Optimization-Based Simulation of Container Terminal Productivity using Yard Truck Double Cycling

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ABSTRACT

Optimization-Simulation of Container Terminal Productivity using Yard Truck Double Cycling

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The growth of global trade transiting over the ocean has been continually increasing. A new generation of large vessels has recently been introduced to the transhipment system. These large vessels can carry more than 16000 twenty-foot equivalent container units (TEUs), maximizing shipping productivity. Container terminals must improve their productivity to meet the rapid increases in trade demand and to keep pace with developments in the shipbuilding industry. Reducing vessel turnaround time in container terminals increases the capacity for world trade. This time reduction can be achieved by improving one or more container terminal major resources or factors.

The objective of this research is to maximize container terminal productivity by minimizing vessel turnaround time within reasonable hourly and unit costs. A new strategy is introduced, employing double cycling to reduce the empty travel of yard trucks. This double-cycling strategy still requires the use a single-cycle strategy before the trucks can be incorporated into double-cycle scheduling. The single-cycle start-up is necessary in order to create enough space to begin loading a vessel if there is no other space.

The strategy is based on combining the efforts of two quay cranes (Unloading and Loading quay cranes) to work as a unit. The technique optimizes the number of trucks in terms of time and cost, minimizing yard truck cycles by minimizing single cycle routes and maximizing double

cycle trips. This requires five steps. First, a good knowledge base of a container terminal's operation and of the behaviours of the Quay cranes (QCs), Yard trucks, and Yard cranes needs to be constructed. Second, analysis of the collected data is required to simulate the container terminal operation and to implement the Genetic algorithm. Third, the double cycling truck strategy is simulated, tested and verified. Fourth, sensitivity analysis is performed to rank and select the best alternatives. Optimization of the selected alternatives in terms of productivity and cost as well as verifying the results using real case studies comprises the fifth step.

Genetic Algorithm is used to optimize the results. Some selection approaches are implemented on the set of the nearest optimum solutions to rank and select the best alternative. The research offers immediate value by improving container terminal productivity using existing facilities and resources. Simulating the yard truck double cycling strategy provides container terminal mangers and decision makers with a clear overview of their handling container operations. Optimizing fleet size is a key factor in minimizing container handling costs and time. The simulation model reveals a productivity improvement of about 19% per QC. A reasonable cost savings in terms of the cost index in unit cost was achieved using yard truck double cycling operation. The genetic algorithm corroborates the achievements thus gained and determines the optimal fleet size that will result in the maximum terminal productivity (quickest vessel turnaround time) with the minimal cost. A time reduction of more than 26% was achieved in most cases, compared to previous research efforts.

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS

CT	Container Terminal
QC	Quay Crane
YC	Yard Crane
YT	Yard Truck
SY	Storage Yard
TEU	Twenty-foot Equivalent container Unit
AGV	Automated Guided Vehicle
RTGC	Rubber-Tired Gantry Crane
RMGC	Rail Mounted Gantry Crane
GA	Genetic Algorithm
P/D	Pick-up and Delivery
BAP	Berth Allocation Problem
DBAP	Dynamic Berth Allocation Problem
QCSNIP	Quay Crane Scheduling with the Non-Interference constrain Problem
TOPSIS	Technique of Order Preference by Similarity to Ideal Solution
PIS	Positive Ideal Solution
NIS	Negative Ideal Solution
MODMP	Multi Objective Decision- Making Problems
VBA	Visual Basic for Applications code

Chapter 1: Introduction

1.1 Problem Statement and Research Motivation

Each container terminal is an important port facility linking international trade. Unexpected increases in demand for global trade require quick and efficient solutions. The annual average increases in container trade volume between 1990 and 2010 were not less than 8.2%, qualifying this type of trade as the fastest growing global sector (Carlo et al. 2014b). For example, in Shenzhen's port, container handlings had jumped 223 times in 2010 compared to its 18,000 TEU in 1990, reaching 4 million TEUs (Yap & Lam 2013). This growth has forced shipping and port companies to search for ways to keep up with this development. Among these alternatives, increasing container vessel capacity was one of the winning choices. Recent-generation container vessels now have a capacity for 18,000 TEUs rather than the 2,400 TEUs container vessels carried in the 1970s, and their capacity is expected to reach 24,000 in the future (see Figure 1- 1) (Lane et al. 2014).
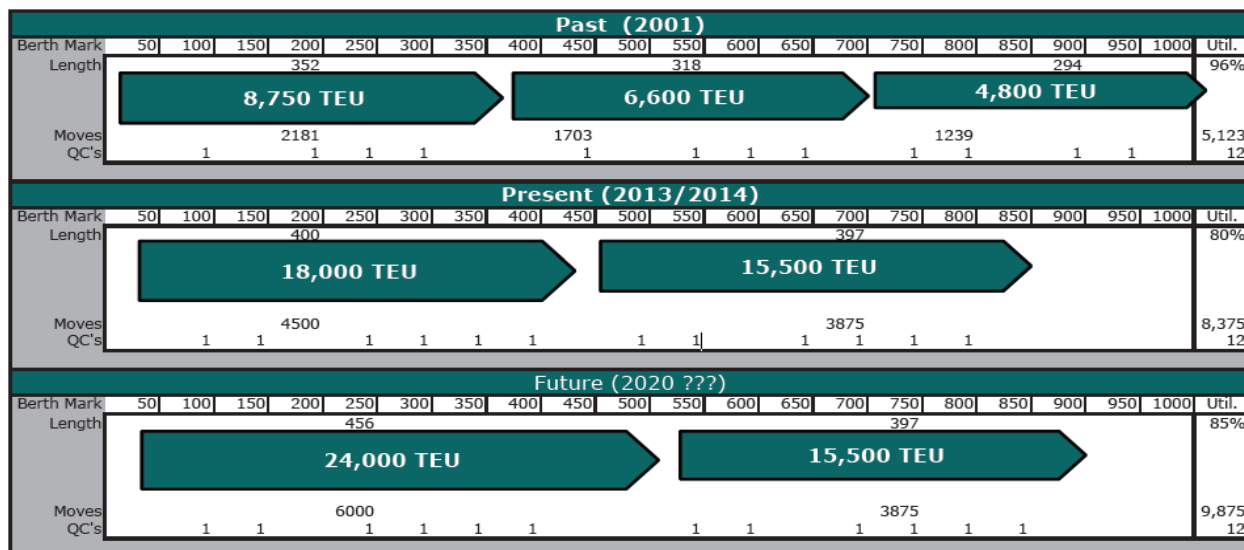
Figure 1- 1: Container vessel capacity development (Lane et al. 2014)

This situation means that container terminals must improve their capacity and raise productivity to keep up with these developments. Since the infrastructure for container port development requires a big timeframe and a large capital investment, it imperative to find adequate solutions to achieve optimum utilization of the available resources and possibilities. Minimizing vessel turnaround time (the time it takes for a vessel to be unloaded and loaded at its berth) accelerates shipping time and reduces delay in delivering trade goods. Improving the productivity of existing container terminals without introducing new major equipment and thereby expanding and/or developing the infrastructure of a facility is the primary objective of this research.

Containers are delivered by vessels to container terminals. Quay cranes (QCs), which are huge and costly machines are used to unload and load containers from and onto sea-going vessels. Horizontal transporters, Yard trucks (YTs), automated guided vehicles (AGVs) and strudel carriers are used to transport containers between the berth and a storage yard (SY). Gantry cranes, both Rubber-Tired Gantry Cranes (RTGCs) and Rail Mounted Gantry Cranes (RMGCs), are yard cranes (YCs) that unload and load containers from and onto vehicles at a SY. A storage yard is an organized space divided into lanes and stakes where containers are stored temporarily before they are submitted to customers (shipping companies, railway or trucks). Any delays in the availability of one of these resources directly leads to a proportional delay for the other resources, and ultimately on the container terminal productivity in general. On the other hand, improving any of these resources will improve container terminal productivity.

Traditionally, vessels are unloaded and then loaded (single cycle) at transhipment container terminals. Recently, a new technique has been proposed by Goodchild (2005), Quay Crane double cycling. The aim of that technique is to improve container terminal productivity by minimizing the empty travel of QCs. Goodchild's technique only produces a slight improvement

because it can only be applied to a single hatch. This research instead is focussed on implementing the double cycling of YTs based on the QC double cycling technique, thereby minimizing empty YT journeys. Some of the limitations of QC double cycling are to be solved over the course of this research. Because of its complexity, container terminal productivity is commonly tested by using simulation. The effectiveness of this developed strategy has been verified via a simulation model. An optimization of the results was produced and utilized to varify the developed strategy. This optimization aimed to optimize the handling containers' YT fleet size to deliver best productivity in order to achieve the minimum vessel turnaround time associated with reasonable costs.

1.2 Objectives

The overall objective of this research is to minimize vessel turnaround time and optimize container fleet size and hourly costs by implementing the yard truck double cycling technique to minimize empty truck journeys. Developing a simulation model is a part of this research and will test the technique. An optimization of the simulation outcome's group solutions is used as an input of the multi-objective Optimization model to optimize fleet size and the associated hourly costs. Several sub-objectives need to be achieved in order to satisfy the main objective:

- Identify and study the various factors that affect container terminal productivity;
- Build a productivity model to improve container terminal operation; and
- Optimize the fleet size that handles containers at a terminal.

1.3 Summary of the Developed Methodology

The research methodology consists of seven phases, as follows:

1. A literature review to assess the research to date in the container terminal field to improve and maximize container terminal productivity, minimize vessel turnaround time, resolve QC allocation problems and promote QC, YC, YT and SY efficiency, as well as to present the state of the art in relevant simulation and optimization models;

2. Introduction of the new strategy of YT double cycling;

3. Formulation of improved vessel turnaround times, along with QC, YC and YT cycle times;

4. Building a simulation model of container handling operations;

5. Building an optimization model that can be implemented using an optimization tool to minimize vessel turnaround time and to optimize the fleet size for handling containers so as to meet the objective function of maximizing productivity and minimizing costs;

6. Data generation, including appropriate case studies to run, verify, and verify the developed simulation and optimization models; and

7. Summarising the conclusions, specific contributions and recommendations for future work.

1.4 Research Organization

This research consists of seven chapters: chapter one is an introduction where the problem statement and research motivations are presented. Chapter two contains the literature review, including the latest work in the container terminal field. It describes the strategies, techniques, models and methodologies currently in use. Chapter three details the thesis methodology, and is where a simulation model for both single and double cycling of handling containers' operations is developed. Optimization models then indicate how to apply the optimization using a Genetic Algorithm optimization tool. Data collection from both theoretical and real case studies that

produce the generated and estimated data that must be simulated in order to implement the optimization model is organised in chapter four. Chapter five contains the implementation of the simulation model, a sensitivity analysis and a genetic algorithm (GA) multi-objective optimization on both theoretical and real cases studies. Several approaches are utilised so that the near optimum solution can be found. Chapter six is where the developed strategy, simulation and optimization models are verified by comparing the results to previous published results, and finally, chapter seven summarizes the achievements, limitations and contributions of the research, and suggests future work.

Chapter 2: Literature Review

2.1 Introduction

The trade volume through container terminals (CTs) has undergone rapid increases since its start in the late 1950s. Large transhipment container terminals now operate 24 hours a day with no stops, all year long, to meet the demand of the worldwide container trade. These operations employ a huge number of YTs, QCs and YCs and require very large SYs to satisfy container terminal customers. Not less than 100,000 containers are transferred weekly between berth side and temporary SYs (Petering and Murty, 2009). CTs need to improve their capacity to meet the increasing demands. Physically expanding existing CTs is not the only way to solve this problem, especially due to the high cost of expansion (and sometimes the physical limits) and time involved. Researchers have been investigating how CT performance can be developed using existing resources. SY, YCs, YTs and QCs are the most common elements of a CT's resources. Any improvement in one of those elements will affect the other elements' productivity, as well as that of the CT operation overall. Scheduling problems have been a major focus of research efforts. Minimizing vessel berth time (turnaround time) is achieved in part by implementing the' solutions developed by researchers and is reflected in the improvement of CT performance and accompanying customer satisfaction.

Vis and De Koster, (2003) stated that the capacity of vessels will be increased by up to 8000 TEU (twenty-foot equivalent unit containers). Vessels today have been upgraded to carry more than 15000 TEUs as one way to minimize container cost shipment. Vessel turnaround time is thus increased by default. Large vessels are usually used to transfer containers through large container terminals to be transhipped by smaller vessels called feeders between medium or small

terminals. This process is called container transhipment. Because of the capital expenses and berthing affects, mega-ships need to be served as fast as possible with little or no delay upon arrival (Imai et al. 2013). This expansion has added more pressure on container terminal mangers to reduce vessel turnaround time and to expand berth lengths to accommodate larger vessels. To assess the effectiveness of container terminals, Vis et al, classified the planning and control functions into three levels: strategic, tactical and operational. For an overview of a transhipment container terminal, Figure 2- 1 shows the container terminal process, a sequence that starts with the arrival of a vessel and ends with its departure (Vis and De Koster, 2003).

Container terminals are classified into five areas; two are on the seaside (Bert and Quay crane), two on the landside (Storage yard and Gate), and the remaining area is the transportation, the connection between the two sides (Carlo, 2014a). Container terminal quay cranes (QCs) capture the researchers' attention because of their high capital outlay and operational costs. Furthermore, new generations of QCs are able to make 40 moves per hour; the average number of movements per hour had been limited to around 25 (Murty, 2007; Petering and Murty, 2009). Accelerating QC capacity has been fuelled by the other CT elements' increased efficiency. Double cycling is a recently-introduced technique to improve CT productivity.

2.2 Storage yard:

Imported and exported containers are stored on the ground at SYs. A SY is a storage space where imported and exported containers are stored temporarily before being moved to their destination. SYs are divided into lanes, each lane is served by YCs that load and unload containers. Another type of machine, a strudel carrier, self-transports and loads or unloads containers from/to the ground. A storage yard's size, layout, its stacking levels and distance from the berth side are measures of its effectiveness.
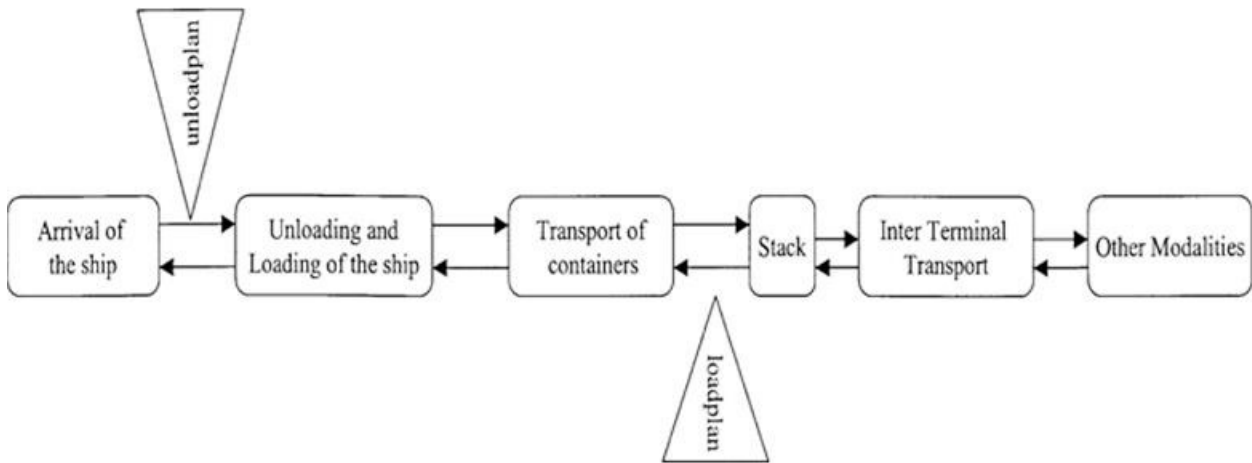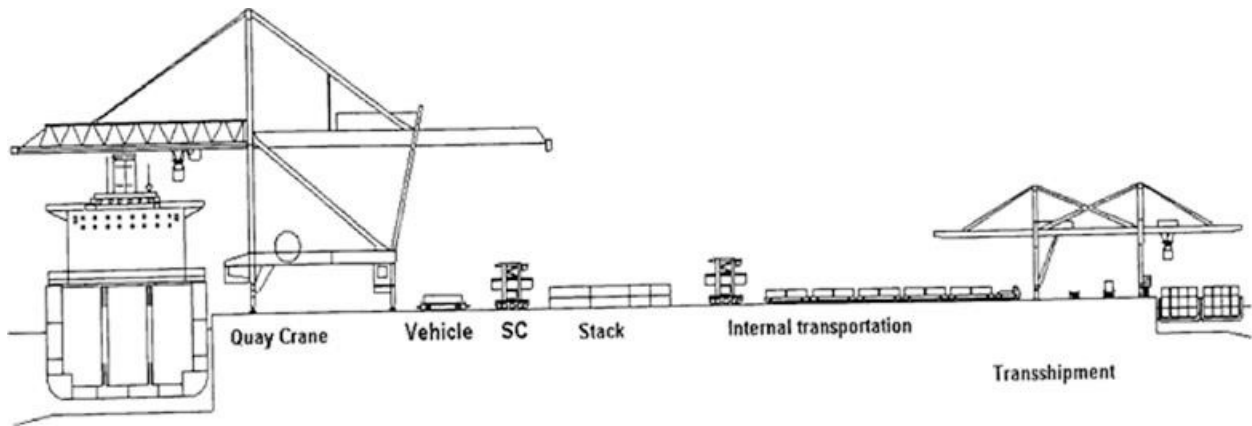
Figure 2- 1: Process of unloading and loading a ship (Vis et al. 2003)

2.2.1. Storage yard size:

There is no doubt that a larger SY provides more flexibility of movement and organization, resulting in a more effective CT. Nevertheless, unnecessary spaces will lead to extra direct and indirect costs. The optimization of SY size within the other CT elements is crucial.

2.2.2 Storage yard layout:

SY layout includes container stacking, the lanes and the road network within the terminal. Effective storage yard layout can accommodate the accelerated flow of increasing container traffic. Yard layout problems have been evaluated in multiple studies. One conclusion is that, while YCs can stack containers above each other in stacks of up to seven, the optimal stacking height has been determined to be 5 levels (Duinkerken et al. 2001). Another aspect of SYs that was studied is their layout. Two possible layouts are traditionally designed to temporarily store containers before they are moved to their final destinations, known as SY layouts A and B. Layout A has containers stacked horizontally along the berth, while layout B has containers stacked vertically or perpendicular to the berth stacking yards, as illustrated in Figure 2- 2. Simulations have shown that yard layout B is more effective than layout A in terms of QC moves per hour. As a part of their research, Liu et al. (2002) modified the original design of the SY shown in Figure 2- 3 by adding Pick-up and Delivery (P/D) buffers on both the gate and the berth sides while keeping the gate buffer, as shown in Figure 2-3. Their simulation demonstrates that cost reduction was achieved with these additional buffers. Dividing an SY into small-size blocks of 6-level stacks can simplify the organization of export, import and empty containers. A similar problem was solved by Zhang et al. (2003). Their goal was to minimize the distance between the storage space and the vessel berth, and they formulated a mathematical model of the problem's planning horizon. Based on those results, Liu et al.(2004) developed a simulation model to evaluate the impact of layout on CT performance. Lee et al.(2007)worked at solving the yard space allocation problem in transhipment terminals by minimizing the traffic congestion caused by the exporting and importing trucks, using a CPLEX method to solve their model. It is not only YT congestion that needs to be solved; YC clashing can occur when more than one

crane work in the same lane. Murty (2007) studied both YT and YC problems. Murty improved the layout design with buffering to eliminate YT congestion and YC clashing.

