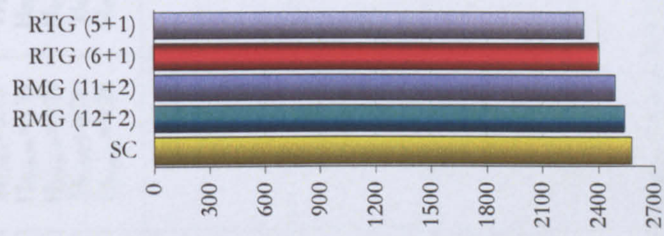

Figure A.3.1 Comparison of GSs for W_{CY} = 300 metres and D_{CY} = 300 metres

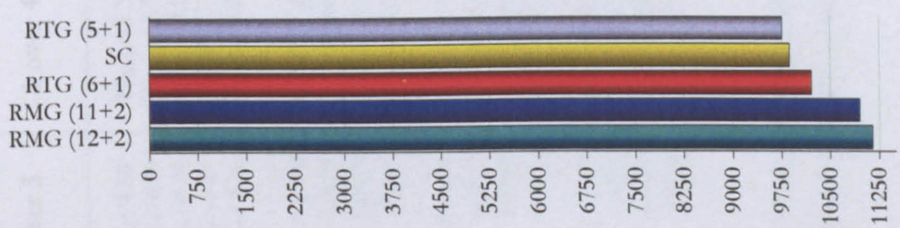

Figure A.3.2 Comparison of GSs for W_{CY} = 600 metres and D_{CY} = 600 metres

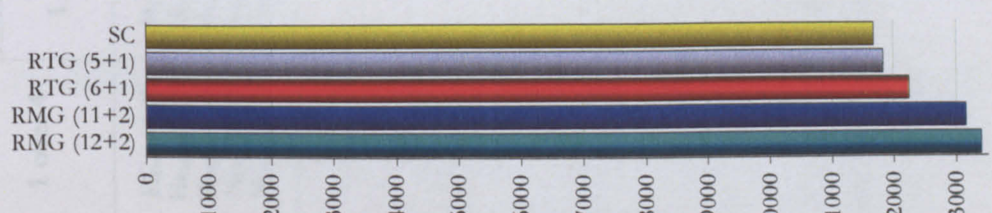

Figure A.3.3 Comparison of GSs for W_{CY} = 700 metres and D_{CY} = 600 metres

Table A.3.1 C_Y for systems with W_{CY} = 300 metres and D_{CY} = 300 metres

Average transhipment ratio	Average dwell days (T_{dwell})	SC			RTG				RMG			
					5 +1		6+1		11+2		12+2	
		1 over 2	1 over 3	1 over 4	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5
		H_{Trans}=2.25 H_{Export}=2.25 H_{Import}=2.00 $H_{G\&R}$=2.25 H_{Empty}=2.25	H_{Trans}=3.00 H_{Export}=3.00 H_{Import}=2.60 $H_{G\&R}$=3.00 H_{Empty}=3.40	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10
0.4	3	503554	667287	834109	751235	907045	777387	938622	805654	972751	821037	991325
	5	302132	400372	500465	450741	544227	466432	563173	483392	583651	492622	594795
	7	215809	285980	357475	321958	388734	333166	402266	345280	416893	351873	424854
	10	151066	200186	250233	225370	272114	233216	281586	241696	291825	246311	297398
0.5	3	564039	747745	934681	841815	1015997	871120	1051366	902796	1089596	920034	1110401
	5	338424	448647	560809	505089	609598	522672	630820	541677	653757	552020	666241
	7	241731	320462	400578	360778	435427	373337	450586	386912	466970	394300	475886
	10	169212	224323	280404	252545	304799	261336	315410	270839	326879	276010	333120
0.6	3	641039	850266	1062832	957233	1154697	990557	1194894	1026575	1238342	1046177	1261988
	5	384624	510159	637699	574340	692818	594334	716936	615945	743005	627706	757193
	7	274731	364400	455500	410243	494870	424524	512097	439961	530718	448361	540852
	10	192312	255080	318850	287170	346409	297167	358468	307973	371503	313853	378596

Tables A.3.1 to A.3.3 show the maximum annual throughput for container terminals with selected sizes. Figures A.3.4 to A.3.15 show the relationship between the annual throughput, dwell-days and the transhipment ratios of 0.4, 0.5 and 0.6 for selected container terminal sizes where the operating system is capable of stacking five containers high (1 over 4).

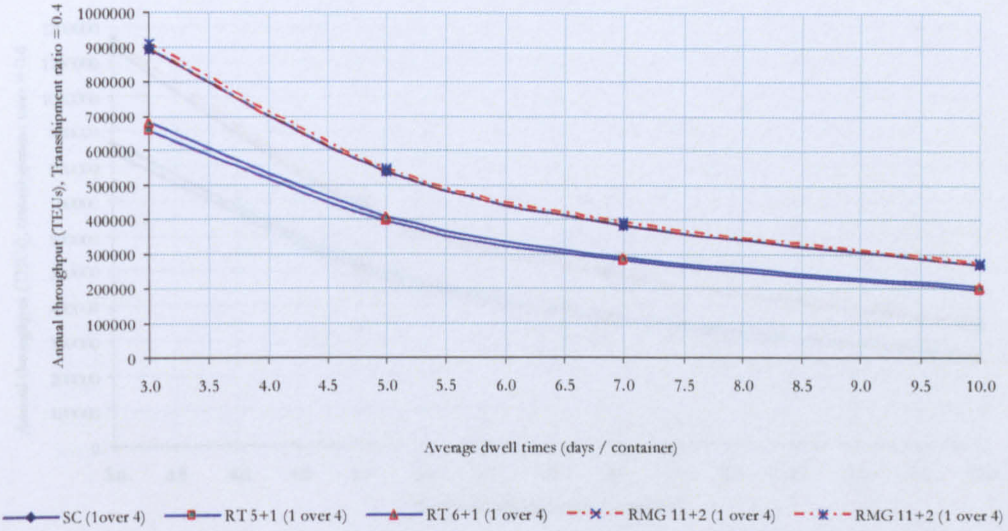

Figure A.3.4 C_Y & T_{dwell} for ω = 40% in W_{CY} = 300 metres and D_{CY} = 300 metres