To solve for the effects of the length of storage blocks and of a system deploying a yard crane among blocks on long-term container terminal performance, Petering and Murty (2009) constructed a discrete event simulation model of terminal operation designed to reproduce a multi-objective, stochastic, real-time environment at a multiple-berth facility. Storage yard allocation problems are also common at container terminals. Assigning adequate storage yards for import, export and empty containers is very important before vessel arrival. It is more effective if the storage allocation is pre-defined so that the target vessel can be berthed at the optimum distance from the SY. Several research studies have been done on storage yard optimization. Some have introduced algorithms and others have proposed a heuristic or taboo search to achieve optimization. For instance; Bazzazi et al. (2009) solved the problem of yard space allocation using efficient Genetic algorithm optimization. Bazzazi verified the proposed algorithm by means of numerical examples which showed the feasible solutions of yard space allocation.

2.3 Yard Crane

A yard crane is a crane that loads and unloads containers from or onto trucks going to or from the storage yard stacks. A YC is designed to move horizontally along the storage lanes, and its trolley moves perpendicular to the lane. They are designed to reach up to 7 stacks of containers from the ground level. Two types of YCs are traditionally used; the Rubber-Tired Gantry (RTGCS) and the Rail-Mounted Gantry (RMCs). RTGCs move on rubber tires and can make 360-degree turns, while RMGCs move along the blocks of a single row on a fixed rail. RTGCs crane can move from one block to another even if they are not in the same row.
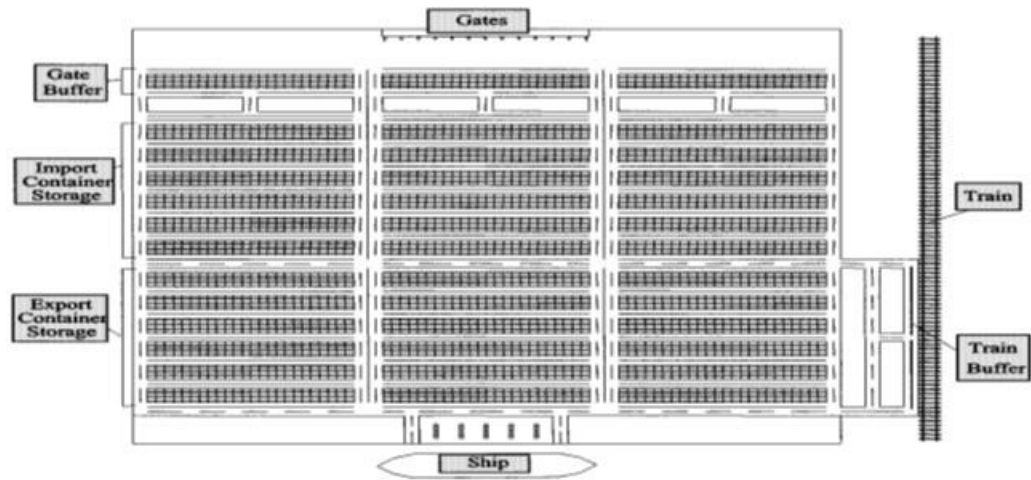
Figure 2- 2: Original CT layout (Chin, 2002)
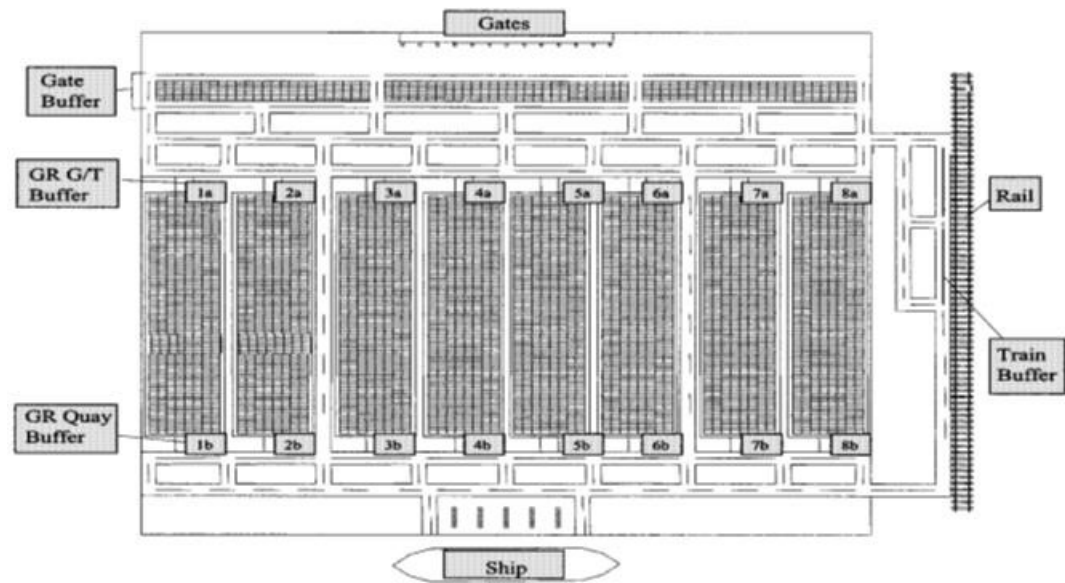
Figure 2- 3: Modified CT layout (Chin, 2002)

The RTG has a width of 7 lanes, which are each equivalent to the container width; 6 lanes are used to store the containers and the 7th lane is customisable for the yard trucks (Linn et al. 2003). Figure 2- 4is a photo that shows the width of an RTG and the lane distribution at a storage block. Other types of equipment are also used, but not as widely, for example, forklift and straddle

carriers. YCs can make 25 moves per hour. This amount of movements is about the half of a QC's productivity. If the QC works at its highest productivity level, its YC will most likely be overloaded

Figure 2- 4: An RTGC with width of 7 lanes; 6 for containers and the 7th

for the trucks (Linn, 2003)

Petering and Murty (2006) stated that "the only way to avoid YC overloading is to choose a good storage location for containers immediately upon arrival at the terminal". Petering et al, proposed a simulation analysis model of algorithms to solve YC scheduling problems. Researchers have introduced another maxim to keep the QC working at its upper capacity: each QC should be serviced by two or more YCs (Murty, 2007). Murty suggested a policy of YC operation that operates all YCs in a zone as a shared pool of YCs. The author believes this will reduce the YC/QC ratio to less than 2.5.

2.4 Yard trucks

Yard trucks (YTs) as a category include strudel carriers, truck vehicles and automated guided vehicles (AGVs). YTs transport containers between berth- or QC-side and the SY. Strudel

carriers can load containers (2 twenty-foot or one forty-foot) from the ground at quay side, transport them and then self-stack or have their container unloaded by a YC at the SY stacks. Truck vehicles are operated by drivers and are unloaded and loaded by QCs and YCs, while AGVs are automatically operated and controlled. Even though strudel carriers can eliminate the need for YCs, they are still costly because of their slow motion and high energy consumption, especially when loading or unloading containers, since the cycle times are longer when they are included in the loading and unloading cycle. Strudel carriers are generally used at CTs where hourly manpower costs are high compared to the hourly costs of strudel carriers. These costs and longer cycles can be eliminated when using YTs or AGVs. In most locations, there is no requirement for CT operators to own a large YT fleet, as they can be hired when needed. In contrast, strudel carriers work exclusively at container terminals. AGVs have certain advantages, such as in terms of environmental/air quality issues, since they are electrical machines, and because no drivers are needed as they are guided electronically, but they are not yet widely used because of their unique infrastructure and initial capital cost. Another disadvantage of AGVs is that a limited number of vehicles can be operated at one time at a terminal. Duinkerken et al. (2001) integrated a simulation model of quay transport and stacking polices at Automated Container terminals. They conclude that there is no improvement accrued when more than 42 AGVs serve at one time. Guenther et al. (2005) introduced having AGVs on-line and off-line, dispatching then in a simulation study to evaluate the dispatching performance. They discovered that the performance suffered when the system sent notice of a deadlock occurrence. They decided to develop a comprehensive plan to address the dilemmas that occur in the operation of the AGV system. Homayouni (2011) proposed a simulation annealing algorithm (SA) with the goal of optimizing an Integrated Scheduling of QCs and AGVs. Their model is

structured to minimize the journeys of AGVs and thereby reduce the make span, or the time required to finish their tasks. This minimization obtained a feasible QC cycle time reduction. Their result indicates that the SA can solve the problem accurately and precisely using a reasonable amount of CPU time. Wang et. al (2015) proposed a hybrid GA to solve the YT Scheduling and storage allocation. The aim of their research is to minimize the delay of YTs in total summation weighted. Their methodology based on how to schedule The YTs fleet to load or discharge the containers in the meanwhile of discharged container storage allocation. Chordeau et. al. (2015) introduced a simulation-based Optimization for the container housekeeping at transhipment container terminals. The Containers housekeeping saves YT cycle times and eliminates the YTs congestion. Chordeau et. al. research objectives includes minimizing YTs travel times. A feasible improvement range has been achieved by implementing their tabu search procedure.

2.5 Berth side

The berth side is the most attractive element for researchers - because it has a direct relation to the customers (vessels), it is the most expensive structure in a port facility, and it is the location of the most important piece of equipment, the QC. The berth allocation problem (BAP), QC cycling and berth scheduling continually draw the attention of researchers. The overall objective is to minimize vessel dwell time and to maximize the QCs' productivity.

2.5.1 Berth Allocation

Berth allocation is important as it assigns the optimal location of each vessel before a vessel has arrived. Many factors have to be considered to allocate a vessel to a berth, including:

(1) Vessel length;

(2) Berth length;

(3) Expected vessel arrival time;

(4) Expected vessel unloading and loading time;

(5) Expected vessel departure time;

(6) The number of containers to be unloaded and loaded;

(7) The location of the storage yard for the containers to be unloaded and loaded; and

(8) The number of QCs to be assigned for the vessel.

Berth allocation is a pivotal decision that can minimize vessel turnaround time and handling container costs. The optimum location should be compatible with the availability of resources, shorter YT cycles and the berth length. The preceding and the succeeding vessels assigned to the same location should also be considered. Static and dynamic berth allocation problems form the basis of berth scheduling algorithms. The dynamic allocation problem is more complex than the static one because of the dynamic changes before and after berthing. Arrival vessel delay, delays in the handling of other vessels' containers at the berth and weather changes are some examples of dynamic changes. Chen, et al. (2008) and Petering et al. (2009) developed a genetic heuristic-based algorithm to solve dynamic berth allocation problems (DBAP) with limited QCs at container terminals. Similarly, Liang et al. (2009) introduced a formulation for berth and quay crane scheduling problems that combine genetic and heuristic algorithms to minimize the handling, waiting and delay times for every ship.

Another solution can be found in algorithms to optimize the berth allocation within QC on-time scheduling, proposed by Lee et al. (2008) and Imai et al. (2008). They extend the optimization to a heuristic to produce an approximate solution to the problem. Even though the results of those optimizations are somewhat complex, the authors concur that it is important to solve the QC

scheduling and berth allocation problem on time. Similar solutions to berth and quay crane scheduling problems have been modeled by Aykagan (2008). One of the best references is the survey of berth allocation and QC scheduling problems introduced by Bierwirth and Meisel (2010). Their survey encompasses a good comprehension of several situations and cases of QC scheduling and vessel arrivals, including dynamic and static scheduling.

2.5.2 Quay cranes

QCs load and unload containers into and from vessels. A QC is the most expensive component for handling containers at container terminals. A QC discharges containers from a vessel and loads them onto trucks or to the ground for access by strudel carriers and it discharges containers from trucks or from the ground to load them into vessels. Trucks arrive at berth side in a queue to be loaded or discharged by the QCs, see Figure 2- 5. A QC can lift two 20-foot containers or one 40-foot container. In other words, it can lift two TEUs at a time. It is designed to make 40 movements an hour on average. Vessel turnaround times is measured by the summation of the total QC moving times for unloading and loading a vessel; see the equation below:

$$T = tu \sum_{i=1} \sum_{j=1} u(i,j) + tl \sum_{g=1} \sum_{\gamma} l(g,\gamma) \hspace{4cm} \text{(Equation 2.1)}$$

For the above reasons and because of its high capital and operational costs, the QC is considered to be a bottleneck of container terminal operations (Moccia et al. 2006). The QC schedule should be planned before a vessel's arrival to ensure the minimum vessel turnaround time and avoid any delays in handling containers. A QC moves along the berth on a railway. It moves from one row to another in the same way. Vessels have been upgraded to carry 22 rows along their length. Each row can be occupied by 20 stacks and each stack can take 18-20 containers, one atop the

other. In large vessels, stacks are divided into two hatches, above and below the vessel deck to ensure stability.

Figure 2- 5: Trucks arrive in a queue to be discharged or loaded by QCs (Linn, 2003)

where:

$T = Vessel\ turnaround\ time$
$i = number\ of\ containers\ per\ row\ to\ be\ unloaded$
$j = number\ of\ rows\ to\ be\ unloaded$
$g = number\ of\ containers\ per\ row\ to\ be\ loaded$
$\gamma = number\ of\ rows\ to\ be\ loaded$
$tu = QC\ average\ time\ to\ unload\ 2\ TEUs\ from\ the\ vessel$
$tl = QC\ average\ time\ to\ load\ 2\ TEUs\ into\ the\ vessel$

It has been proven that a vessel can be serviced by more than one QC to minimize the vessel turnaround time (Daganzo, 1989). Each QC should serve its own truck fleet to avoid conflicts and to keep the QC busy continuously. There is an exception to this condition at automated container terminals. At automated terminals, the online ATGV's dispatching is based on the principle of **"first come, first serve" (**Daganzo 1989**).** The number of QCs assigned to a vessel depends on the vessel length, the berth location and the safety policy of how much distance

should be allocated between each QC. The number of QCs also depends on a container terminal's handling equipment availability and its internal road capacity. The more trucks that move within the same time, the more likely it is that traffic congestion could arise, which would cause delays in the truck cycle time. When more than one QC is assigned to a vessel, solving the quay crane scheduling with the non-Interference constraint problem (QCSNIP) algorithm should be considered. Managers usually divide a vessel into bays, and each bay is assigned its own QC. QC scheduling problems should be examined before deciding how many QCs should be assigned. Daganzo (1989) examined the static and dynamic quay crane scheduling problem with the assumption of dividing a vessel into holds. Each hold can be serviced with only one crane at a time, and the crane can move freely between holds with the condition that the vessel never departs until all the work in its holds has been finished. An efficient algorithm for solving QC scheduling problems was developed to solve QC scheduling and assignment to vessels (Tavakkoli-Moghaddam et al. 2009).

When using multiple QCs to service one vessel, the turnaround time is equal to the maximum time one of the QCs must spend to unload and load its assigned hold. The following equation explains how to calculate the turnaround time using multiple QCs:

$$T = \max([tu1 \ \textstyle\sum_{i=1}\sum_{j=1} u(i,j) + tl1 \sum_{g=1}\sum_{\gamma} l(g,\gamma)], [tu2 .. \sum_{b=1}\sum_{s=1} u(b,s) +$$
$$tl2 \sum_{d=1}\sum_{m=1} l(d,m)], [tu(n) \sum_{k=1}\sum_{q} u(k,q) + tl(n) \sum_{z=1}\sum_{v} l(z,v)]) . \qquad \text{(Equation 2.2)}$$

where:
i, b, k *are the numbers of containers per row of the assigned hold to be unloaded;*
g, d, z *are the number of containers per row per assigned holds to be loaded;.*
j, s, q *are the number of rows per assigned hold to be unloaded*
γ, m, v *are the number of rows per assigned hold to be loaded;*
$tu1, tu2, \dots \dots tu(n)$ *are the unloading times for multiple QCs;*

$tl1, tl2, ..., tl(n)$ *are the loading times for multiple QCs; and*

 1, 2, ...n are the number of holds per vessel.

To assign more than two quay cranes to a single vessel to work separately on two holds at the same time, some factors have to be taken in consideration. For instance:

1- QCs cannot conflict with each other, as they use the same railway;

2- The QCs at the middle holds must stay there until the vessel has been completely loaded; and

3- QCs should be allocated at an appropriate and safe distance from each other to avoid conflict, forced stops and accidents.

Optimizing the QC schedule problem is necessary in order to keep the middle-hold QCs continuously occupied until the work has been completed. QC scheduling and berth allocation problems are usually coincident to each other. The number of QCs assigned to a vessel controls the vessel berth location. Container terminals with limited QCs must focus on QC scheduling, and often have to choose the more flexible vessel berthing location to allow QCs to move freely as soon as any QC finishes its assigned work on a vessel's hold (Park & Kim 2003). Lee and Wang (2010) proposed an algorithm for QC scheduling to assign handling priority to solve this problem. A tabu search algorithm was developed by Sammarra et al. (2007) to optimize QC scheduling and minimize vessel turnaround time. Goodchild (2005) and Goodchild and Daganzo(2005) introduced a new technique to optimize QC productivity and minimize vessel dwell time. This technique is called QC double cycling. Goodchild and Daganzo improved their work to cover the impaction of QC double cycling (Goodchild and Daganzo, 2006; 2007). Zhang and Kim (2009) expanded QC double cycling to implement not only under hatch, but so

that it works over hatch eventually. The QC double cycling and the authors work have been explained widely in the next section.

2.6 Quay crane double cycling

Before delving into the double cycling technique, it is worthwhile to review single cycling. Traditionally, single cycling is the most commonly-used technique in most container terminals. Before the introduction of double cycling, the only way to unload containers was the single cycling technique. Single cycling means that the imported containers from a vessel must be unloaded first, and then the exported containers can be loaded. In contrast, double cycling means that the loading and unloading of containers is carried out at the same time, under the unloading conditions. QC double cycling is "a technique that can be used to improve the efficiency of quay cranes by eliminating some empty crane moves" Goodchild, (2005). Goodchild shows the difference between the single cycle and double cycle techniques.