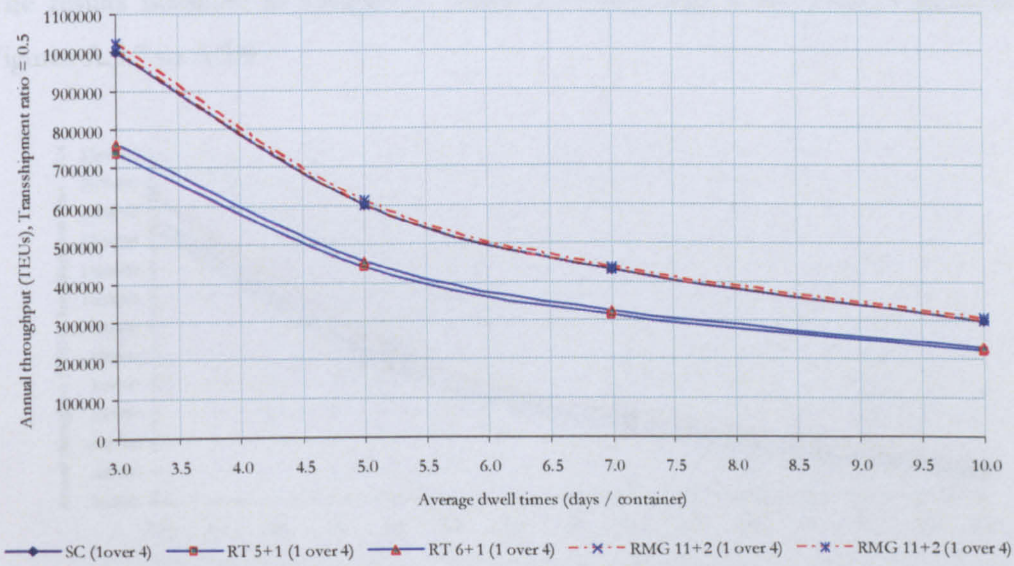

Figure A.3.5 C_Y & T_{dwell} for ω = 50% in W_{CY} = 300 metres and D_{CY} = 300 metres

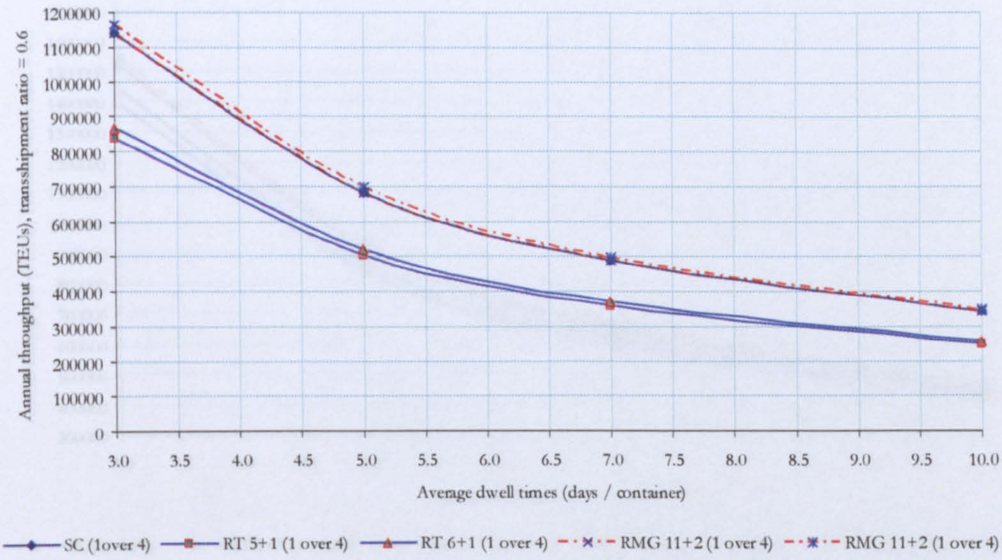

Figure A.3.6 C_Y & T_{dwell} for ω = 60% in W_{CY} = 300 metres and D_{CY} = 300 metres

The results obtained in Chapter 5, Table 5.10 and Step 8 are used to illustrate Figures A.3.7 to A.3.9

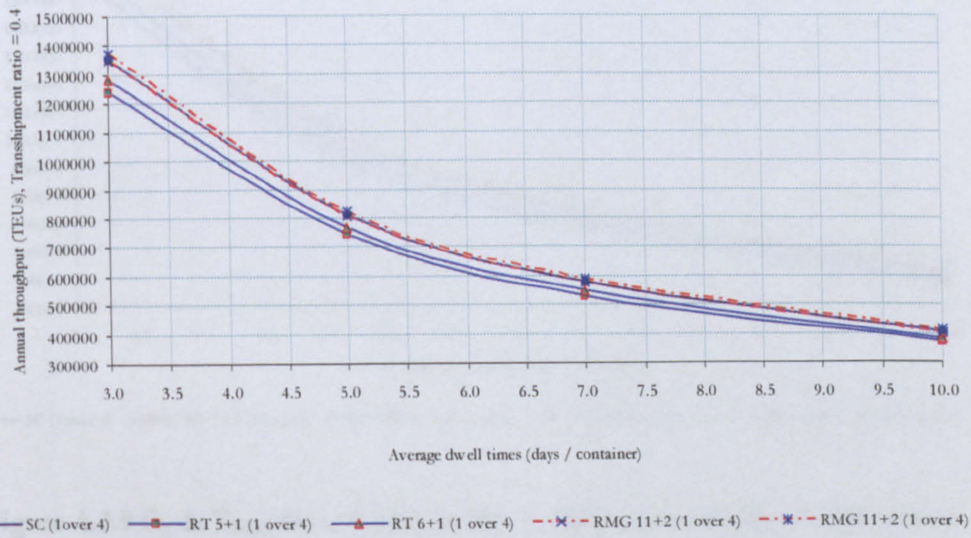

Figure A.3.7 C_Y & T_{dwell} for ω = 40% in W_{CY} = 350 metres and D_{CY} = 400 metres