A scheduling problem that can be solved by double cycling is presumed by Goodchild and Deganzo (2005).
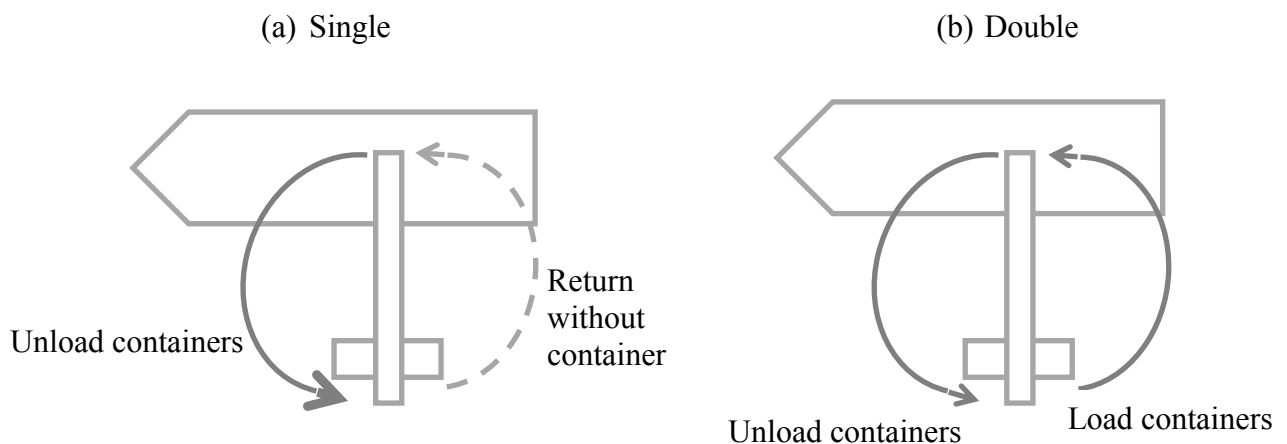
Figure 2- 6: (a) Single cycle unloading, (b) loading and unloading, double cycling

(Goodchild 2005)

With the aim of reducing the turnaround time of a group of vessels, they proposed a simple formula and algorithm of quay crane double cycling. The formula was then optimally solved by using Johnson's rule. They further extended their analysis to hatched vessels. A 20% reduction of total QC cycles and an operation time reduction of 10% were achieved by using double cycling. Goodchild and Deganzo (2007) suggested additional planning and modification of the CT operation strategy to optimize it with the double cycling technique. Their suggestion also includes SY utilization. Thanks to their research, terminal planners can benefit from a clear preview of the resource and management requirements when implementing the double cycling technique. Zhang and Kim (2009) extended Goodchild and Deganzo's (2005) research so that it would no longer be limited to the stacks under a hatch, but would also work for above-hatch stacks. Based on the most common arrangement, where a hatch usually covers three stacks under it, the authors suggest a strategy to work above hatches. Their approach is to unload the first three stacks above a hatch, then remove the hatch and unload the first stack under the hatch in single cycle, and then return to double cycling. At the end of a row, the QC backs up to load the remaining stacks under the hatch, re-installs the hatch and loads the three stacks above the hatch in single-cycle mode. A heuristic algorithm to apply this strategy has been formulated and tested. Even though Zhang and Kim have eliminated the limitations of working above a hatch, other limitations have not yet been resolved. In general, the results show that the approach has a good potential to be applied successfully.

To reduce empty YT trips, Nguyen and Kim (2010) introduced a heuristic algorithm and tested it via simulation for various scenarios with different QC operation types (single cycle, double cycling and a combination of two QCs -- one loading and the other unloading) in different locations. One of their conclusions is that YT efficiency is affected by the QC operation type.

Pap et al. (2011) support the advantages of the double cycling technique as a service method for improving container terminal productivity. They enhanced the conception that double cycling is a cost reduction method which does not require any improvement of existing infrastructure or introduce new technology. The authors optimized the QC double cycling in both sea and river container terminals. They state that using QC double cycling is more efficient in river terminals than it is in sea terminals. They attributed this difference to the fact that the only handling machine in a river terminal is the QC (see Figure 2- 7). This supports the conclusion that QC performance is influenced by the performance of other container terminal elements. A greedy randomised adaptive search procedure was introduced to solve scheduling problems considering QC double cycling by Meisel & Wichmann (2010); they re-positioned the reshuffled containers on the bay rather than unloading them to accelerate the vessel turnaround time. Zhang et. al (2015) suggested a mixed of two programming integrated model of QC and YC. The model does not cover the YT scheduling and allocation. The integrated model of QC and YC double cycling model concludes as it is easy implemented approach and efficient method of handling containers.

2.7 Container terminal process simulation:

Container terminal operation analysis is a complex process. These complexity forces container terminal decision makers to be forward-looking and to search for support tools to help them continually optimize container terminal operation. Simulation modeling is one of the tools that are widely used to solve container terminal operation problems, including the operation starting from the arrival of a vessel and ending with the land handling of the containers or the reloading and departure of said vessel.
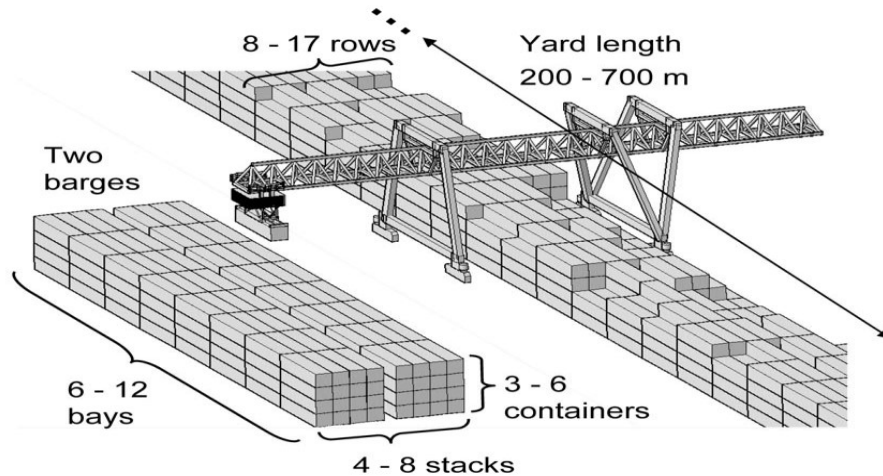
Figure 2- 7: Characteristic river container terminal (Pap et al, 2011)

Nam et al. (2002) proposed a simulation model to solve the berth allocation and Quay crane scheduling problem. This problem is based on berth length shortage and QC limitations. They consider a berth as being divided into four berths, each operated by an individual company and each company owning 3 QCs. The number of QCs assigned to a vessel depends on the vessel size. The authors suggest four scenarios to solve the problem:(1) each company operates individually, (2) each two neighbouring companies share their QCs, (3) three companies share their QCs and the fourth one works individually, and (4) the four companies share their QCs as one owner. The idea is that if a QC is idle, it is more beneficial to use it even if that involves hiring or borrowing. As a result, the authors conclude that *"The more berths per operator, the higher the productivity achieved"* (Nam et al. 2002). They also show that optimal use of the available resources can improve performance by up to 25%. Since the aim is to increase container terminal productivity, CT operation simulation is similar to that of any other operation, such as in construction and manufacturing. Lee et al. (2003) used the ARENA version 4 to simulate the logistics of a container port supply chain. As a result of their simulation they stated *"The deeper the partnership between the ship operator and the terminal operator, the shorter*

time will be taken for container handling and strategy. The more information the operator has the more vessels that can be handled efficiently" (Lee et al. 2003).This statement points to the use of some of the simulation models designed for construction work, such as Micro cyclone or EZStrobe. Another example of a simulation model for the planning stage to examine container terminal productivity is proposed by Beškovnik and Twrdy, (2010). Their simulation contains six parts. They recommend using a simulation model to determine container terminal research solutions to provide feasible solutions and a sensible overview, even if it is a simple one. Beškovnik and Twrdy agree that most of the simulations to date have focused on the sea- or river-side areas that contain the berths and the QCs, while fewer studies have focussed on the other areas such as SYs, YTs and YCs, even though container terminal productivity is influenced by all of those areas.

The developed simulation will compensate for the lack of YT simulation to date. This approach adds a YT double cycling strategy to improve container terminal productivity (Ahmed et al. 2014a). The YT double cycling strategy needs to be tested and evaluated. A simulation of the strategy will indicate its efficiency and a sensitivity analysis were employed to optimize the number of YTs when using YT double cycling (Ahmed et al. 2014b).

2.8 Container terminal productivity optimization

Optimizing container terminal productivity using only existing resources is very attractive to container terminal operators. Researchers are continually working to optimize terminal productivity in different terminal areas and in accordance with different factors. Some of these are mentioned in the previous sections of this chapter and others will be discussed later. For example, optimizing the stack levels at a storage yard has been addressed and the optimum stack level determined to be five stacks (Duinkerken et al. 2001). Vessel turnaround time can be

optimized by minimizing container handling and vessel waiting time. A multi-objective optimization to solve scheduling problem is introduced by (Cheong et al. 2010). The optimal number of AGVs working at one time has also been determined, with the conclusion that more than 24 vehicles are not beneficial to work at the same time(Duinkerken et al. 2001). Homayouni (2011) optimized an integrated scheduling of QCs and AGVs. Other resource optimizations such as berth allocation and QC scheduling have also been presented. Since the optimization of fleet size to maximize productivity and minimize costs is a part of this research, the optimization literature that will be deeply extended in this future work is the work on delays.

2.9 Genetic algorithm

The use of genetic algorithms (GA) is a method developed by John Holland in 1975. GA mimics the biological process of natural selection. To produce optimal solutions, GA generates better solutions by developing improved new generations (children).The parents with the best characteristics (genes) are the ones used to produce each successive generation. This operation continues for a pre-determined number of generations or until further improvement is no longer possible, resulting in winning solution.

2.9.1 GA implementation steps

(Haupt et al. 2004) ordered the GA implementation steps as follows:

1- Initialise or generate the first population;

2- Evaluate the fitness function;

3- If the fitness function is satisfied, go to step 8;

4- Select the new parents;

5- Crossover;

6- Mutate;

7- Back to step 2;

8- Select the best solution (winner);

Brief clarifications of the previous steps are given below:

1- Initialisation is the processes of generating the initial or the first population, also called the parents. Each parent is a set of solutions (chromosomes) which are used in selection, crossover and mutation. A good definition of population size can optimize the time the algorithm will need to run. Put another way, a higher population size takes more time to finish the algorithm and find the solution, but it must be large enough to achieve the desired solution and satisfy the fitness function.

2- The fitness function is also known as the objective function. A fitness function is the function by which the desired solution (optimum solution) will be achieved.

3- Crossover is the mixing of two parents' chromosomes to generate a new generation. Normally, the operation shares the better chromosomes between two parents to generate a better solution, but that does not mean a worse solution will not be generated occasionally. In general, there are three types of crossover.

a- One point crossover. In this type of crossover a child will keep the genes of parent A before the point of cross between parents A and B, and the genes of parent B after the point of cross. The other child will do the same but with the opposite genes of parents A and B, see Figure 2- 8.
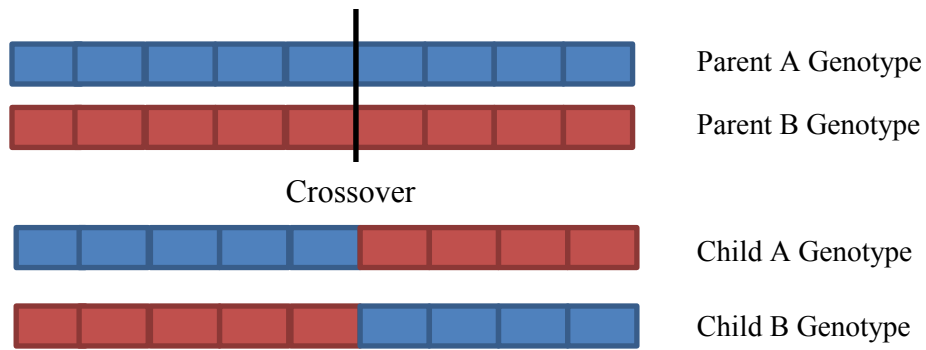
Figure 2- 8: One point crossover

b-Multiple point crossover. The same procedure is followed as in one point crossover, but with more than one cross over point. Figure 2- 9 shows an example of multiple point crossover in detail.
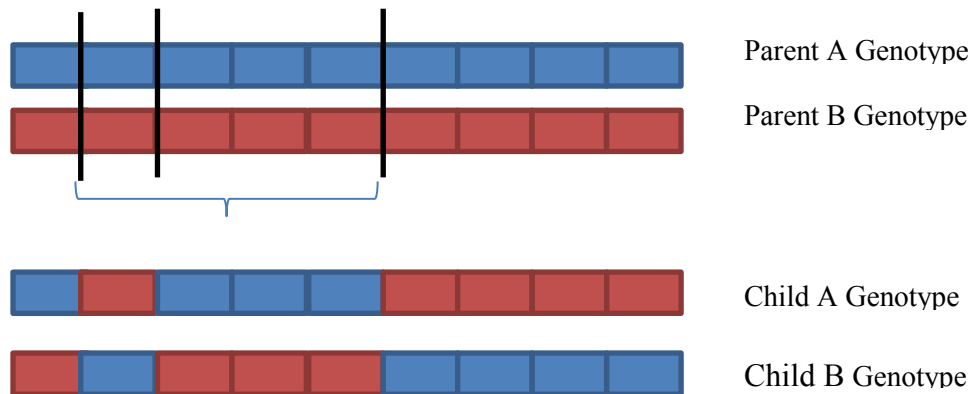
Figure 2- 9: Multi point crossover

c- Uniform random crossover. This type of the crossover is ultimate case of multi point crossover. The parent genes get distributed uniformly and randomly in child A and child B; this step acts as a redistribution of the gene positions in the chromosome.

4- Mutation is the process of considering unexplored genes in the population. It is used to avoid the selection of non-optimum solutions. Based on the user's desire for using the mutation step, the rate of the mutation can be specified. A higher rate of mutation leads to

a higher number of mutated chromosomes, which is not recommended, as one wants to avoid the devolution of an optimization search to a random search.

2.9.2 Selection of optimum solution and ranking

In single-objective optimization, there is only one solution to be selected and so no conflict can be countered. On the other hand, with multiple-objective optimization (more than one objective function), two or more solutions could be ranked as near-optimum solutions. For instance, if we have two objective functions (to maximise productivity and minimize costs), one solution might satisfy the maximum productivity and the other one the minimum cost. In this case or in similar ones, a ranking tool is needed to help the decision makers select the optimum solution. Many approaches can be used to solve this problem; four methods are used in the present research.

2.10 Alternatives' selection approaches

1- Pareto frontier approach

2- Technique of Order Preference by Similarity to Ideal Solution (TOPSIS)

3- Cost index and decision index approach

4- Simulate the best ranked solutions using EZStrobe simulation

a- Pareto front approach

The Pareto front approach helps the operator or decision makers to evaluate the set of solutions in terms of their multi-objective criteria.

b- TOPSIS

TOPSIS is used to select the solution that is geometrically nearest to the best solution and farthest from the worst solution. First developed by Hwang et al. (1993), TOPSIS

takes into consideration all the criteria of each alternative. The principle of TOPSIS is to select the alternative that has " *the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS), which is equivalent to minimising the distance from the PSI and maximizing the distance from the NIS*" (Hwang et al. 1993). This means that an alternative that has one or more negative ideal criterion could be selected as a winner according to the other nearest criteria to the ideal solution. This method compares the alternatives by identifying the weights of the criteria according to the priorities set by the decision makers and normalizes these standards to identify the best solutions with the shortest geometrical distance from the best solution. This approach is widely used in multi-objective decision making problems (MODMP) to solve conflicts in alternative selection. For instance, Roshandel et al. (2013) used hierarchical fuzzy TOPSIS in evaluating and selecting the suppliers in the detergent production industry, Yong (2006) optimized plant location selection based on fuzzy TOPSIS, Zhang and Qi (2012)induced interval-valued intuitionistic fuzzy hybrid aggregation operators with TOPSIS order-inducing variables, Katalinic (2011) prioritized the selection of AS/RSS by using a fuzzy TOPSIS method, and Iason (2014) used TOPSIS to assess subway network performance.

- *TOPSIS principle concept*

The principle of TOPSIS is to select the variable that leads to the farthest from negative optimal solution (NOS) and is the nearest to the positive optimal solution (POS). These alternatives must be evaluated with respect to the values of the criteria. The procedure for implementing TOPSIS is as follows:

1- Assume we have multiple solutions or alternatives (m) and that these alternatives have different criteria (n).

2- Make a matrix (m*n) of $Z = (Z_{ij})$ where i represents the alternatives and j represents the criteria.

3- Assume J represents the set of positive criteria, where a higher value is better, and $\bar{J}$ represents the negative criteria, where a lower value is better.

4- Define decision matrix $R = r_{ij}$ by normalizing Z where $r_{ij} = z_{ij} / (\Sigma z^2_{ij})$ for i = 1, ..., m and j = 1, ..., n

5- Assume weight associated by each criterion; w_j for criteria j

6- Multiply the columns in the decision matrix by their associated w_j values;

7- The new matrix elements are $y_{ij} = w_j * r_{ij}$

8- The PIS is then $A^a = \{y_1{}^a, ...y_n{}^a\}$,

where: $y_j{}^a$ is {max (y_{ij}) if j$\in$J; min (y_{ij}) if j$\in\bar{J}$

9- The NOS is then $A^b = \{y_1{}^b, ...y_n{}^b\}$,

Where $y_j{}^b$ is {min (y_{ij}) if j$\in$J; max (y_{ij}) if j$\in\bar{J}$

10- Define the POI and the NOI separation measures for each alternative, where:

$S_i{}^a$ is the separation measures from POI, $S_i{}^a = [\Sigma (y_{ij} - y_{ij}{}^a)^2]^{1/2}$;

$S_i{}^b$ is the separation measures from PNI, $S_i{}^b = [\Sigma (y_{ij} - y_{ij}{}^b)^2]^{1/2}$

11- The last step is to find $C_i{}^a = [S_i{}^b / (S_i{}^b + S_i{}^a)]$

The largest value of $C_i{}^a$ is thus the best option to be selected where $0 < C_i{}^a < 1$.

c- *Cost index and decision index*

The cost index approach developed by Zayed & Halpin (2001) supports the conclusion in multiple-objective solutions; the minimum cost alternative is not usually the best solution. The authors suggest evaluating the other alternatives in the ideal solution zone. They propose an approach that divides the cost by the productivity of each alternative, as they are the two objectives in their case, called the cost index. The lowest cost index is the best solution alternative. To identify the decision index, they went further to be more specific by dividing the cost index of

each alternative by the cost index corresponding to the lowest alternative cost. This make the decision index of the lowest cost alternative equal to one, as it is dividing by itself. The other decision indexes will vary more and/or less than one. The lowest decision index will reflect the best solution alternative.

2.11 Limitations of Existing Literature

According to the literature review, to keep pace with the rapid growth of the container trade without resorting to the expansion of existing terminals, optimal solutions for raising the productivity of container terminal elements must be found. Any improvement measures for any element of the operation chain result in an improvement of the other elements and of the terminal efficiency as a whole. Reducing vessel berthing time and realizing operation cost savings using the available resources are the main concerns of researchers in CT efficiency. These limitations will be addressed and container terminal productivity improved by introducing this new strategy and by applying double cycling only in yard trucks. The limitations of the literature are defined and summarised as follows:

➢ Despite the many research efforts that have been done to solve the problem of handling containers delays and increasing the productivity or minimizing vessels turnaround times, there is still a delay in container handling operations and the lack of access to productive best to cover this deficit.

➢ In literature, fewer studies have focussed on the other areas such as SYs, YTs and YCs comparing to berth side and QCs which precisely improves the container terminal productivity and effect on the QC productivity.

➢ The quay crane double cycling technique proposed recently by Goodchild (2005) is a new technique to improve terminal efficiency, and it has been proven theoretically.

However, some technical deficiencies and limitations can affect the efficacy of this technique.

1- The technique may be not being effective if the loading and unloading container lanes are far apart.

2- For vessels with deck hatches, applying quay crane double cycling is not useful for the containers above a hatch, as all the containers above a hatch must be unloaded before applying double cycling.

3- In each row, one or more stacks need to be unloaded in single-cycle mode, as well as ending with single cycling, which may confuse the QC and YT operators and reduce the fluctuation of the learning frequency for repetitive work. In addition, double cycling requires more trucks than single cycling because of its longer cycle, which means that some yard trucks are not utilized during the use of single cycling in each row.

4- For each cycle, the YT has to wait for the QC to be loaded before it departs, as the discharge time is considered to be a time lost.

5- This technique works with 100% efficiency when a vessel does not have hatch decks, but for those that have a hatch deck, the single-cycle technique must be applied to unload and load the containers above the hatch.

6- Even though Zhang and Kim (2009) solved the above-hatch problem with a modified use of single and double cycling, still other limitations remain to be solved.

Chapter 3: Research Methodology

3.1 Chapter Overview:

This research is composed of three main phases as detailed in Figure 3-1. Each phase is divided into its sub-phases according to the priority order. The first phase addresses the understanding of container terminals, and starts with a comprehensive literature review organized and detailed as in the previous chapter. This phase includes a state of the art review of yard crane scheduling, container transporting between storage yard and berth, temporary container storage yards, quay crane and berth allocation problems and quay crane double cycling. This phase also focuses on the factors that affect container terminal operation in terms of productivity and costs. The second phase is the simulation phase. It starts with the collection of the data needed to run the simulation, followed by simulation modeling of both single and double cycling, simulation implementation and sensitivity analysis. The last phase is called the optimization phase. It consist of time and cost modeling to optimize the fleet size so as to select the best combination of maximum productivity and minimum cost. The chapter ends with a conclusion and recommendation based on the results from the previous phases.

The methodology is based on introducing a new strategy of container handling, called the YT double cycling technique. The new strategy depends on being able to combine two QCs to work as a single unit with one crane discharging the vessel while the other loads it. Both QCs will serve the same truck; unloading a container from the truck to be loaded into the vessel and loading it with the discharged container from the vessel. Each truck will transport containers from the storage yard to the vessel and from the vessel to the storage yard in the same cycle. Just as with the QCs, two YCs will load and discharge the trucks at the storage yard.

QCs must be located more than two rows of forty feet apart. In the interest of safety and to prevent conflicts, the QCs in this system will be three rows of forty feet apart. The yard cranes will be allocated according to the layout of the storage yard. They could be in the same lane, in two neighboring lanes or even further apart. Shorter distances produce better results. Before implementing the new strategy, some factors that affect container terminal productivity must be addressed: the particular qualities of the QCs, YCs, YTs and SYs. The first three factors are machines that are considered as a fleet for handling containers, while the fourth is the yard where the containers are stored temporarily before or after shipping. These factors are will be investigated and formulated in the next chapter. An EZStrobe simulation will be used to simulate the operation in order to calculate the cycle time, the productivity rate and the hourly cost of container handling.

3.2 Factors that affect container terminal productivity

3.2.1 Quay crane cycle times:

3.2.1.1 Quay crane cycle times procedure:

The quay crane cycle time starts from the movement of the trolley (empty or loaded) from the truck lane to the (discharged or loaded) container position in the bay indicated in (Figure 3- 2 and Figure 3- 3). The trolley makes different forward and backward moves. The trolley's vertical speed is purposely different between its loaded and empty movements. In addition, in some locations, the operators resort to combining horizontal and vertical movements at the same time, in what are known as diagonal movements. To assess diagonal movement, the longest time of the two is the one recorded. For more details about movement, see Figure 3- 4.
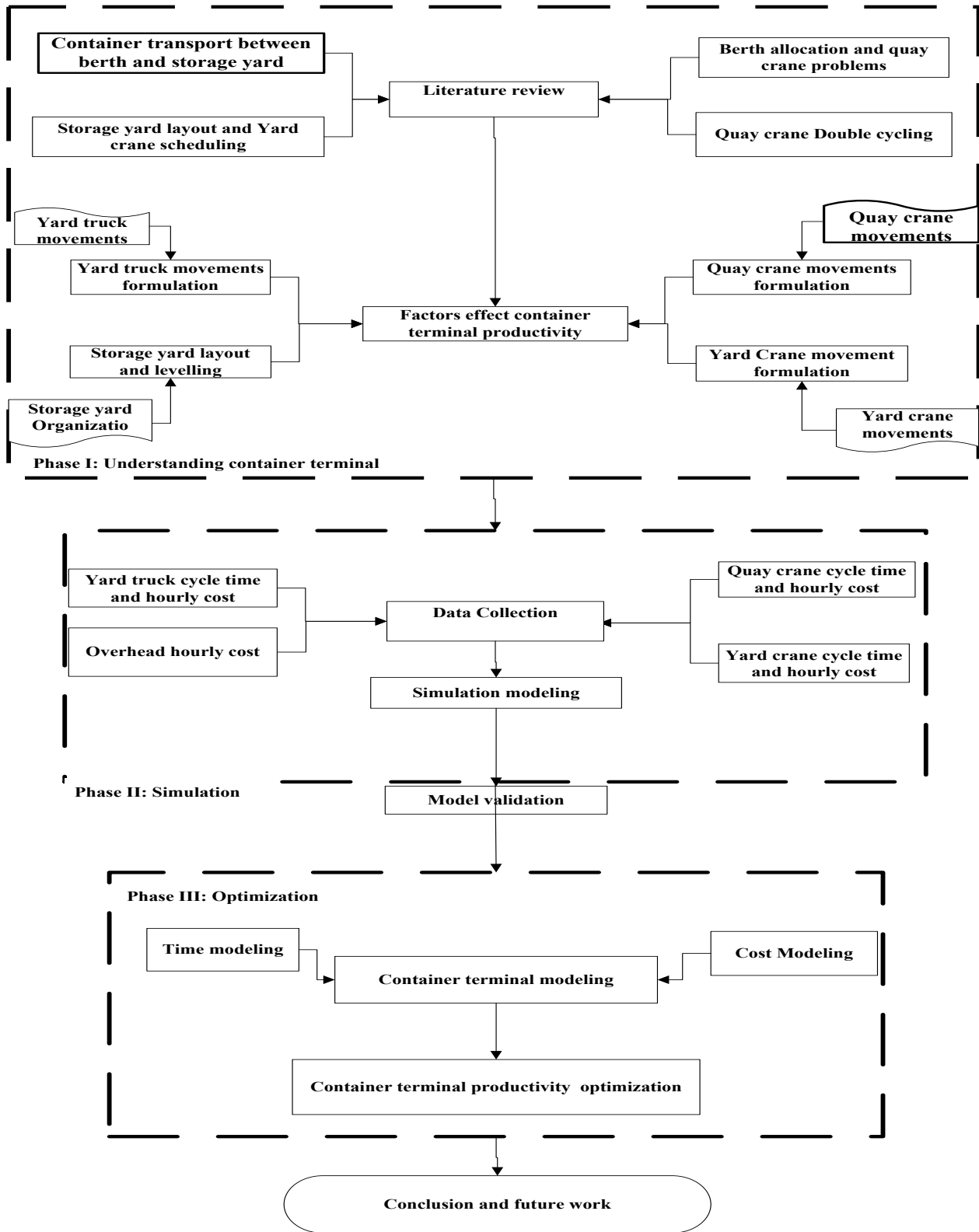
Figure 3- 1: Research Methodology
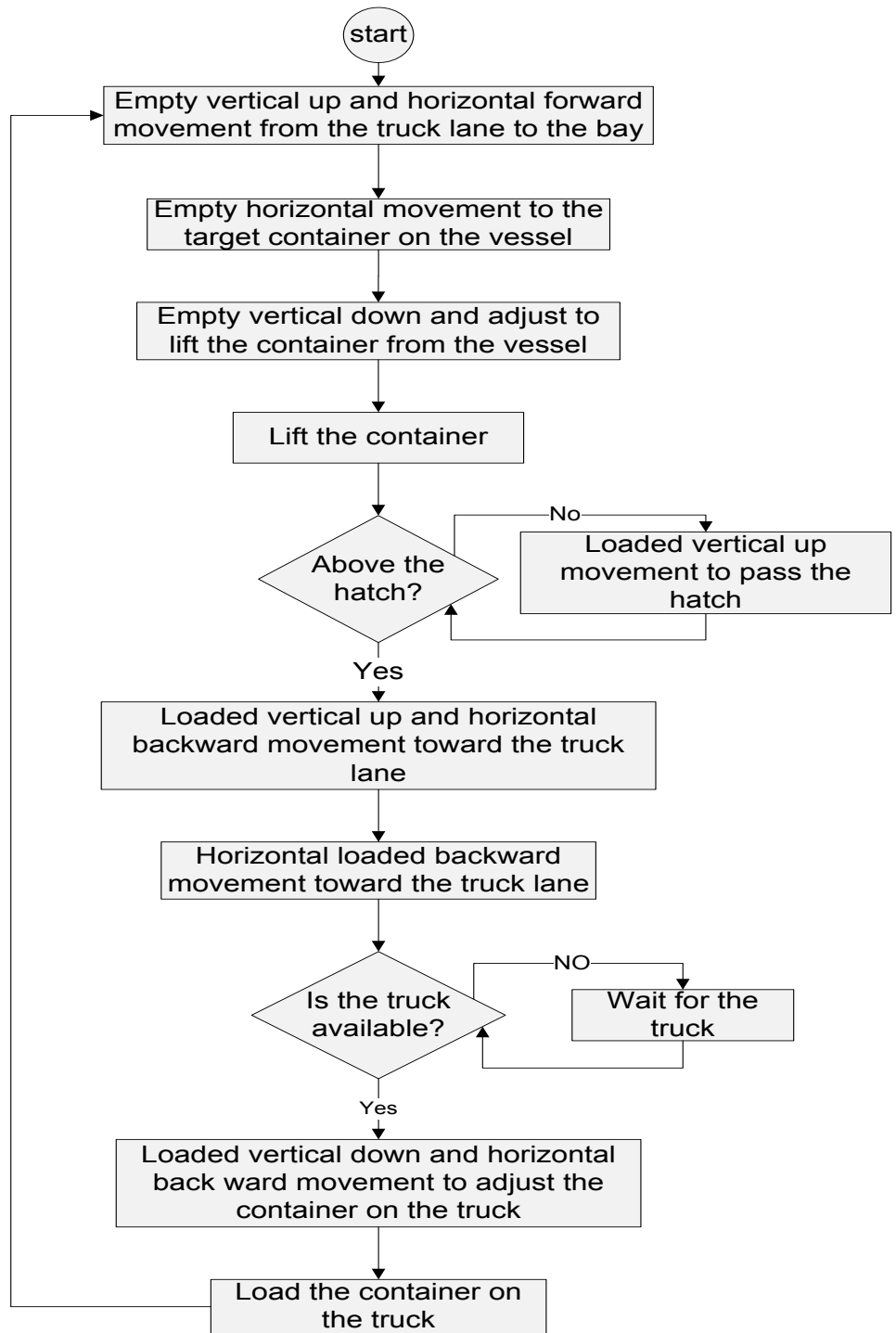
Figure 3- 2: QC unloading cycle time

```
                              ┌─────────┐
                              │  start  │
                              └────┬────┘
                                   ▼
                    ┌──────────────────────────┐
                    │   Lift the container      │ ◄──────────┐
                    │     from the truck        │            │
                    └──────────────┬───────────┘             │
                                   ▼                         │
              ┌─────────────────────────────────┐           │
              │  Loaded vertical up and horizontal│          │
              │  forward movement toward the bay  │          │
              └────────────────┬──────────────────┘          │
                               ▼                             │
              ┌─────────────────────────────────┐           │
              │   Loaded horizontal forward       │          │
              │     movement toard the bay        │          │
              └────────────────┬──────────────────┘          │
                               ▼                             │
          ┌───────────────────────────────────────┐         │
          │ Vertical down and horizontal forward   │         │
          │ movement to load adjust the container  │         │
          │           on the vessel                │         │
          └────────────────┬───────────────────────┘         │
                           ▼                                 │
              ┌─────────────────────────────┐               │
              │   Load the container on       │              │
              │       the vessel              │              │
              └──────────────┬───────────────┘               │
                             ▼        NO                     │
                         ◇ Above the ◇──────► ┌────────────────────────┐
                         ◇  hatch?   ◇        │ Empty vertical up movement│
                         ◇           ◇◄───────│   to pass the hatch      │
                             │                └────────────────────────┘
                            Yes
                             ▼
          ┌─────────────────────────────────────────┐
          │ Empty vertical up and horizontal backward│
          │    movement toward the truck lane         │
          └────────────────┬──────────────────────────┘
                           ▼
          ┌─────────────────────────────────────────┐
          │ Horizontal empty backward movement        │
          │       toward the truck lane               │
          └────────────────┬──────────────────────────┘
                           ▼          NO
                      ◇ Is the truck ◇──────► ┌──────────────────┐
                      ◇  available   ◇        │ Wait for the truck│
                      ◇              ◇◄────────│                  │
                           │                  └──────────────────┘
                          Yes
                           ▼
          ┌─────────────────────────────────────────┐
          │ Empty  vertical down and horizontal backward│
          │ movement to lift the container from the truck│
          └─────────────────────────────────────────┘
```

Figure 3- 3: QC loading cycle

When discharging containers, the trolley starts empty, moving forward up vertically and horizontally at the same time (diagonally) in order to save time. Next, it moves horizontally to be close to the container location. The trolley again makes a diagonal movement, downward to be able to lift the container. If the container is above the hatch, lifting the container is the next step. If not, the trolley will move the container vertically down and then lift the container. After lifting the container, loaded backward moves will be applied. The same steps of moving forward, but in the opposite direction, begin from where the bay ends to the truck lane. If the truck is available, the QC will load the container on the truck. If it is not available, the QC will wait until a truck arrives. This delay will add to the cycle time and be counted as a late time. To load the vessel, the trolley makes the same moves, only replacing the empty with loaded and the loaded with empty moves.
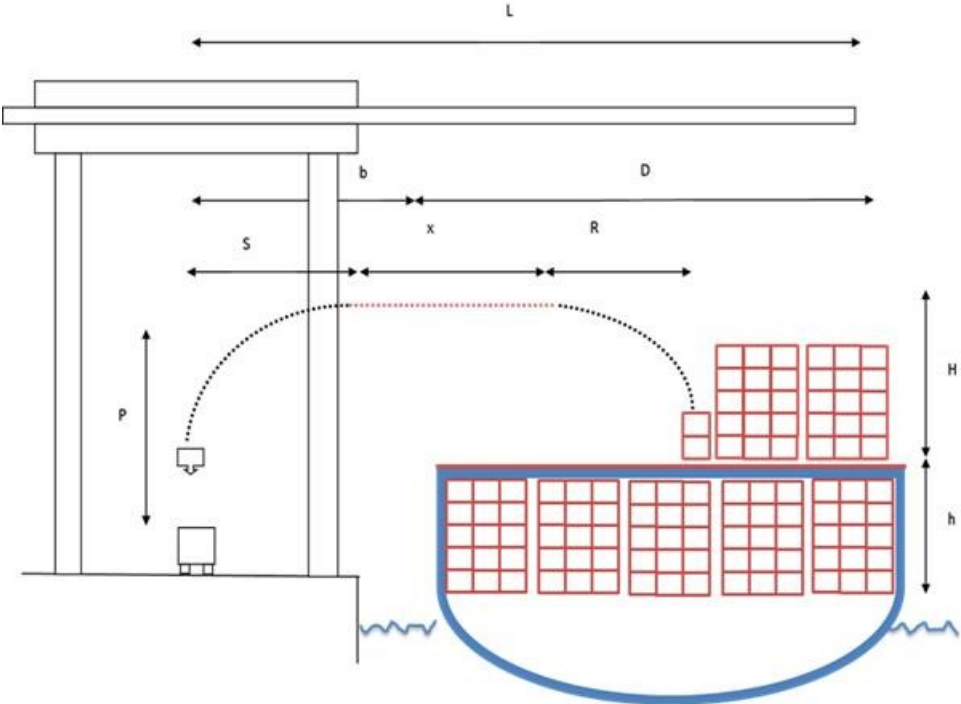
Figure 3- 4: QC possible forward and backward trolley movements

The handling time varies from one container to another depending on its position in the cell of the row matrix. Because of the large number of containers, and neglecting the difference in time between neighboring stacks, the horizontal distribution of 40-ft containers (2TEUs) are divided into segments of two containers (4 TEUs) to simplify the calculations. Figure 3-5, shows the segment distribution.
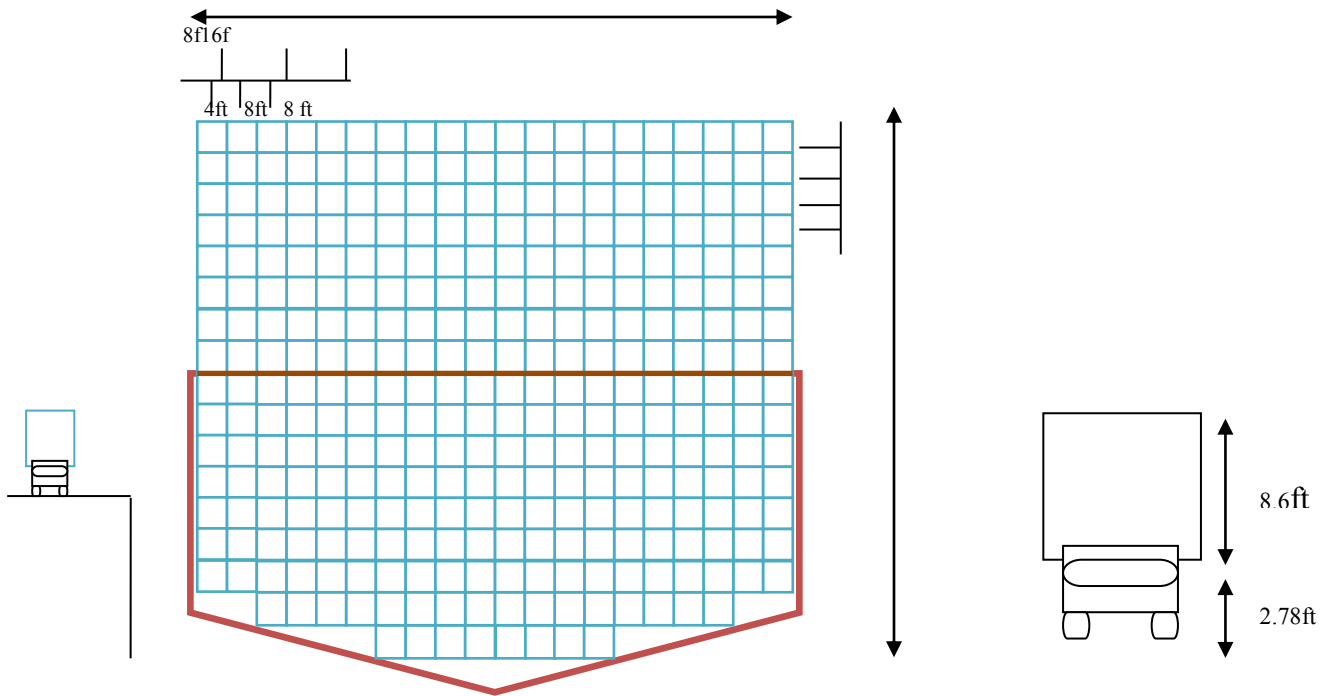
Figure 3- 5: row container distribution on the vessel

3.2.1.2 Quay crane unloading cycle time formulation

Let wu represent the QC unloaded cycle time, and considering that all distances are in feet and times are in minutes, where:

wu= Quay crane cycle time=
[$\sum$(forward times when empty)+t_{lift}+$\sum$(backward times when loaded)]+ t_{load} + lt.

$$wu = [(t1 + t2 + t3 + t4) + t5 + (t6 + t7 + t8 + t9) + t10 + lt].$$ (Equation 3.1)

39

$wu =$

$\{(max[\frac{dP}{dv2},\frac{ds}{dv1}]+\frac{dx}{dv1} + max[\frac{dH}{dv2},\frac{dR}{dv1}]+\frac{dh}{dv2})+t5+(\frac{dh}{dv3}+max[\frac{dH}{dv3},\frac{dR}{dv1}]) +$

$(\frac{dx}{dv1}max[\frac{dP}{dv3},\frac{ds}{dv1}]) + t10 + lt\},$ (Equation 3.2)

where:

$t1$= Time to make an up-forward diagonal movement, in minutes;

    $= max[\frac{dP}{dv2},\frac{ds}{dv1}].$ (Equation 3.3)

$t2$= Time to pass a horizontal distance forward along the vessel width;

    $= \frac{dx}{dv1}.$ (Equation 3.4)

$t3$ = Time to make a downward diagonal movement;

    $= max[\frac{dH}{dv2},\frac{dR}{dv1}].$ (Equation 3.5)

$t4$= Time to make a vertical movement under the hatch;

    $= \frac{dh}{dv2}.$ (Equation 3.6)

$t5$ = Time (in minutes) to lift a container from the vessel;

$t6$ = Time (in minutes) to make an upward vertical movement to pass the hatch;

    $= \frac{dh}{dv3}.$ (Equation 3.7)

$t7$ = Time to make an upwards backward diagonal movement;

    $= max[\frac{dH}{dv3},\frac{dR}{dv1}].$ (Equation 3.8)

$t8$ = Time to pass a horizontal distance backward along the vessel width;

    $= \frac{dx}{dv1}.$ (Equation 3.9)

$t9$= Time to make a downwards backward diagonal movement; and

    $= max[\frac{dP}{dv3},\frac{ds}{dv1}].$ (Equation 3.10)

$t10$ =The time required to load the container on the truck.