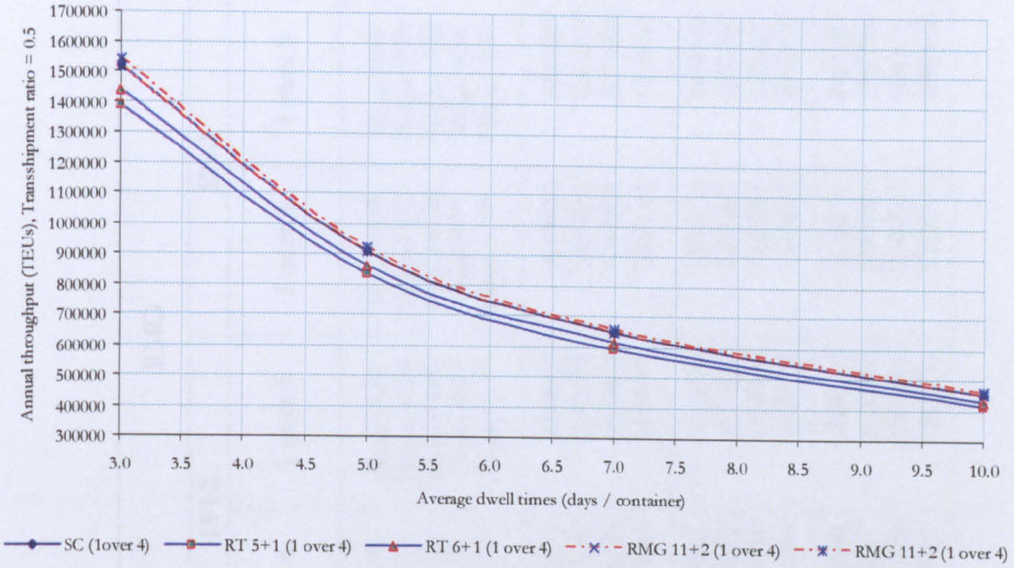

Figure A.3.8 C_Y & T_{dwell} for ω = 50% in W_{CY} = 350 metres and D_{CY} = 400 metres

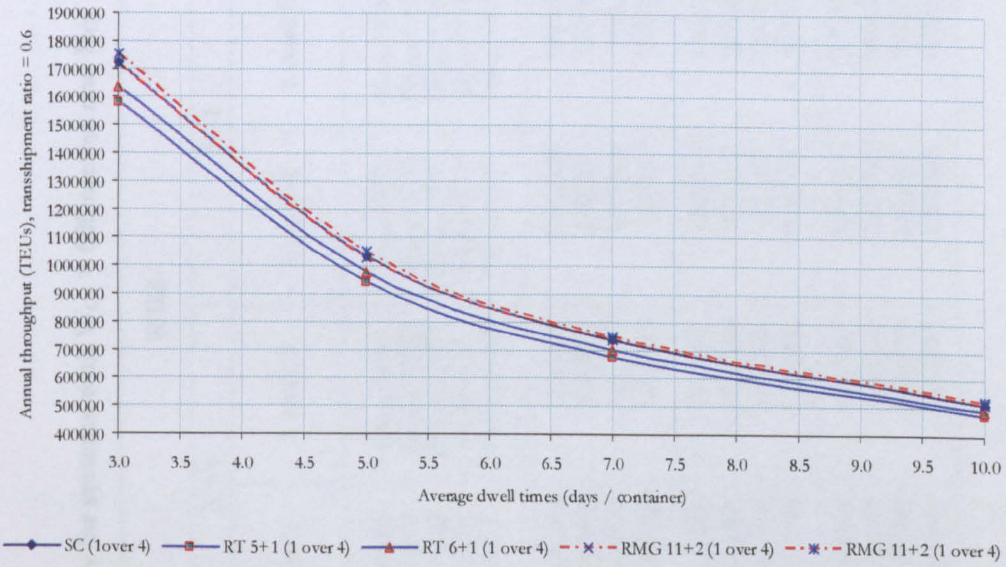

Figure A.3.9 C_Y & T_{dwell} for ω = 60% in W_{CY} = 350 metres and D_{CY} = 400 metres

Table A.3.2 C_Y for systems with W_{CY} = 600 metres and D_{CY} = 600 metres

Average transhipment ratio	Average dwell days (T_{dwell})	SC			RTG				RMG			
					5 +1		6+1		11+2		12+2	
		1 over 2	1 over 3	1 over 4	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5
		H_{Trans}=2.25 H_{Export}=2.25 H_{Import}=2.00 $H_{G\&R}$=2.25 H_{Empty}=2.25	H_{Trans}=3.00 H_{Export}=3.00 H_{Import}=2.60 $H_{G\&R}$=3.00 H_{Empty}=3.40	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10	H_{Trans}=3.75 H_{Export}=3.75 H_{Import}=3.25 $H_{G\&R}$=3.75 H_{Empty}=4.25	H_{Trans}=4.50 H_{Export}=4.50 H_{Import}=4.00 $H_{G\&R}$=4.50 H_{Empty}=5.10
0.4	3	2145164	2842675	3553344	3188088	3849316	3301024	3985676	3932671	4748330	4008815	4840267
	5	1287099	1705605	2132007	1912853	2309590	1980614	2391405	2359603	2848998	2405289	2904160
	7	919356	1218289	1522862	1366323	1649707	1414724	1708147	1685430	2034999	1718064	2074400
	10	643549	852803	1066003	956426	1154795	990307	1195703	1179801	1424499	1202645	1452080
0.5	3	2402836	3185431	3981789	3572492	4311687	3699045	4464425	4406853	5318688	4492178	5421668
	5	1441702	1911259	2389073	2143495	2587012	2219427	2678655	2644112	3191213	2695307	3253001
	7	1029787	1365185	1706481	1531068	1847866	1585305	1913325	1888651	2279438	1925219	2323572
	10	720851	955629	1194537	1071748	1293506	1109713	1339327	1322056	1595606	1347653	1626500
0.6	3	2730860	3622175	4527719	4062304	4900298	4206208	5073887	5011062	6044770	5108086	6161809
	5	1638516	2173305	2716631	2437383	2940179	2523725	3044332	3006637	3626862	3064851	3697085
	7	1170369	1552361	1940451	1740988	2100128	1802661	2174523	2147598	2590616	2189180	2640775
	10	819258	1086652	1358316	1218691	1470089	1261863	1522166	1503319	1813431	1532426	1848543