Parameter definitions:

lt is the time that the QC has to wait for the truck;

P is the vertical upward distance from the top of the container on the truck to the maximum height distance the trolley can reach, in ft;

S is the horizontal distance from the truck lane to the closest side of the bay;

X is the horizontal distance from the lane closest to the bay to the target container, before applying diagonal movement;

The lower bound of 8 ft is the width of the first lane, which is assigned for emergency vehicles;

b Represents the horizontal distance from the truck lanes to the edge of the bay (vessel wall on the lane side);

R is the horizontal movement that will occur when using empty downward diagonal movement;

H is vertical downward distance from the maximum height distance the trolley can reach in the hatch;

h is vertical downward distance from the hatch to the top of the lowest container; and

D represents the vessel width.

The trolley's speeds are designated as follows:

Maximum horizontal speed =240 m/min= 787.4 ft/min;

Vertical speed when empty = 170 m/min= 557.7 ft/min; and

Vertical speed when loaded = 70 m/min= 229.7 ft/min.

The variables v1 – v3 for the trolley speeds can thus be expressed as:

v1 The trolley horizontal speed in ft/min so that $0 \leq v1 \leq 787.4$;

v2 The trolley vertical speed when it is empty, $0 \leq v2 \leq 557.7$; and

v3 The trolley vertical down speed when it is loaded, $0 \leq v3 \leq 229.7$.

3.2.1.3 Quay crane loading cycle time formulation

The same moves for unloading apply to loading, except that the empty moves are replaced by loaded ones, and vice versa.

Let *wl* represent the QC unloaded cycle time, where:
wl= Quay crane cycle time

=[∑(forward times when loaded)+∑(backward times when empty)]+ *lt*.

$wl = [(t1 + t2 + t3 + t4) + \text{t5} + (t6 + t7 + t8 + t9) + \text{t10} + lt].$ (Equation 3.11)

$$= \{(max[\tfrac{dP}{dv3}, \tfrac{ds}{dv1}]+\tfrac{dx}{dv1} + \ max[\tfrac{dH}{dv3}, \tfrac{dR}{dv1}\ ]+\tfrac{dh}{dv3})+t5 +(\tfrac{dh}{dv2} +max[\tfrac{dH}{dv2}, \tfrac{dR}{dv1}\ ]+\tfrac{dx}{dv1}+max[\tfrac{dP}{dv2}, \tfrac{ds}{dv1}$$
$$])+t10 + lt\}. \hspace{4cm} \text{(Equation 3.12)}$$

$(t5, t10)$ represents the time to lift the container from the truck and the time to load the container on the vessel, respectively.

3.3 Yard crane cycle time

3.3.1 Yard crane cycle time procedure

As with the quay crane, the yard crane cycle time starts from the movement of the trolley (empty or loaded) from the truck lane to the (discharged or loaded) container position in the pre-assigned storage yard (see Figure 3- 6 and Figure 3- 7). The trolley makes the same set of forward and backward moves. YC trolleys also have different vertical speeds when they are loaded than when empty. As with QCs, diagonal movements are applied to save time. For more movement details see Figure 3- 8. Almost all of the QC's forward and backward movement procedures can be implemented by YCs (except those for the hatch, as storage yards do not have hatches). The truck delay will lead to YC delay time. This delay is added to the cycle time and counted as late time.

3.3.1.1 Yard crane unloading cycle time derivation

Let wu represent the QC unloaded cycle time, where:

wu = Quay crane cycle time= [∑(forward times when loaded)
+∑(backward times when empty)] + lt.

$$wu = \{t1 + (t2 + t3 + t4)\} + [t5 + (t6 + t7 + t8)] + \ lt\}. \hspace{2cm} \text{(Equation 3.13)}$$

$$= \{t1 + (max[\tfrac{dh}{dv2}, \tfrac{ds}{dv1}\ ]+\tfrac{dx}{dv1} + \ max[\tfrac{dP}{dv2}, \tfrac{dR}{dv1}\ ]) +(\ t5 + \ max[\tfrac{dP}{dv3}, \tfrac{dR}{dv1}\ ]+\tfrac{dx}{dv1}+max[\tfrac{dh}{dv3}, \tfrac{ds}{dv1}$$
$$]) + lt\}. \hspace{5cm} \text{(Equation 3.14)}$$

Note: all times are in minutes, distances are in feet and speeds are in min/ft.

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```
                              ┌───────────┐
                              │   Start   │
                              └─────┬─────┘
                                    │
          ┌─────────────────────────▼──────────────────────────┐
          │         Lift the container from the truck           │
          └─────────────────────────┬──────────────────────────┘
          │                          │
          │         ┌────────────────▼─────────────────┐
          │         │  Vertical up and forward move from │
          │         │  the truck lane to the assigned    │
          │         │  space.                            │
          │         └────────────────┬─────────────────┘
          │                          │
          │         ┌────────────────▼─────────────────┐
          │         │  Horizontal forward move to the    │
          │         │  target storage space              │
          │         └────────────────┬─────────────────┘
          │                          │
          │         ┌────────────────▼─────────────────┐
          │         │  Loaded vertical down movement to  │
          │         │  discharge the container           │
          │         └────────────────┬─────────────────┘
          │                          │
          │         ┌────────────────▼─────────────────┐
          │         │  Discharge the container           │
          │         │  on the stack                      │
          │         └────────────────┬─────────────────┘
          │                          │
          │         ┌────────────────▼─────────────────┐
          │         │  Empty vertical up and             │
          │         │  horizontal movement               │
          │         └────────────────┬─────────────────┘
          │                          │
          │  ┌───────────────────────▼────────────────────────┐
          │  │  Empty horizontal backward movement             │
          │  │  from the storage space to the truck lane       │
          │  └───────────────────────┬────────────────────────┘
          │                          │
          │                          ▼           NO    ┌──────────────────┐
          │                    ╱ Is the truck ╲────────│ Wait for the truck│
          │                    ╲  available    ╱◄──────└──────────────────┘
          │                          │
          │                          ▼
          │  ┌───────────────────────────────────────────────┐
          └──│  Vertical down and horizontal movement and      │
             │  adjust to lift the container from the truck    │
             └───────────────────────────────────────────────┘
```

Figure 3- 6: YC unloading cycle
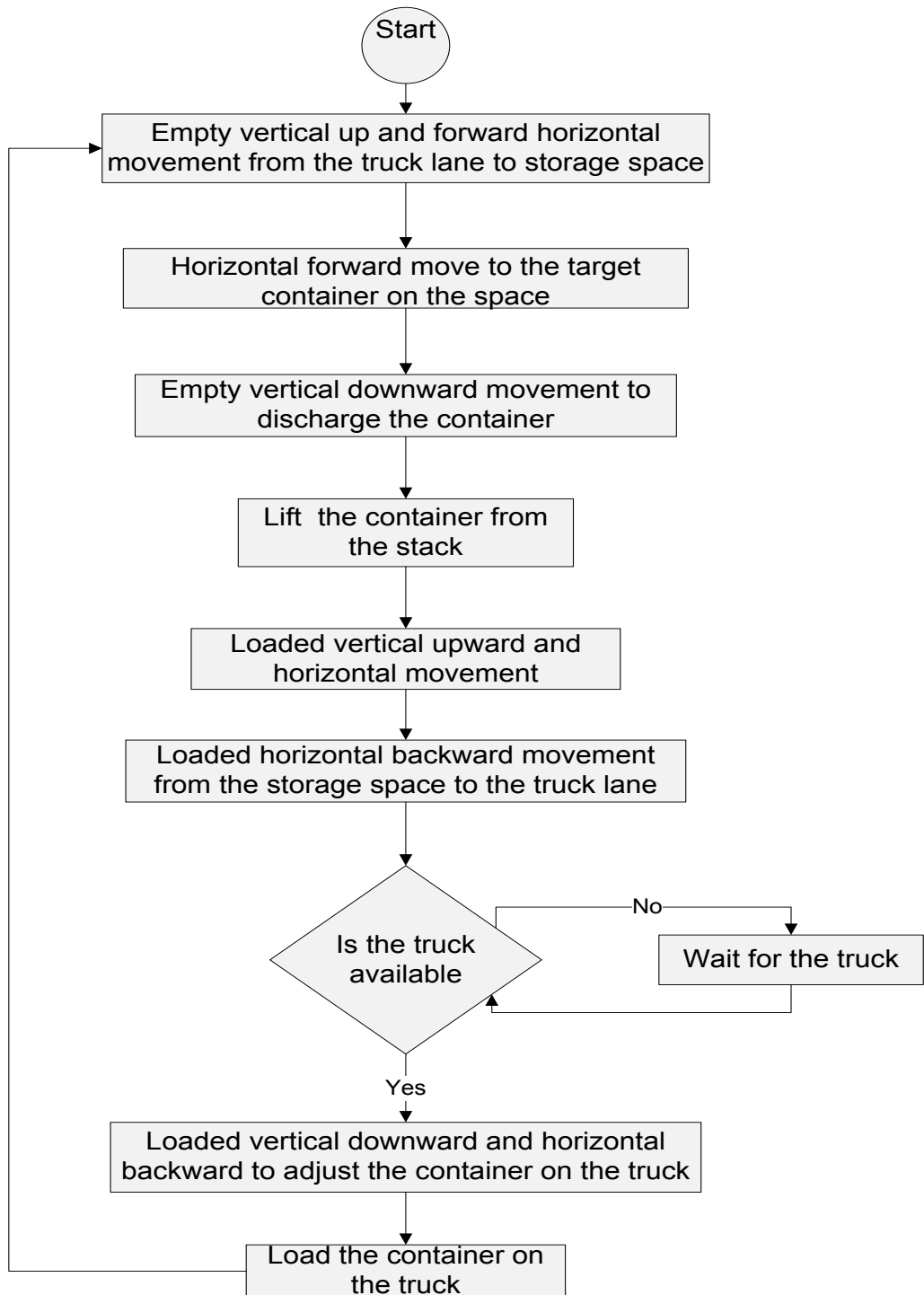
Figure 3- 7: YC Loading cycle flow chart
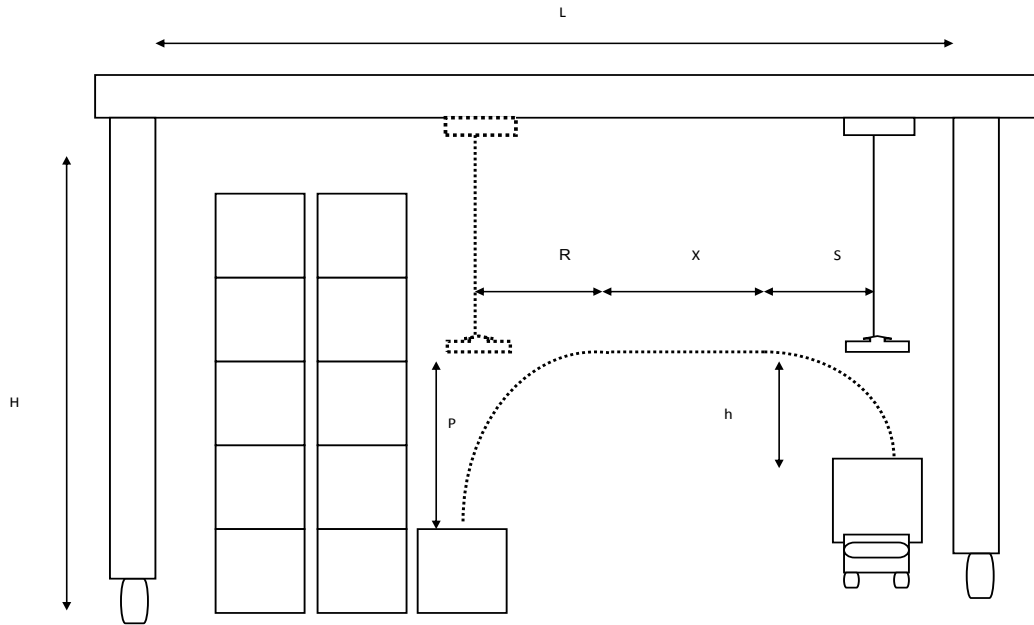
Figure 3- 8: Yard crane motions in a storage yard

$t1$ = the time to lift a container from a truck

$t2$= the time to make an upward forward diagonal movement.

$$= max[\frac{dh}{dv2}, \frac{ds}{dv1}].$$ (Equation 3.15)

$t3$= the time to pass the horizontal distance forward along the vessel width.

$$= \frac{dx}{dv1}.$$ (Equation 3.16)

$t4$ = the time to make the downward diagonal movement.

$$= max[\frac{dP}{dv2}, \frac{dR}{dv1}].$$ (Equation 3.17)

$t5$ = the time to unload the container in the stack.

$t6$= the time to make an upwards backward diagonal movement.

$$= max[\frac{dP}{dv3}, \frac{dR}{dv1}].$$ (Equation 3.18)

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$t7$= the time to pass the horizontal distance backwards along the vessel width.

$$= \frac{dx}{dv1}.$$
(Equation 3.19)

$t8$= the time to make a downwards-backward diagonal movement.

$$= max[\frac{dh}{dv3}, \frac{ds}{dv1}].$$
(Equation 3.20)

lt = the time that the YC must wait for the truck.

h -- is the vertical upward distance from the top of the container on the truck to the maximum height distance the trolley can reach, in ft;

S -- is the horizontal distance from the truck lane to the closest side of the container stacks;

X- the horizontal distance from the side of the container stacks closest to the target container before applying diagonal movement, in ft;

$R$the horizontal distance using loaded downwards diagonal movement; and

$P$the vertical downwards distance from the maximum height the trolley can reach to the top of the lowest container, in ft..

The trolley's speeds are designed to be as follows:

Horizontal speed = 70 m/min= 229.7 ft/min;

Vertical speed when loaded = 20 m/min= 65.62 ft/min; and

Vertical speed when empty = 40 m/min= 131.2 ft/min.

Thus, the trolley's speed ranges can be expressed as:

$v1$ -- is the trolley's horizontal speed in $0 \le v1 \le 229.7$;

$v2$is the trolley's vertical speed when loaded $0 \le v2 \le 65.62$; and

$v3$ -- is the trolley's vertical downward speed when empty $0 \le v3 \le 131.2$.

3.3.1.2 Yard crane loading cycle time formulation

For loading a vessel, the same moves will apply, but the empty moves will be replaced by loaded ones, and vice versa.

Let wl represent the YC unloaded cycle time, where: wl= YC crane cycle time

$$= [\sum(\text{forward times when empty}) + \sum(\text{backward times when loaded})] + lt. \qquad \text{(Equation 3.21)}$$

$$wl = \{[(t2 + t3 + t4) + t5] + [(t6 + t7 + t8) + t1] + lt\}. \qquad \text{(Equation 3.22)}$$

$$= \{(max[\frac{dh}{dv3},\frac{ds}{dv1}] + \frac{dx}{dv1} + max[\frac{dP}{dv3},\frac{dR}{dv1}] + t5) + (max[\frac{dP}{dv2},\frac{dR}{dv1}] + \frac{dx}{dv1} + max[\frac{dh}{dv2},\frac{ds}{dv1}] + t1)$$
$$+ lt\}. \qquad \text{(Equation 3.23)}$$

3.4 Impact of storage yard layout on container terminal productivity

At the storage yard, the containers are loaded in stacks of five containers with more than five stacks per row, as shown in Figure 3- 9. The number of rows varies, depending on the size and layout of the storage yard. The yard crane cycle time is directly influenced by the SY size and layout. A well-designed and organized layout results in effective and efficient YC productivity. Different layouts for import and export storage yards are commonly used, according to each storage yard's area, berth length and the location of the land gates. Some of the most commonly used layouts are side-by-side, back-to-front, column-by-column, row-by-row and diamond. These layouts are represented in Figure 3- 10.
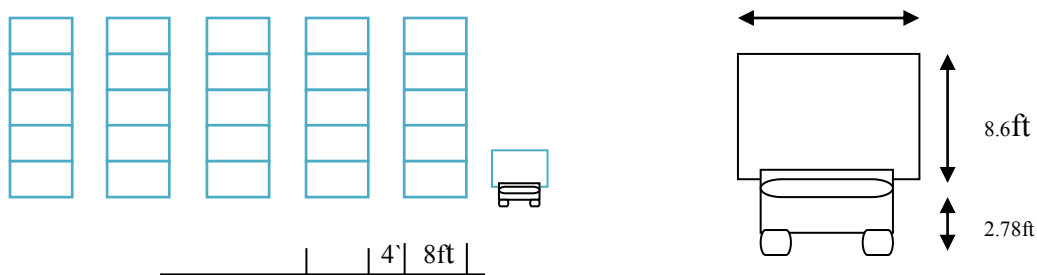
Figure 3- 9: Storage yard stacks

(a) Side by side layout   (b) front back layout

(C) Column by column layout   (d) row by row layout

(e) Diamond layout
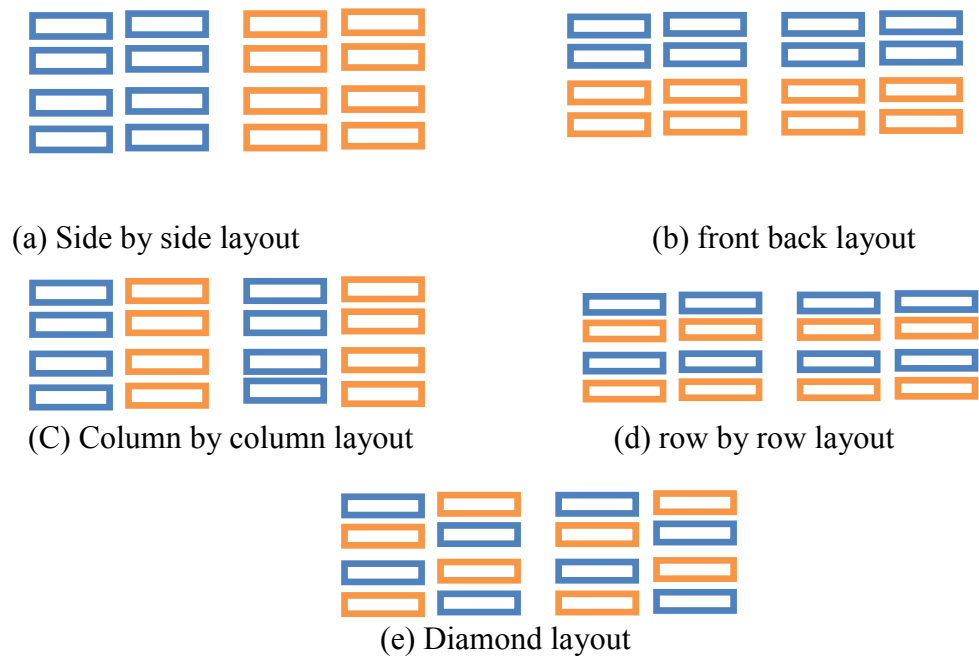
Figure 3- 10 Possible SY layouts

3.5 Yard truck cycle time

3.5.1 Yard truck single cycle unloading

YT single-cycle unloading starts with a YT moving from the truck pool or storage yard to the berth side. At the truck lane on the berth side, the truck will be loaded by the QC if it is ready. Otherwise, the truck waits for the QC to be ready. After being loaded, the YT returns to the storage yard to a pre-assigned lane, where a YC discharges the truck when it is available. A waiting time will be added if the YC is not ready. The YT will repeat the process until the last imported container is fully unloaded from the vessel. A specific number of YTs is needed to do the job in order to keep the cranes busy. Figure 3- 11 shows the detailed movement and actions of yard truck single-cycle unloading.

3.5.2 Yard truck single cycle loading

Yard truck single cycle loading starts at the same place as YT single cycle unloading, in the storage yard. The only difference is that the YT has to be loaded with the exported container before it departs the storage yard. A YC loads the container on the truck. The loaded YT then moves to the berth side to be discharged by the QC when it is ready. Just as with YT single cycle unloading, if the QC is not ready, a late time will be added to the cycle time. After being unloaded by the QC, YT will move back empty to the storage yard. At the SY, the YC should be ready to reload the truck. If it is not ready, a late time will be added to the cycle time. Figure 3-12 represents the detailed moves and actions. A reasonable number of trucks should be assigned to assure that the cranes are kept busy.

3.5.3 Yard truck double cycling

In double cycling, the first YC starts the cycle by loading the YT. The loaded YT then moves to the berth side to be discharged by the first QC. After discharging, the YT moves empty to the second QC to be loaded. Next, it returns to the storage yard to unload the container at an import lane. The second YC should be ready to discharge the truck, which then departs empty to the export lane to be loaded by the first YC, thus starting a new cycle. Any delay or waiting time for a crane will be added to the cycle time as late time. A fleet of YTs will continue the work until reverting back to single cycle loading to load the remaining containers. For more details, see Figure 3- 13.

3.5.4 Yard truck cycle times derivation

The YT cycle time varies, as it is dependent upon the storage yard distance from the berth and the berth allocation, the maximum speed policy, the external road conditions, the YT operator's skills, and especially, the storage yard layout.
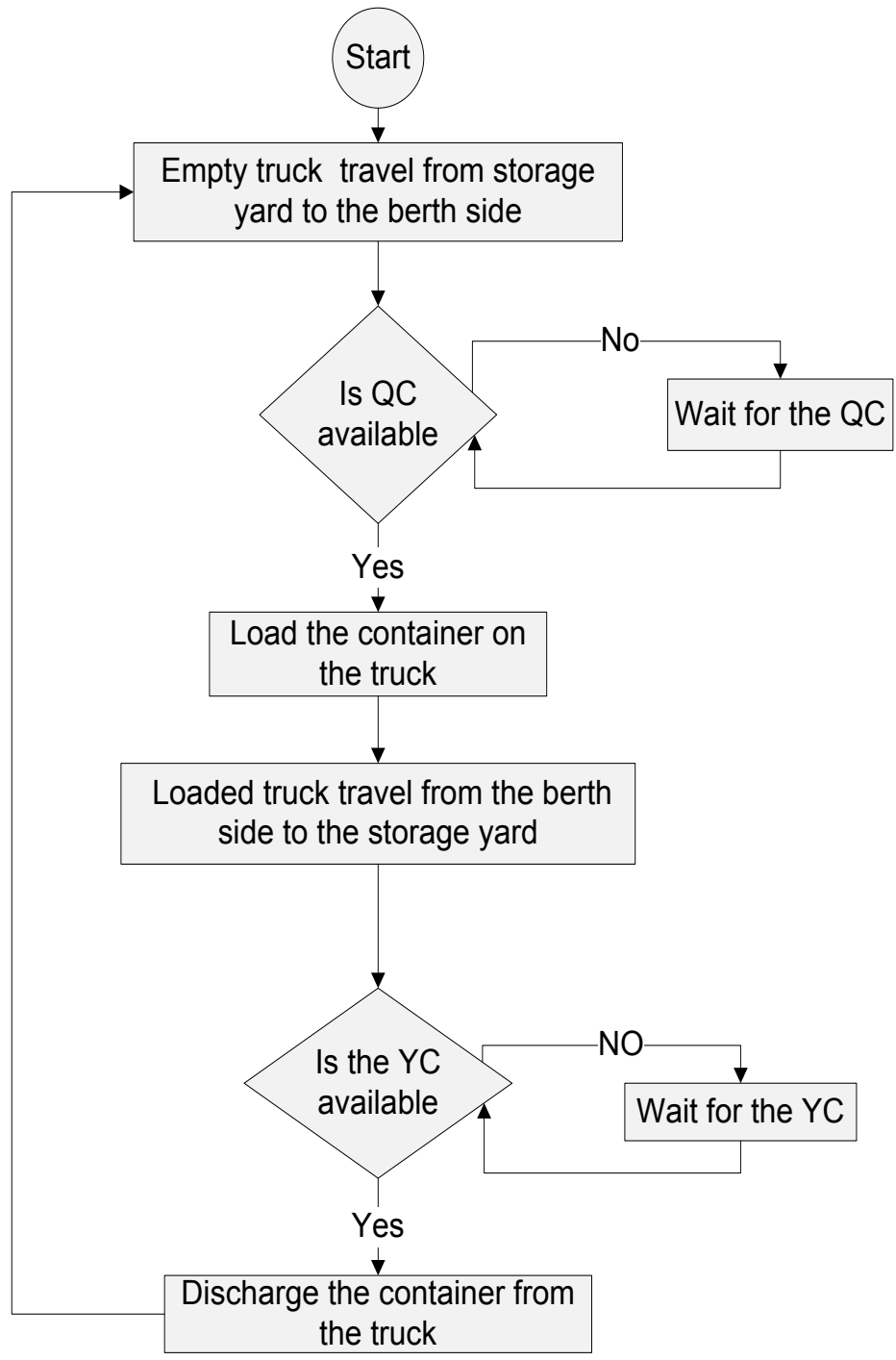
Figure 3- 11 YT single cycle unloading flow chart