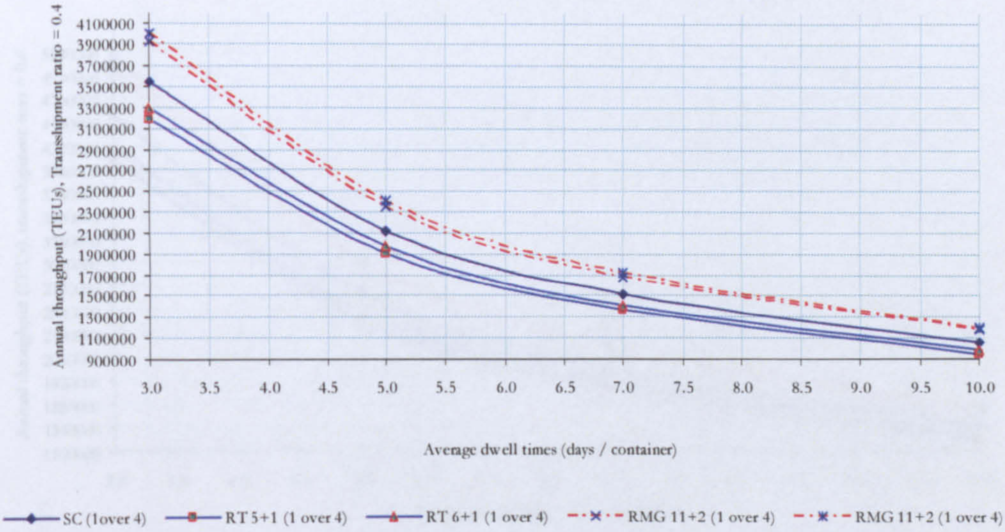

Figure A.3.10 C_Y & T_{dwell} for ω = 40% in W_{CY} = 600 metres and D_{CY} = 600 metres

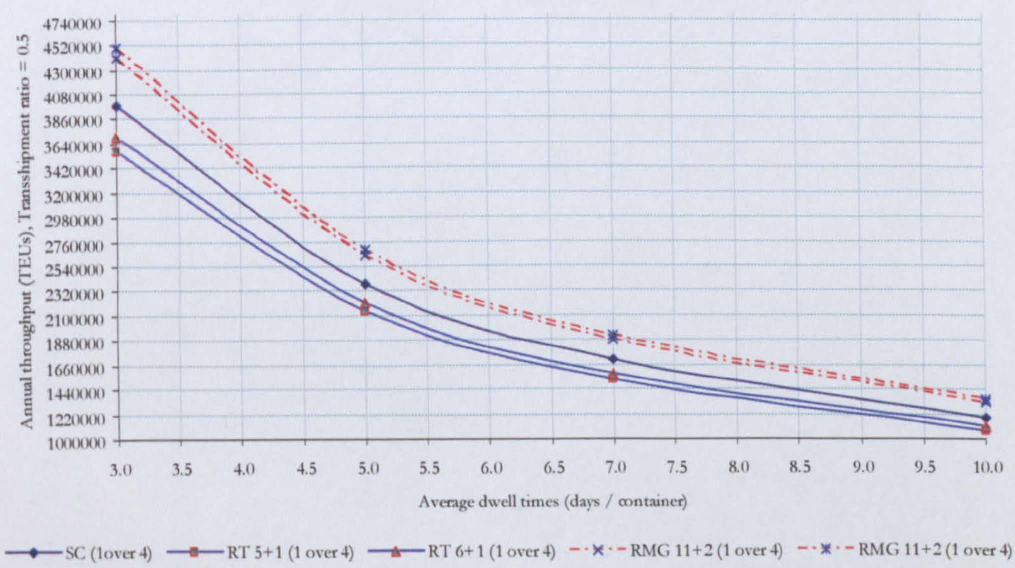

Figure A.3.11 C_Y & T_{dwell} for ω = 50% in W_{CY} = 600 metres and D_{CY} = 600 metres

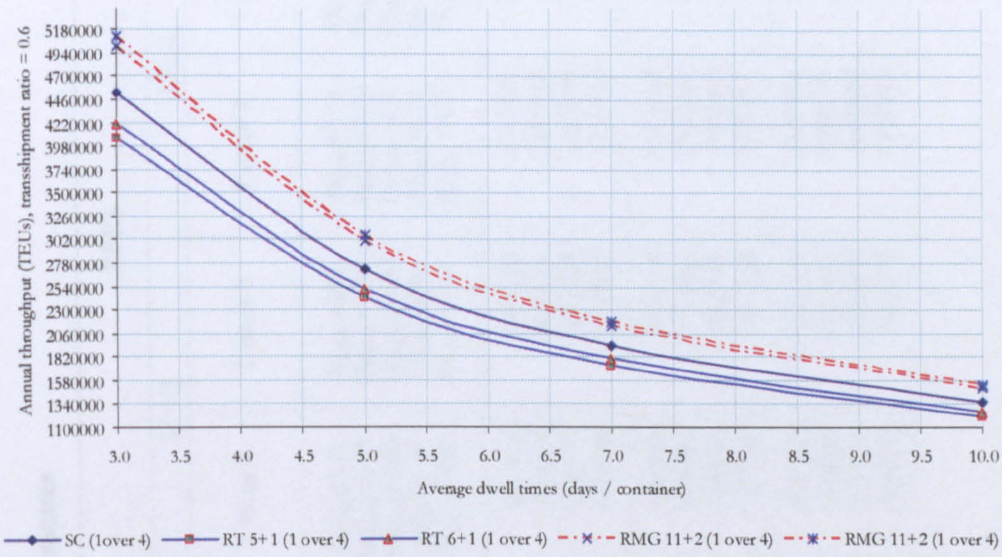

Figure A.3.12 C_Y & T_{dwell} for $\omega = 60\%$ in $W_{CY} = 600$ metres and $D_{CY} = 600$ metres

Table A.3.3 C_Y for systems with W_{CY} = 700 metres and D_{CY} = 600 metres

Average transhipment ratio	Average dwell days (T_{dwell})	SC			RTG				RMG			
					5 +1		6+1		11+2		12+2	
		1 over 2	1 over 3	1 over 4	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5
		$H_{Trans}=2.25$ $H_{Export}=2.25$ $H_{Import}=2.00$ $H_{G\&R}=2.25$ $H_{Empty}=2.25$	$H_{Trans}=3.00$ $H_{Export}=3.00$ $H_{Import}=2.60$ $H_{G\&R}=3.00$ $H_{Empty}=3.40$	$H_{Trans}=3.75$ $H_{Export}=3.75$ $H_{Import}=3.25$ $H_{G\&R}=3.75$ $H_{Empty}=4.25$	$H_{Trans}=3.75$ $H_{Export}=3.75$ $H_{Import}=3.25$ $H_{G\&R}=3.75$ $H_{Empty}=4.25$	$H_{Trans}=4.50$ $H_{Export}=4.50$ $H_{Import}=4.00$ $H_{G\&R}=4.50$ $H_{Empty}=5.10$	$H_{Trans}=3.75$ $H_{Export}=3.75$ $H_{Import}=3.25$ $H_{G\&R}=3.75$ $H_{Empty}=4.25$	$H_{Trans}=4.50$ $H_{Export}=4.50$ $H_{Import}=4.00$ $H_{G\&R}=4.50$ $H_{Empty}=5.10$	$H_{Trans}=3.75$ $H_{Export}=3.75$ $H_{Import}=3.25$ $H_{G\&R}=3.75$ $H_{Empty}=4.25$	$H_{Trans}=4.50$ $H_{Export}=4.50$ $H_{Import}=4.00$ $H_{G\&R}=4.50$ $H_{Empty}=5.10$	$H_{Trans}=3.75$ $H_{Export}=3.75$ $H_{Import}=3.25$ $H_{G\&R}=3.75$ $H_{Empty}=4.25$	$H_{Trans}=4.50$ $H_{Export}=4.50$ $H_{Import}=4.00$ $H_{G\&R}=4.50$ $H_{Empty}=5.10$
0.4	3	2697818	3575027	4468784	4242635	5122582	4392375	5303379	3616136	4366144	3741881	4517969
	5	1618691	2145016	2681270	2545581	3073549	2635425	3182028	2169682	2619686	2245128	2710781
	7	1156208	1532155	1915193	1818272	2195393	1882446	2272877	1549773	1871205	1603663	1936272
	10	809345	1072508	1340635	1272790	1536775	1317712	1591014	1084841	1309843	1122564	1355391
0.5	3	3021873	4006086	5007608	4754191	5737894	4921986	5940408	4052152	4890594	4193058	5060656
	5	1813124	2403652	3004565	2852514	3442737	2953191	3564245	2431291	2934356	2515835	3036394
	7	1295089	1716894	2146118	2037510	2459098	2109422	2545889	1736636	2095969	1797025	2168853
	10	906562	1201826	1502282	1426257	1721368	1476596	1782122	1215645	1467178	1257917	1518197
0.6	3	3434405	4555347	5694184	5406022	6521205	5596823	6751365	4607729	5558235	4767954	5751513
	5	2060643	2733208	3416511	3243613	3912723	3358094	4050819	2764637	3334941	2860773	3450908
	7	1471888	1952292	2440365	2316867	2794802	2398638	2893442	1974741	2382101	2043409	2464934
	10	1030322	1366604	1708255	1621807	1956361	1679047	2025409	1382319	1667471	1430386	1725454

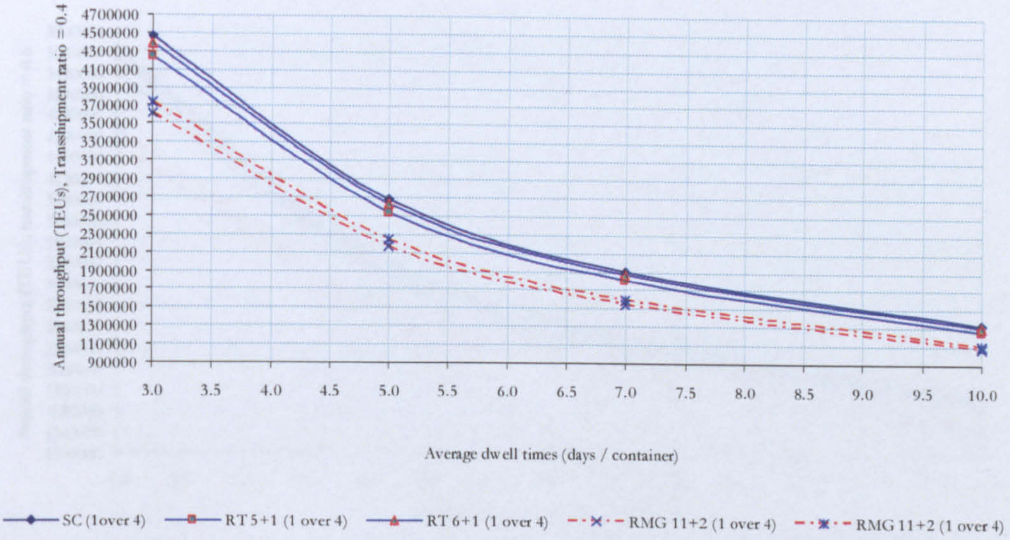

Figure A.3.13 C_Y & T_{dwell} for ω = 40% in W_{CY} =700 metres and D_{CY} = 600 metres