```
                        ┌─────────┐
                        │  Start  │
                        └────┬────┘
                             │
                             ▼
              ┌──────────────────────────┐
              │  Load the truck at export │
              │       storage yard        │
              └──────────────┬───────────┘
                             │
                             ▼
              ┌──────────────────────────┐
              │  Loaded truck travel from │
              │ storage yard to the berth side │
              └──────────────┬───────────┘
                             │
                             ▼
                          ◇ Is QC ◇───No──►┌──────────────────┐
                          ◇ available ◇     │  Wait for the QC │
                             │              └──────────────────┘
                            Yes
                             ▼
              ┌──────────────────────────┐
              │    Discharge the truck    │
              └──────────────┬───────────┘
                             │
                             ▼
              ┌──────────────────────────┐
              │ Empty truck travel from the berth │
              │  side to the storage yard │
              └──────────────┬───────────┘
                             │
                             ▼
                          ◇ Is the YC ◇───No──►┌──────────────────┐
                          ◇ available ◇         │  Wait for the YC │
                             │                  └──────────────────┘
                            Yes
```
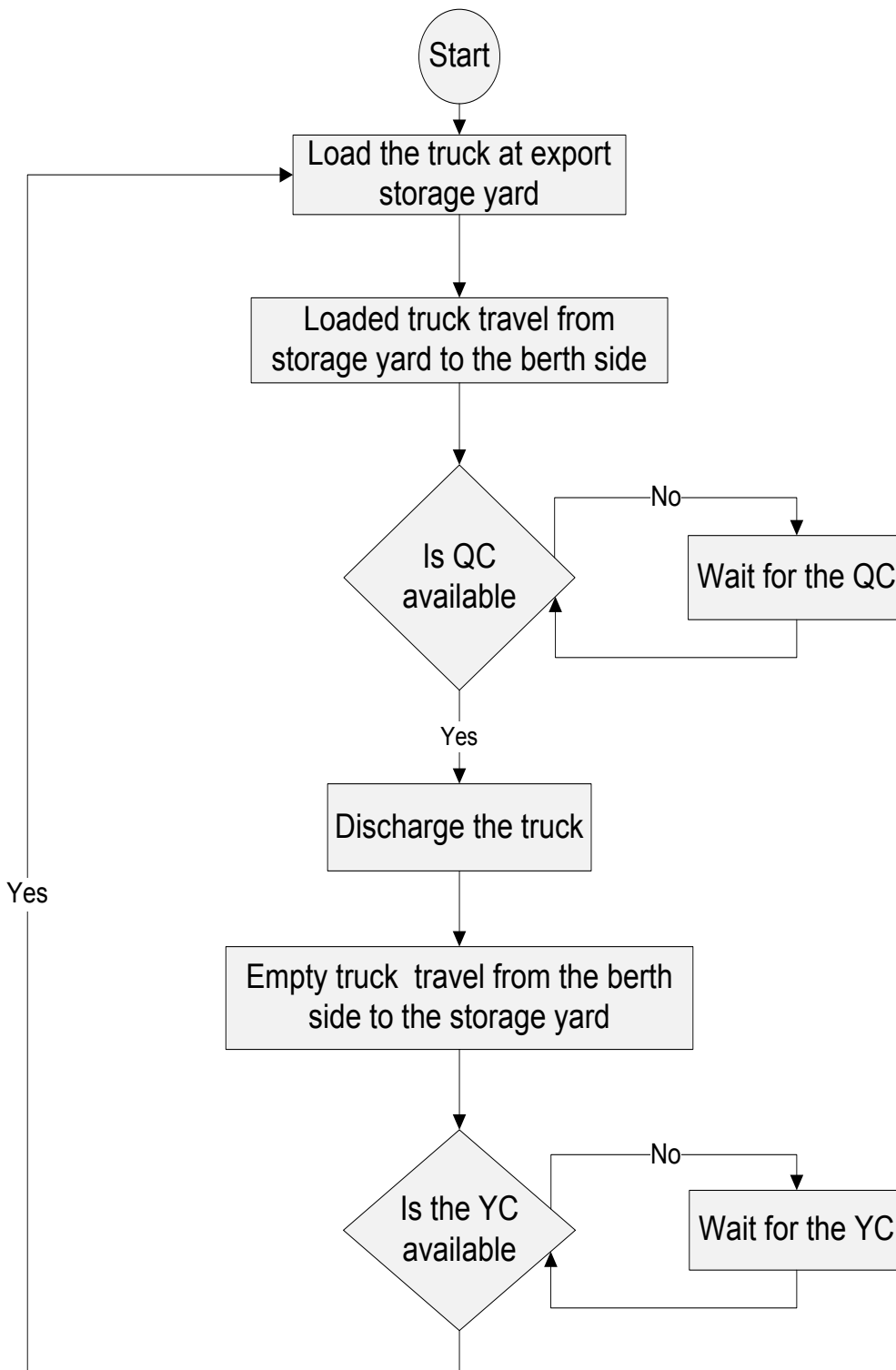
Figure 3- 12 YT single cycle loading flow chart
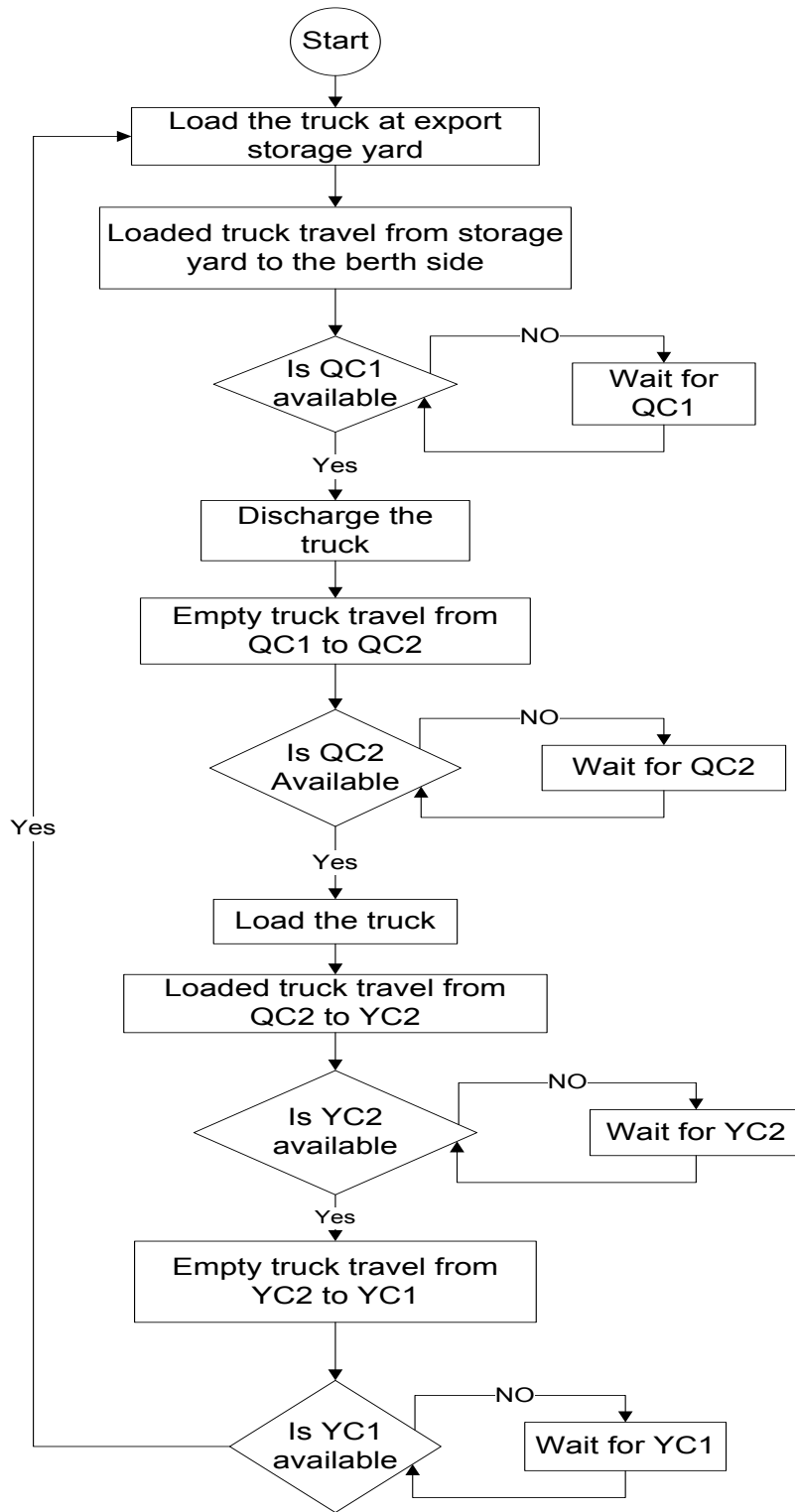
Figure 3- 13 YT Double cycling flow chart

3.5.4.1 Yard truck single cycle unloading formulation

Since the unloading formulation varies between single cycle unloading and loading and double cycle unloading and loading, the formulation of single cycle loading is expected to begin as shown in Figure 3- 14.
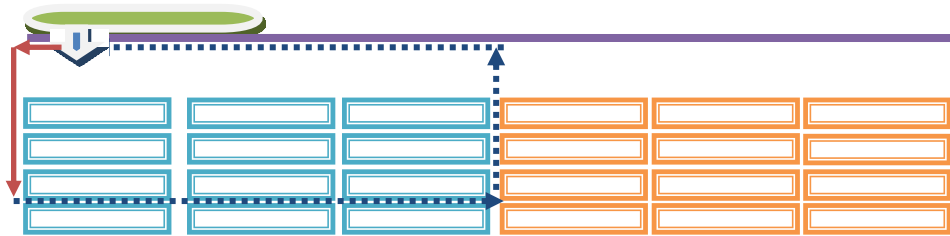
Figure 3- 14 YT single cycle unloading journey

Where:

 Vessel to be discharged of imported containers and loaded with exported containers.

 Unload quay crane.

 Lanes to be loaded by imported containers.

 Lanes to be unloaded of exported containers.

—— Shoreline

——► Loaded truck`s travel path from the storage yard to the bay (X_1).

•••••► Empty truck`s travel path from the bay to the exported container lanes (X_2).

$$T = w1 + \left(\frac{dx1}{dv1}\right) + w2 + \left(\frac{dx2}{dv2}\right) + \sum ly + \sum lb. \qquad \text{(Equation 3.24)}$$

where:

(T)Represents the yard truck unloading cycle time;

$w1$is the container unloading time by QC at the bay;

$w2$ is the unloading time at the storage yard using an YC;

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$x1$Represents the empty trucks' travel path between the storage yard and bay side;

$x2$ is the loaded truck's travel path from the bay to the storage yard;

$v1$ represents the truck's speed when empty, $0 < v2 \leq 2187$;

$v2$ Represents the truck's speed when loaded, $0 < v2 \leq 1367$;

ly Represents the truck waiting time at the yard zone; and

lb Represents the truck waiting time at the bay or berth side;

3.5.4.2 Yard truck single cycle loading formulation

The YT single cycle loading formulation is the same as for single cycle unloading, except that moving empty YTs are replaced by loaded YTs moving from the berth to the storage yard. The calculation is based on the representation in 3-15.
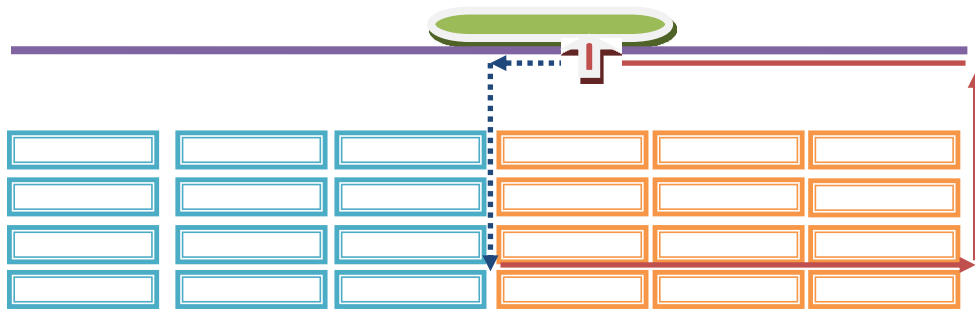
Figure 3- 15 YT single cycle loading journey

where:

Vessel to be discharged of imported containers and loaded with exported containers.

Load quay crane.

Lanes to be unloaded of exported containers.

Shoreline

Loaded truck`s travel path from the storage yard to the bay (X_1).

Empty truck`s travel path from the bay to the exported container lanes (X_2).

$$T = w1 + \left(\frac{dx1}{dv2}\right) + w2 + \left(\frac{dx2}{dv1}\right) + \sum ly + \sum lb. \qquad \text{(Equation 3.25)}$$

where:

(T) Represents the yard truck unloading cycle time;

w1 is the container loading time at the storage yard using a YC);

w2 is the container loading time using a QC at the bay;

x1 is the loaded trucks' travel path from the storage yard to the bay;

x2 is the empty trucks' travel path from the bay side to the storage yard.

v1 is the speed of an empty truck ft/min. $0 < v2 \leq 365$ ft/min;

v2 is the speed of a loaded truck ft/min. $0 < v2 \leq 365$ ft/min;

ly is the truck waiting time at the yard zone in minutes; and

lb is the truck waiting time at the bay or berth side in minutes.

3.5.4.3 Yard truck double cycling formulation

YT double cycling is different than single cycling. There a partial compensation for the two loading and unloading single cycles by replacing the paths between the SY and the Berth side with loaded travels exclusively. The only empty travels are the short distances between the two QCs and between the two YCs. Figure 3- 16 indicates the empty and the loaded travel paths.

$$T = w1 + \left(\frac{dx1}{dv1}\right) + w2 + \left(\frac{dx2}{dv2}\right) + w3 + \left(\frac{dx3}{dv1}\right) + w4 + \left(\frac{dx4}{dv2}\right) + \sum ly + \sum lb. \quad \text{(Equation 3.26)}$$

$$T = w1 + w2 + w3 + w4 + \left(\frac{dx1+dx3}{dv1}\right) + \left(\frac{dx2+dx4}{dv2}\right) + \sum ly + \sum lb \qquad \text{(Equation 3.27)}$$

It is assumed that $1 = w4$, and $w2 = w3$.

$$T = (w1 + w2) + \left(\frac{dx1+dx3}{dv1}\right) + \left(\frac{dx2+dx4}{dv2}\right) + \sum ly + \sum lb. \qquad \text{(Equation 3.28)}$$
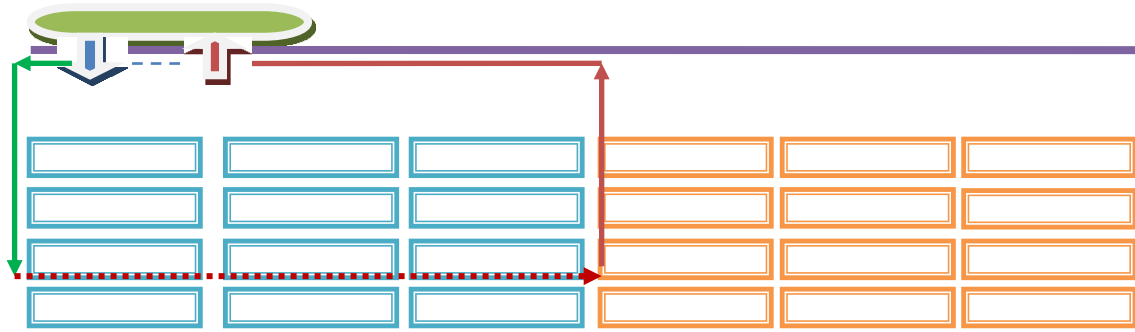
Figure 3- 16 YT double cycle journey

where:

Vessel to be discharged of imported containers and loaded with exported containers.

Unloading quay crane   loading quay crane

unloaded imported containers   loaded lanes of exported containers

Shoreline.

Loaded trucks travel path from the bay to the storage yard (X_1)

Empty trucks travel path between export and import lanes (X_2)

Loaded trucks travel path from the export container lanes to the bay (X_3)

Empty trucks travel path between export and import lanes (X_4)

Note: times are in minutes, distances are in feet and speeds are in ft/min;

where:

T = yard truck unloading and loading (double) cycle time;

$w1$ = container unloading time by QC_1 at the bay;

$w2$ = unloading time at the storage yard, using a Yard crane (YC_1);

$w3$ = loading time at the storage yard, using a Yard crane (YC_2);

$w4 =$ *container loading time by QC$_2$ at the bay;*

$X1 =$ *loaded trucks' travel path from the bay to the storage yard;*

$X2 =$*empty trucks' travel path between export and import lanes;*

$X3 =$ *loaded trucks' travel path from the exported container lanes to the bay;*

$X4 =$ *empty trucks' travel bath between the export and import lanes;*

$v1 =$ *the speed of loaded trucks, in ft/min.* $0 < v1 \leq 1367;$

$v2 =$ *the speed of empty trucks,* $0 < v2 \leq 2187;$

$ly =$ *summation of the late/waiting time at the yard zone; and*

$lb =$ *summation of the late/waiting times at the bay or berth side, in minutes.*

3.6 Simulation of Container terminal operation

Simulating the container terminal operation makes it possible to:

1- Test the developed strategy's workability, effectiveness and efficiency;

2- Monitor the resource flow and determine where any bottlenecks may occur;

3- Define the improvements when replacing YT single cycling with double cycling, in terms of productivity, time and cost savings by comparing the two strategies using the same conditions and parameters; and

4- Know how many other resources are needed to keep the QC busy, as it is the most important, most expensive machine in the handling container fleet. Simulation could determine how many YTs are needed to optimize the QC's productivity by employing the sensitivity analysis method.

The simulation steps for both the single-cycle and the developed double-cycle strategies are presented in the flow charts in Figure 3- 17. The EZStrobe simulation system is used for modeling the container terminal operation due to its simplicity and power. To apply the EZStrobe simulation system, some steps must be followed as shown in the simulation flow chart

mentioned above. The data collection stage will be clarified in depth in the next chapter, followed by a case study to test and verify the simulation models.

3.6.1 Single cycle simulation model

A single cycle simulation model is designed according to the steps indicated in the single cycle problem detailed in Figure 3- 18.

Since the unloading process precedes the loading, the truck cycle will start moving empty from the storage yard or truck pool toward the berth side. At the same time, the QC starts its cycle by its empty movement towards the target container to be unloaded from the vessel. Once a truck arrives at the berth, the QC loads the container onto the truck. Next, the truck moves loaded to the SY to be discharged by the YC, and then it travels back to the berth side (empty) to make another cycle. Meanwhile, the YC moves the container into the lane at the storage yard. The other trucks repeat this process until the last container is unloaded. Next, the loading process starts by loading containers on the trucks at the export storage yard, to be transported to the berth, where the QCs load the containers onto the vessel. Figure 3- 19shows the single cycle model and Figure 3- 20 shows the simulation parameters and resources.

3.6.2 Double cycle simulation model

The double cycle simulation model is designed as a form of integration between single and double cycling. This integration begins with unloading three or more rows before starting double cycling as a pre-condition, in order to minimize the fleet size and maximize crane use. The steps of this double cycling strategy are implemented as shown in Figure 3- 21. They start with the unloading of three rows in single cycle unloading mode. Next, the unloading QC_1 will change from unloading to loading the containers on the vessel. Another QC, QC_2,is introduced to to

continue unloading the containers from the fourth row to the end. QC$_1$ starts loading the containers from the first to the last row. The trucks, loaded by YC$_1$ at the export storage yard,
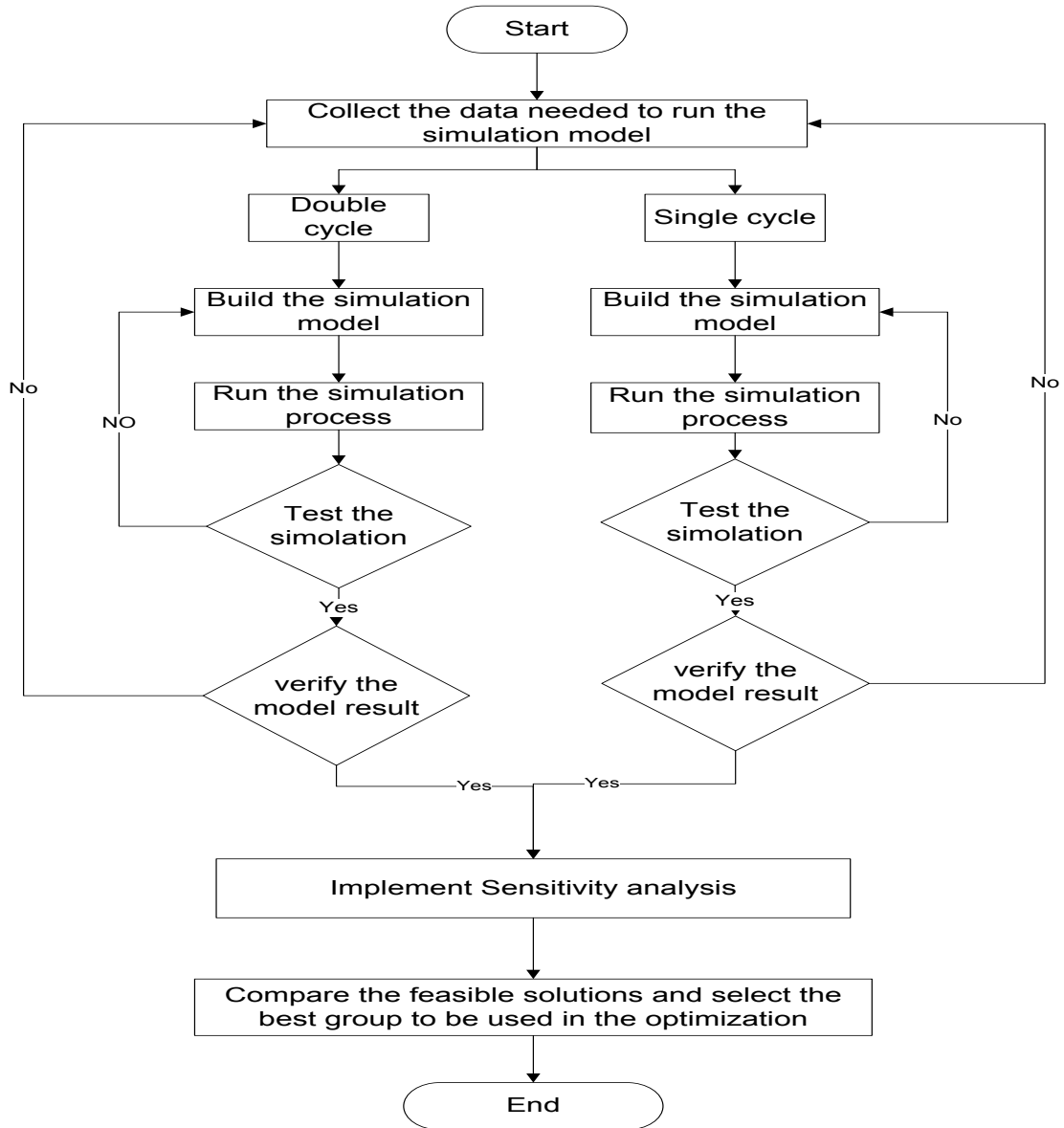
Figure 3- 17 Single and double cycling simulation procedures