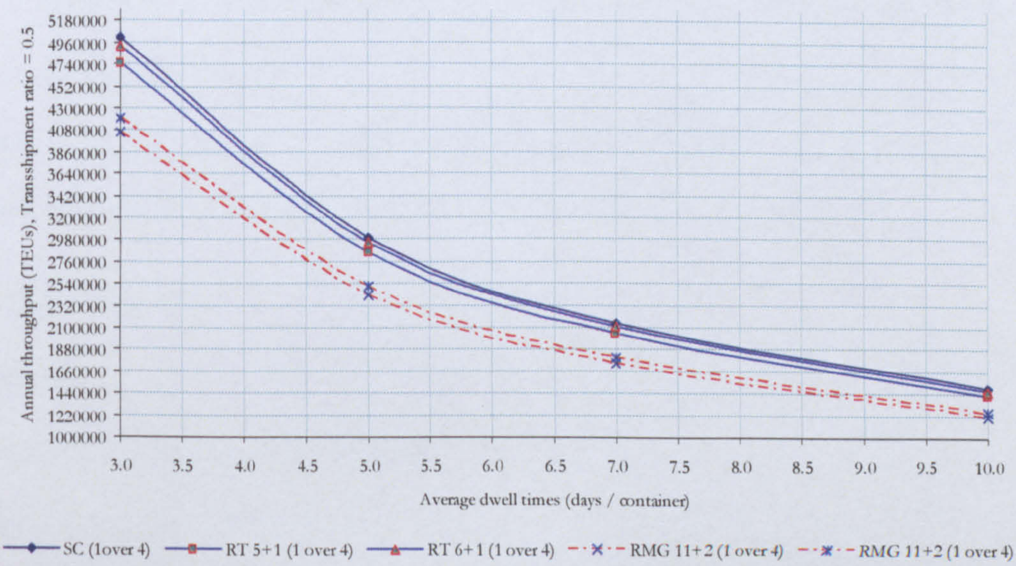

Figure A.3.14 C_Y & T_{dwell} for ω = 50% in W_{CY} =700 metres and D_{CY} = 600 metres

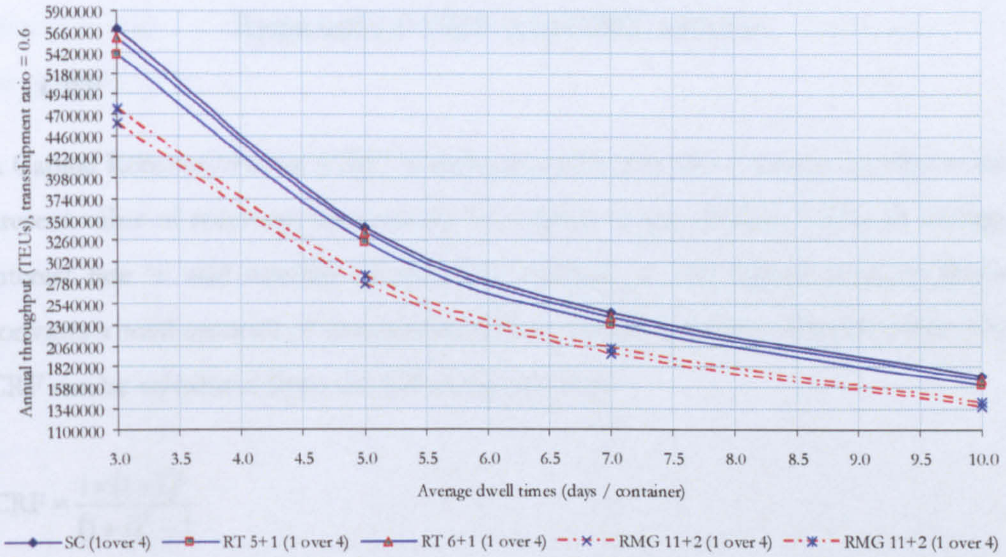

Figure A.3.15 C_Y & T_{dwell} for ω = 60% in W_{CY} =700 metres and D_{CY} = 600 metres

Appendix 4 CRF and FWF values

- **CRF**

A Capital Recovery Factor (CRF) is defined as the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Using an average interest rate `i` and number of annuities received `t`, the capital recovery factor converts a total amount of investment into an annuity amount of equal series. The CRF can be calculated from the following equation:

$$CRF = \frac{i \times (1+i)^t}{(1+i)^t - 1}$$

where:

t = Number of project life and

i = Average interest rate.

If `t = 1`, then CRF reduces to `1+i`. As `t` goes to infinity, the CRF goes to `i`. In this context, an annual cost of an investment can be expressed as follows:

P(IC) = IC x CRF

where:

P(IC) = Annual cost of investment.

IC = Initial cost of investment.

On the basis of the above statements, a total cost of an investment [TP(IC)] may be defined as:

TP(IC) = P(IC) x t.

- **FWF**

A Future Worth Factor (FWF) converts a present value of an investment into a future amount using an average interest rate `i` and number of economic life in years expected from a project `t`. The FWF = $(1+i)^{t-1}$. In this context `1/ $(1+i)^{t-1}$` would be a Present Worth Factor (PWF) that converts a future amount into a present value. If `t = 0`, then FWF reduces to `1`. As `t` goes to infinity, the CRF goes to infinity. The CRF and FWF values for an average annual interest rate of 8% are given in Table A.4.1.

Table A.4.1 CRF and FWF values

Year	CRF	FWF	Year	CRF	FWF	Year	CRF	FWF
1	1.080	1.080	18	0.107	3.996	35	0.086	14.785
2	0.561	1.166	19	0.104	4.316	36	0.085	15.968
3	0.388	1.260	20	0.102	4.661	37	0.085	17.246
4	0.302	1.360	21	0.100	5.034	38	0.085	18.625
5	0.250	1.469	22	0.098	5.437	39	0.084	20.115
6	0.216	1.587	23	0.096	5.871	40	0.084	21.725
7	0.192	1.714	24	0.095	6.341	41	0.084	23.462
8	0.174	1.851	25	0.094	6.848	42	0.083	25.339
9	0.160	1.999	26	0.093	7.396	43	0.083	27.367
10	0.149	2.159	27	0.091	7.988	44	0.083	29.556
11	0.140	2.332	28	0.090	8.627	45	0.083	31.920
12	0.133	2.518	29	0.090	9.317	46	0.082	34.474
13	0.127	2.720	30	0.089	10.063	47	0.082	37.232
14	0.121	2.937	31	0.088	10.868	48	0.082	40.211
15	0.117	3.172	32	0.087	11.737	49	0.082	43.427
16	0.113	3.426	33	0.087	12.676	50	0.082	46.902
17	0.110	3.700	34	0.086	13.690			

Appendix 5 Summary of some expert, professional, operator, manufacturer and academics' opinions and judgements

Information regarding the technical capabilities, prices, costs, professional judgements for qualitative and quantitative values for decision-making for quayside cranes and container yard operating systems has been collectively obtained from the following sources:

1) Container ports such as:

- Bandar Abbas Container Terminals (BACT), Bandar Imam Container Terminals (BICT) and Chabahar Container Terminals (CCT), Iran.
- Pasir Panjang, Singapore.
- Rokko and Port Island Container Terminals, Kobe, Japan.
- Port of Liverpool Container Terminals.
- Port of Felixstowe Container Terminals.
- Port of Southampton Container Terminals.
- Thamesport Container Terminals.

2) Manufacturers:

- Kalmar, Gottwald, Bosh and Siemens Industries, Germany.
- Mitsubishi and TCM Industries, Japan.
- ABB, Sweden.

3) Academics:

- Liverpool John Moores University, UK.
- University of Cardiff, UK.
- City University, London, UK.
- Metropolitan University, London, UK.
- Chabahar Maritime University, Iran.

- University of Amir Kabir, Iran.

The opinions are obtained directly for post-Panamax QSCs during the time of study is summarised in Table A.5.1. The experts have given their opinions that reflect the performance measures and the most difficulties they have experienced while supervising or directly operating the quayside cranes as the crane operators.

a) Post-Panamax QSCs

The aim was to identify the most important factors that port operators with different operational ranks, crane manufacturers and academics with port specialisation recognise as performance factors. The following three were identified as the most important factors for QSCs operations:

i) Rate of loading / discharging in TEUs/ second

ii) Crane Net-Time (CNT) in Hours / crane / vessel

iii) Berth Net Productivity (BNP) (see definition for BNP at Chapter 1, Section 1.8)

Table A.5.1 Performance factors recognised for semi-automated post-Panamax quayside cranes

		Number and / or Position of Experts Responded		Rate of Loading / Discharging TEUs / Seconds	Crane Net-Time (CNT) Hours / Crane / Vessel	Berth Net Productivity (CNP)
Manufacturers	Mitsubishi	1		√	-	-
	TCM	1		√	-	-
	Kalmar	2		√	-	-
	Gottwald	1		√	-	-
	Bosh and Siemens	1		√	-	-
	ABB	1		√	-	-
Port Operators	BACT, BICT and CCT	1	SM	√	-	-
		1	OM	-	√	-
		2	MM	√	-	-
		8	CO	√	√	-
	Thamesport	0	SM	-	-	-
		1	OM	-	-	√
		1	MM	√	-	-
		2	CO	√	-	-
	Port of Liverpool	1	SM	-	√	-
		1	OM	-	√	-
		0	MM	-	-	-
		2	CO	√	√	-
	Port of Felixstowe	0	SM	-	-	-
		1	OM	-	√	-
		0	MM	-	-	-
		3	CO	√	√	-
Academics		5		√	√	-

Key:

SM = Senior Manager

OM = Operation Manager

MM = Maintenance Manager

CO = Crane Operator

In the process of investigation, the most difficulties experienced with post-Panamax QSCs were identified and addressed. The problems are given in the Table A.5.2.

Table A.5.2 Difficulties identified in the operation of post-Panamax quayside cranes

		Number and / or Position of Experts Responded		Sway of the Load	Load Snag	Yaw, Roll, Pitch, Sway, Surge and Heave Effects of Vessel	Bowing Effect of Crane
Manufacturers	Mitsubishi	1		H	-	-	-
	TCM	0		-	-	-	-
	Kalmar	1		H	H	-	-
	Gottwald	1		H	-	-	-
	Bosh and Siemens	0		H	-	-	-
	ABB	1		H	-	-	-
Port Operators	BACT, BICT and CCT	1	SM	-	VH	MD	-
		1	OM	VH		MD	H
		2	MM	H	-	MD	VL
		8	CO	VH	MD	H	LW
	Thamesport	0	SM	-	-	-	-
		1	OM	H	MD	LW	VL
		1	MM	H	-	LW	LW
		2	CO	H	LW	MD	LW
	Port of Liverpool	1	SM	H	-	L	VL
		1	OM	H	LW	-	-
		0	MM	-	-	-	-
		2	CO	H	MD	H	VL
	Port of Felixstowe	0	SM	-	-	-	-
		1	OM	H	L	VL	-
		0	MM	-	-	-	-
		3	CO	H	L	MD	VL
	Port of Southampton	0	SM	-	-	-	-
		1	OM	MD	LW	VL	-
		0	MM	-	-	-	-
		1	CO	MD	LW	VL	-
Academics		5		H	MD	LW	VL