```
                              ┌─────────┐
                              │  Start  │
                              └─────────┘
                                   │
                                   ▼
        ┌──────────────────────────────────────────┐
        │  Empty truck travel from storage yard to  │
        │              the berth side               │
        └──────────────────────────────────────────┘
                                   │
                                   ▼
                              ╱─────────╲         No        ┌──────────────────┐
                             ╱  Is QC    ╲───────────────→  │  Wait for the QC* │
                             ╲ available? ╱                 └──────────────────┘
                              ╲─────────╱
                                   │ Yes
                                   ▼
                    ┌──────────────────────────────┐
                    │  Load the container on the truck │
                    └──────────────────────────────┘
                                   │
                                   ▼
                    ┌──────────────────────────────┐
                    │  Loaded truck travel from the berth │
                    │     side to the storage yard   │
                    └──────────────────────────────┘
                                   │
                                   ▼
                              ╱─────────╲        NO         ┌──────────────────┐
                             ╱  Is the YC ╲───────────────→ │  Wait for the YC** │
                             ╲ available?  ╱                └──────────────────┘
                              ╲─────────╱
                                   │ Yes
                                   ▼
                    ┌──────────────────────────────┐
                    │  Discharge the container from  │
                    │           the truck            │
                    └──────────────────────────────┘
                                   │
                                   ▼
                              ╱─────────╲
                No ←─────────╱ Unloading  ╲
                             ╲ finished?   ╱
                              ╲─────────╱
                                   │ Yes
                                   ▼
                    ┌──────────────────────────────┐
                    │  Return to export storage yard to begin │
                    │        loading the vessel'      │
                    └──────────────────────────────┘
                                   │
                                   ▼
                              ┌─────────┐
                              │    A    │
                              └─────────┘
```
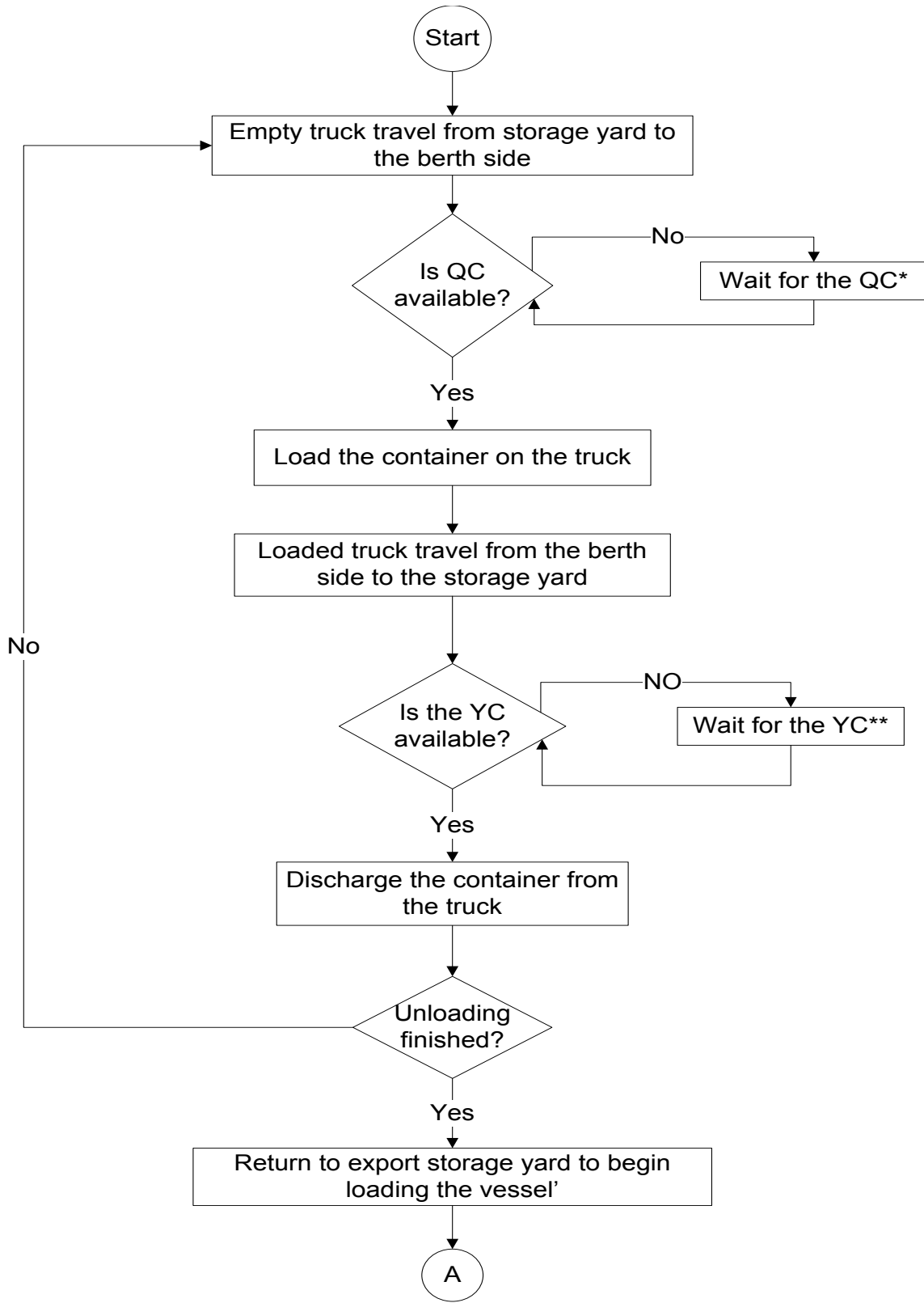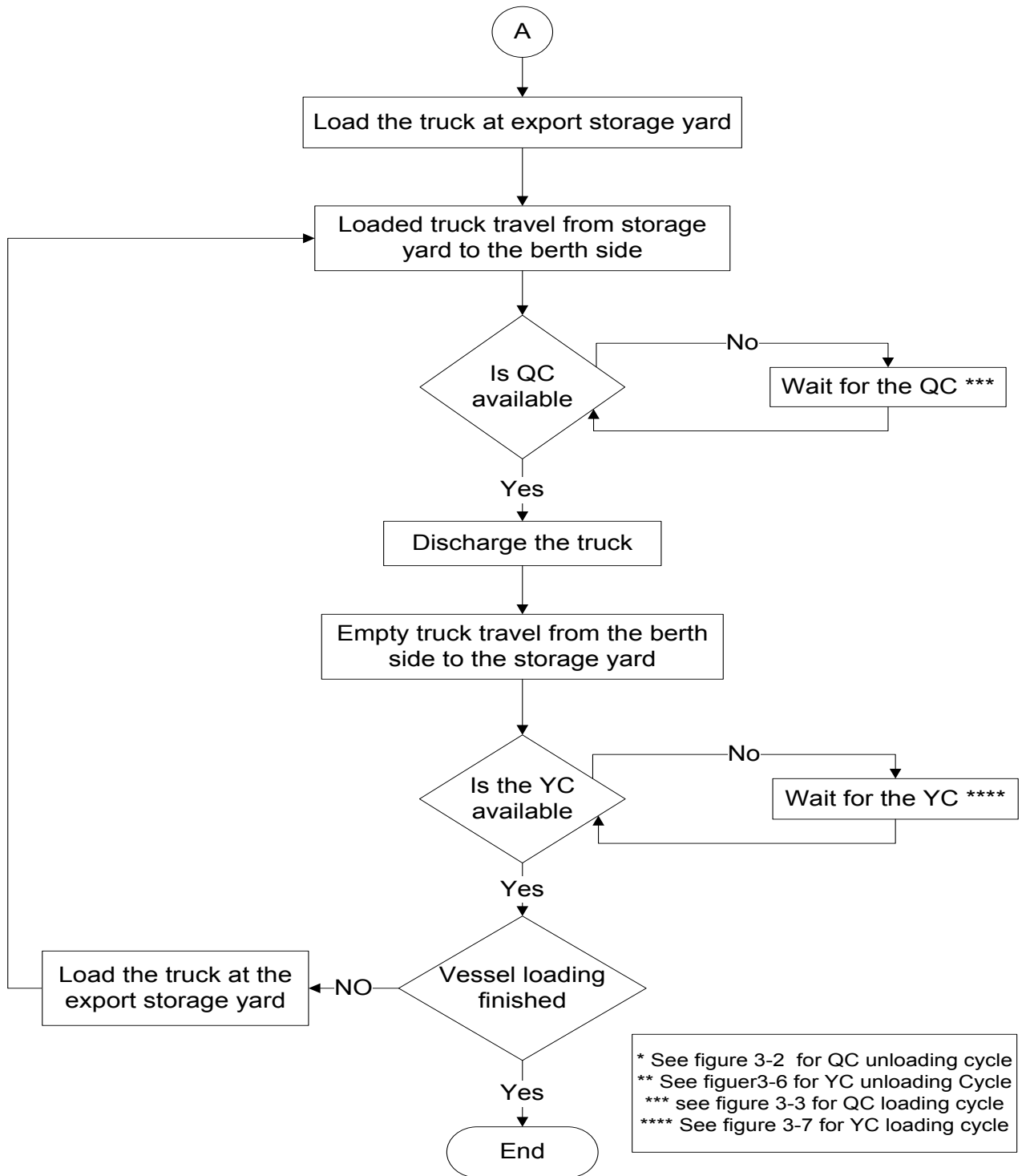
Figure 3- 18 Single cycle simulation steps application
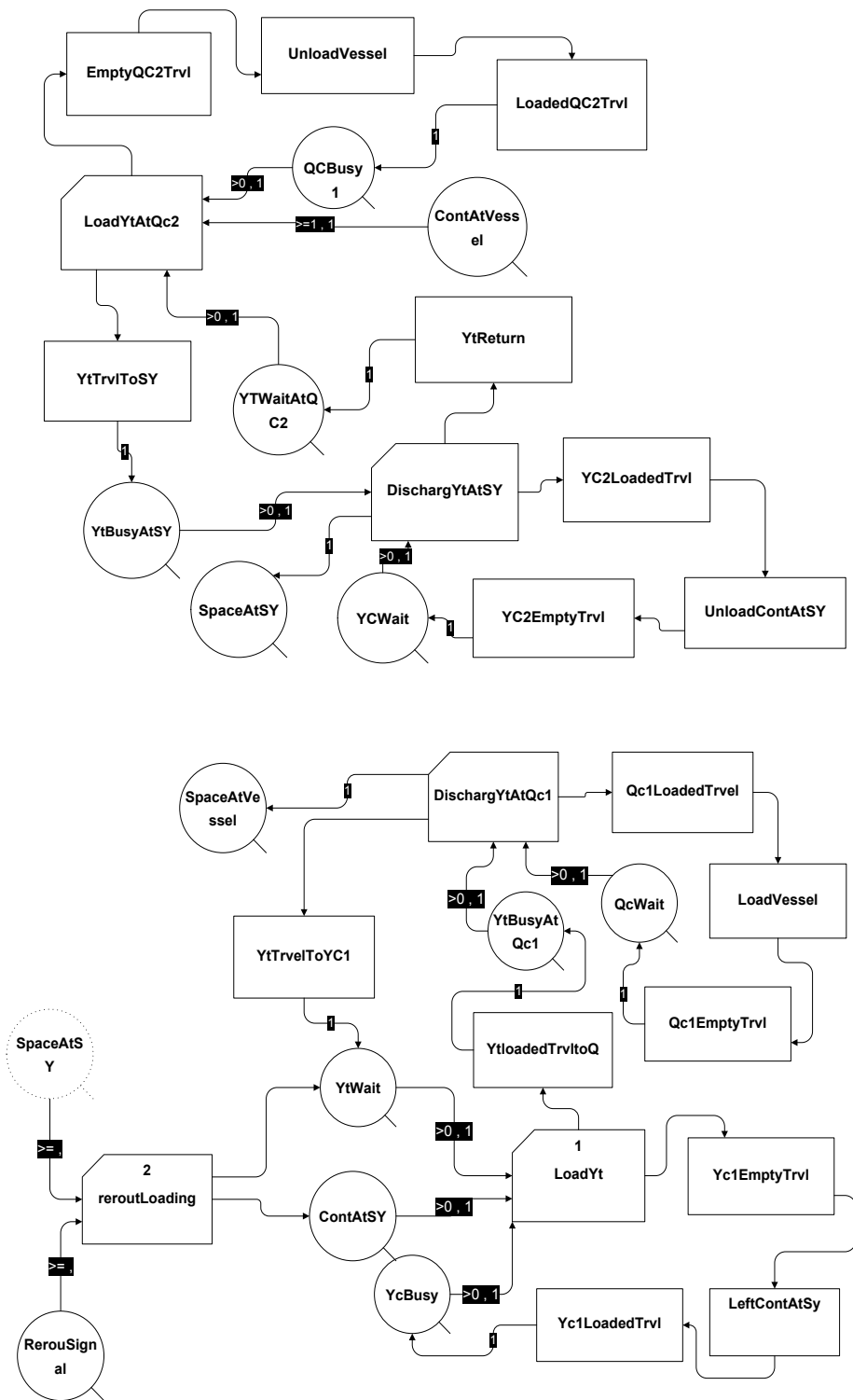
Figure 3- 19: Single cycle simulation model

nYTs	yard truck	n
nQC	QC loading cranes	n
nYC	YC Loading yard crane	n
QCCst	Loading Quay cranel cost ($/hr)	$
YCCst	Loading Yard crane cost ($/hr)	$
YTCst	Yard Truc cost ($/hr)	$
OHCst	Overhead cost ($/hr)	$

Hrs	Hrs needed to load and unload 1600 40` containers (3200 TEUs)	SimTime/60
ProdRate	Productivity rate (TEU)/hr)	(4*SpaceAtVessel.CurCount/Hrs)
HourlyCst	Hourly Cost	OHCst+nQC*QCCst+nYC*YCCst+nYTs*YTCst
UnitCst	Unit Cost ($/ETU)	HourlyCst/ProdRate

Figure 3- 20: Single cycle simulation parameters

arrive at the berth side to be discharged by QC_1. After being discharged, each truck will precede empty to QC_2, to be loaded with a container unloaded from the vessel. QC_1 simultaneously starts its cycle to load its container on the vessel. The loaded truck will move back to the (import) storage yard to be discharged by YC_2, which should be ready for this discharge.