Scale:

1 2 3 4 5 6 7 8 9

VL LW MD H VH

Key:
VL = Very Low
LW = Low
MD = Medium
H = High
VH = Very High

b) Container yard operating systems

The port operators and academics were asked to rank the most important attributes identified for container operating systems on a preference basis. In some cases, the conception has been taken by author from the explanation, information and instructions given by the operators that are presented in the same way as reflected in the tables. The scale was expressed as "very low, low, medium, high and very high" to indicate the operators' preference over other attributes or alternatives. By incorporating the scale of 1 to 9, the responses were used for evaluation of Multiple Attribute Decision-Making (MADM) and Analytical Hierarchy Process (AHP) in Chapter 7. The experts' opinions obtained are reflected in Tables A.5.3, A.5.4 and A.5.5 namely for SCs, RTGs and RMGs while taking other systems such as RSs, T-T, etc. into considerations in the valuing process.

Table A.5.3 Performance factors and average values given for SCs

		Number and / or Position of Experts Responded		Cost					Automation				Operations			
				$C_{transfer}$	CPC	MCC	OC	PC	t	LA	SH	C_Y	RGA	ESA	FL	RM
Port Operators	BACT	1	SM	H	LW	MD	H	VL	MD	LW	VL	H	LW	LW	H	H
		1	OM	MD	VL	LW	VH	-	MD	LW	VL	MD	-	LW	H	H
		2	MM	-	-	MD	-	-	MD	VL	-	-	-	VL	H	-
		3	CO	-	-	-	-	-	MD	LW	LW	-	-	-	VH	H
	BICT	0	SM	-	-	-	-	-	-	-	-	-	-	-	-	-
		1	OM	H	LW	MD	H	-	LW	LW	LW	H	VL	LW	VH	H
		1	MM	-	-	H	-	-	LW	LW	-	-	-	VL	VH	-
		1	CO	-	-	-	-	-	MD	LW	VL	-	-	-	VH	MD
	Southampton	1	SM	H	LW	MD	VH	LW	LW	LW	LW	MD	LW	LW	VH	H
		1	OM	-	LW	H	VH	-	LW	LW	LW	H	-	LW	VH	H
		0	MM	-	-	-	-	-	-	-	-	-	-	LW	VH	-
		1	CO	-	-	-	-	-	MD	VL	LW	-	-	-	H	H
Academics		2		H	LW	MD	VH	LW	MD	LW	LW	H	LW	LW	VH	H

Key:
C_Y = Container yard throughput
SH = Stacking height advantage
t = Economic life
LA = Level of automation
PC = Procurement cost
MCC = Maintenance cost of cranes
OC = Container yard operation cost
$C_{transfer}$ = Transfer operation cost
CPC = Cost per container
FL = Flexibility

RGA = Random grounding applicability
RM = Re-handling management
ESA = Environmental and social acceptability

Table A.5.4 Performance factors and average values given for RTG cranes

		Number and / or Position of Experts Responded		Cost					Automation				Operations			
				$C_{transfer}$	CPC	MCC	OC	PC	t	LA	SH	C_Y	RGA	ESA	FL	RM
Port Operators	BACT	1	SM	LW	LW	LW	VH	MD	H	MD	LW	H	LW	MD	H	MD
		1	OM	-	-	-	H	-	-	-	LW	-	MD	LW	MD	LW
		1	MM	-	-	MD	-	-	H	MD	-	-	-	-	-	-
		2	CO	-	-	-	-	-	-	-	MD	-	-	-	MD	LW
	CCT	1	SM	MD	LW	MD	H	MD	H	H	LW	H	LW	LW	H	MD
		1	OM	-	-	-	H	-	H	-	-	-	LW	LW	H	MD
		1	MM	-	-	LW	-	-	H	MD	-	-	-	-	MD	-
		2	CO	-	-	-	-	-	-	-	LW	-	-	-	H	MD
	Port of Felixstowe	0	SM	-	-	-	-	-	-	-	-	-	-	-	-	-
		1	OM	MD	-	-	H	-	H	MD	MD	H	LW	MD	MD	MD
		0	MM	-	-	MD	-	-	MD	MD	-	-	-	-	-	-
		1	CO	-	-	-	-	-	-	MD	LW	-	-	-	H	LW
Academics		1		MD	LW	MD	H	MD	H	MD	LW	H	LW	LW	H	MD

Table A.5.5 Performance factors and average values given for RMG cranes

		Number and / or Position of Experts Responded		Cost					Automation				Operations			
				$C_{transfer}$	CPC	MCC	OC	PC	t	LA	SH	C_Y	RGA	ESA	FL	RM
Port Operators	BACT	1	SM	VL	VH	VH	MD	H	MD	H	H	H	MD	MD	LW	LW
		1	OM	VL	-	-	MD	-	H	H	H	VH	MD	MD	LW	LW
		2	MM	-	-	VH	-	-	H	VH	-	-	-	-	MD	-
		2	CO	-	-	-	-	-	-	-	H	VH	-	-	LW	LW
	Thamesport	0	SM	-	-	-	-	-	-	-	-	-	-	-	-	-
		1	OM	LW	VH	-	MD	VH	MD	VH	H	VH	H	H	LW	MD
		0	MM	-	-	-	-	-	-	-	-	-	-	-	-	-
		1	CO	-	-	-	-	-	H	VH	H	VH	-	-	LW	LW
	Port of Liverpool	0	SM	-	-	-	-	-	-	-	-	-	-	-	-	-
		1	OM	VL	VH	-	H	H	MD	H	H	H	MD	MD	LW	LW
		0	MM	-	-	VH	-	-	-	-	-	-	-	H	-	-
		1	CO	-	-	-	-	-	-	H	H	-	-	-	-	LW
Academics		1		VL	VH	VH	MD	H	MD	H	H	VH	MD	MD	LW	LW