```
                    ┌─────────┐
                    │  Start  │
                    └────┬────┘
                         │
         ┌───────────────▼────────────────┐
         │ Empty truck  travel from storage│
         │ yard to the berth side          │
         └───────────────┬─────────────────┘
                         │
                    ◇ Is QC ◇────No────┐
                    ◇available?◇        │
                         │         ┌────▼──────────┐
                        Yes        │ Wait for the QC*│
                         │         └────────────────┘
         ┌───────────────▼────────────────┐
         │ Load the container on the truck │
         │ by unloading the first 3 rows   │
         └───────────────┬─────────────────┘
                         │
         ┌───────────────▼────────────────┐
         │ Loaded Truck travel from the    │
         │ berth side to the storage yard  │
         └───────────────┬─────────────────┘
                         │
                    ◇ Is the YC ◇───NO────┐
                    ◇ available? ◇         │
                         │          ┌──────▼─────────┐
                        Yes         │ Wait for the YC**│
                         │          └─────────────────┘
         ┌───────────────▼────────────────┐
         │ Discharge the container         │
         │ from the truck                  │
         └───────────────┬─────────────────┘
                         │
                    ◇ Unloading the firs ◇───No───┐ (to Empty truck travel)
                    ◇ 3 rows finished?   ◇
                         │
                        Yes
                         │
         ┌───────────────▼────────────────┐
         │ Retrieve to double              │
         │ cycling                         │
         └───────────────┬─────────────────┘
                         │
                    ┌────▼────┐
                    │    A    │
                    └─────────┘
```

```
                          ( A )
                            │
                            ▼
          ┌──────────────────────────────────────┐
          │  Load the truck at export storage yard │
          └──────────────────────────────────────┘
                            │
                            ▼
          ┌──────────────────────────────────────┐
          │ Loaded truck travel from storage yard to│
          │              the berth side            │
          └──────────────────────────────────────┘
                            │
                            ▼
                     ╱ Is QC1  ╲      NO      ┌──────────────────┐
                    ⟨  available ⟩───────────▶│  Wait for  QC1*** │
                     ╲         ╱              └──────────────────┘
                         │
                        Yes
                         ▼
          ┌──────────────────────────┐
          │     Discharge the truck   │
          └──────────────────────────┘
                         │
                         ▼
          ┌──────────────────────────┐
          │  Truck empty travel from  │
          │        QC1 to QC2         │
          └──────────────────────────┘
                         │
                         ▼
                     ╱ Is QC2  ╲      NO      ┌──────────────────┐
                    ⟨ Available ⟩───────────▶│   Wait for QC2 *  │
                     ╲         ╱              └──────────────────┘
                         │
                        Yes
                         ▼
          ┌──────────────────────────┐
          │      Load the truck       │
          └──────────────────────────┘
                         │
                         ▼
          ┌──────────────────────────┐
          │  Loaded truck travel from │
          │        QC2 to YC2         │
          └──────────────────────────┘
                         │
                         ▼
                     ╱ Is YC2  ╲      NO      ┌──────────────────┐
                    ⟨ available ⟩───────────▶│   Wait for YC2**  │
                     ╲         ╱              └──────────────────┘
                         │
                        Yes
                         ▼
          ┌──────────────────────────┐
          │  Empty truck tavel from   │
          │        YC2 to YC1         │
          └──────────────────────────┘
                         │
                         ▼
                     ╱ Is YC1  ╲      NO      ┌──────────────────┐
                    ⟨ available ⟩───────────▶│  Wait for YC1**** │
                     ╲         ╱              └──────────────────┘
                         │
                        Yes
                         ▼
                       ( C )

       ( B )
```

Figure 3- 21: Double cycling simulation steps application

After being discharged by YC_2, the truck will proceed to the export SY to be loaded by YC_1 and start a new cycle. YC_2 starts its cycle as soon as it lifts a container from a truck. The YTs, QCs and YCs continue repeating their cycles until the last container has been fully unloaded. The fleet will then be reduced to one QC and one YC and fewer trucks to complete loading the vessel as a single cycle, as described earlier in the single-cycling simulation. Figure 3- 22 shows the designed model and Figure 3- 23 presents the parameters and resources.

3.7 Modeling and Optimization

3.7.1 Vessel turnaround time modeling overview

Vessel turnaround time is the total time for the unloading and loading operation. The turnaround time can also be determined as the summation of the QC cycle times required to load and unload the containers, which indicates that the QCs are the bottleneck of vessel turnaround time. So, keeping the QC busy is a logical target for improving container terminal productivity. Container terminals usually contain two servers to load/unload the trucks, one at the berth, the (QC) and the other at the yard, the (YC). Even though they are considered as two servers, it is still the QC that is considered to be the main server due to its complexity, expense and its direct relation to the vessel. Vessel turnaround time starts with the unloading of the first imported container and ends with the loading of the last exported container. This can be done by only one QC or multiple QCs, by means of the single cycling technique or by double cycling (or a combination thereof). Logically, the turnaround time is less when using double cycling than single cycling because some of the unloading and loading times overlap. Shorter vessel turnaround time attracts and satisfies costumers (shipping companies), even though it involves larger fleets (trucks, YCs, QCs).

EmptyQC2Trvl

UnloadVessel

LoadedQC2Trvl

QC2Busy

ContAtVessel

>0 , 1

>=1 , 1

LoadYtAtQc2

YtReturn

SpaceAtSY

>0 , 1

YtIdelAtQc2

YtTrvlToSY

DischargYtAtSY

YC2LoadedTrvl

1

YtBusyAtSY

>0 , 1

>0 , 1

YC2Wait

YC2EmptyTrvl

UnloadContAtSY

1

SpceAtVesselDbl
0

1

DschrgYtAtQc1Db

Qc1LoddTrvelDbl

LoadVesselDbl

YtTrvelToQC2

>0 , 1

Qc1Wait
Dbl

Qc1EmptyTrvlDbl

>0 , 1

1

YtIdelAtQc2Dbl

YtBusyAt
Qc1

1

YtloddTrvlDbl

YtWaitDbl
0

>0 , 1

Rute RuteToDblCycl

ContAtSYDbl

>=1 , 1

1

LoadYtDbl

Yc1EmptyTrvlDbl

SpaceAtSY

>=,

>0 , 1

>=,

SgnlRerutDble

Yc1BusyDbl

Yc1LodedTrvlDbl

LeftContAtSyDbl

1

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Figure 3- 22: Double cycling simulation model

UnloddContan	Containers to be Unloaded	n
LoddContaine r	Contaners to be Loaded	n
nYTs	yard truck	n
nQC1	QC1 loading cranes	n
nQC2	QC2 unloading crane	n
nYC1	YC1 Loading yard crane	n
nYC2	YC2 Unloading Yard crane	n
QC1Cst	Loading Quay cranel cost ($/hr)	$
QC2Cst	Unloading Quay crane cost ($/hr)	$
YC1Cst	Loading Yard crane cost ($/hr)	$
YC2Cst	Unloading Yard crane cost ($/hr)	$
YTCst	Yard Truck cost ($/hr)	$
OHCst	Overhead cost ($/hr)	$

Hrs	Hrs needed to load and unload 16000 40` containers (32000 TEUs)	SimTime/60
ProdRate	Productivity rate (TEU)/hr)	(((24*SpceAtVesselLst.CurCount)+(3200))/Hrs)
HourlyCst	Hourly Cost	OHCst+nQC1*QC1Cst+nQC2*QC2Cst+nYC1*YC1Cst+nYC2*YC2Cst+nYTs*YTCst
UnitCst	Unit Cost ($/ETU)	HourlyCst/ProdRate

Figure 3- 23 Double cycle simulation parameters

3.7.1 Modeling Vessel turnaround time using the single-cycling technique

Vessel turnaround time starts with the unloading of the first imported container when using the single cycling technique. Unloading continues until the imported containers have been fully discharged. Only then will the QC(s) change to loading the vessel. The vessel departs after the last exported container has been loaded. The total unloading and loading time is then counted as the vessel turnaround time. Figure 3- 24 describes the procedure.

(a) discharge the vessel first (turnaround time starts)   (b) start loading after discharging

Lc J=m

Lci= n

(c) Vessel depart after loading the last container (turnaround time is complete)
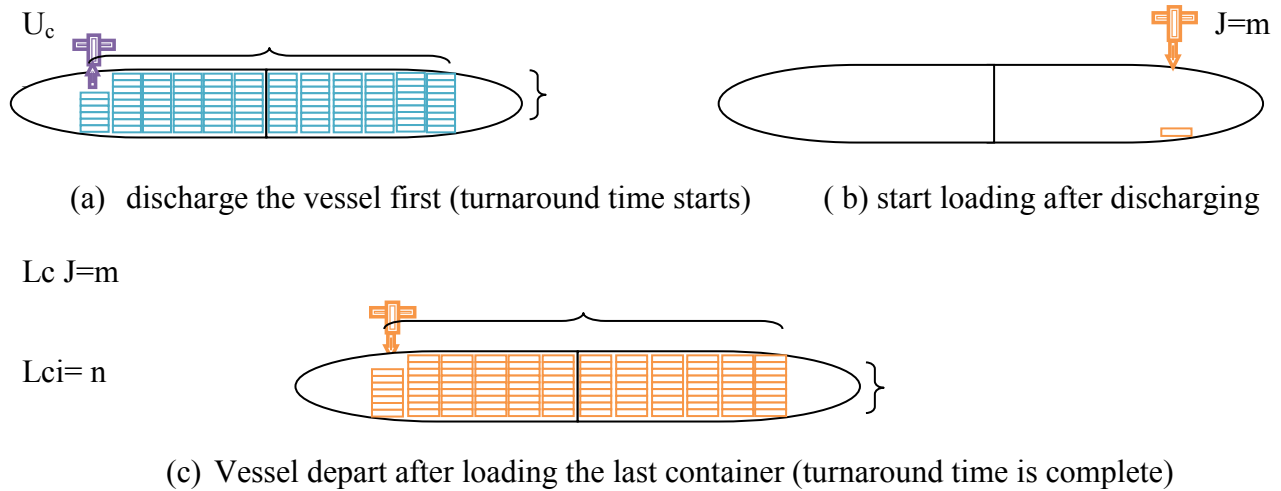
Figure 3- 24: Single cycle container handling procedure

Single-cycle modeling optimizes T_s as the objective function to be minimized, where:

T_s= Vessel turnaround time when using single cycling technique;

 = time to unload imported containers + time to load exported containers;

$\omega 1$= average QC unloading cycle time= average time to unload (2TEUs) containers;

$\omega 2$= average QC loading cycle time= average time to load (2TEUs) containers;

Assume$\omega 1 = \omega 2 = \omega = $ average QC cycle time;

Uc = containers to be unloaded; and

Lc = containers to be loaded.

The objective function to minimize the vessel turnaround time using single cycling (T_s) is:

$T_s = w * [\sum_{i=0}^{n} \sum_{j=1}^{m} Uc\,(i,j) + \sum_{\beta=0}^{s} \sum_{\gamma=1}^{g} lc\,(\beta,\gamma)].$ (Equation 3.29)

This function is subject to the following constraints:

Total number of unloading containers per row=$\sum_{i=1}^{n} Uc\,i$;   (Equation 3.30)

i= number of containers to be unloaded per row, where $1 \le i \le n$;

Total number of rows to be unloaded on the vessel=$\sum_{j=1}^{m} j$;   (Equation 3.31)

j= number of rows on the vessel, where $1 \le j \le m$;

Total numbers of containers to be unloaded =$\sum_{i=0}^{n} \sum_{j=1}^{m} Uc\,(i,j)$;   (Equation 3.32)

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Total number of loaded containers $=\sum_{\beta=1}^{s}\beta$*;* (Equation 3.33)

β = number of containers to be loaded per row, $1 \leq \beta \leq s$*;*

Total number of rows to be loaded on the vessel $=\sum_{\gamma=1}^{g}\gamma$*;* (Equation 3.34)

γ = number of rows to be loaded, $1 \leq \gamma \leq g$*; and*

Total number of containers to be loaded $=\sum_{\beta=0}^{s}\sum_{\gamma=1}^{g}lc\,(\beta,\gamma)$*.* (Equation 3.35)

Equation (3.29) is the objective function and the number of rows *j* varies according to the number of holds that a vessel is divided into. For each hold there is only one QC to unload and load the containers in that hold. The number of holds depends on the three conditions mentioned in section (2.5.2).

Equation (3.32) verifies that unloading has been completed before loading begins.

Equation (3.35) insures that a vessel will not depart until the last container has been loaded.

The operation can be described as in the bar chart in Figure 3- 25, where the unloading activity precedes the loading activity. The total time T_s is the summation of the unloading and loading times.
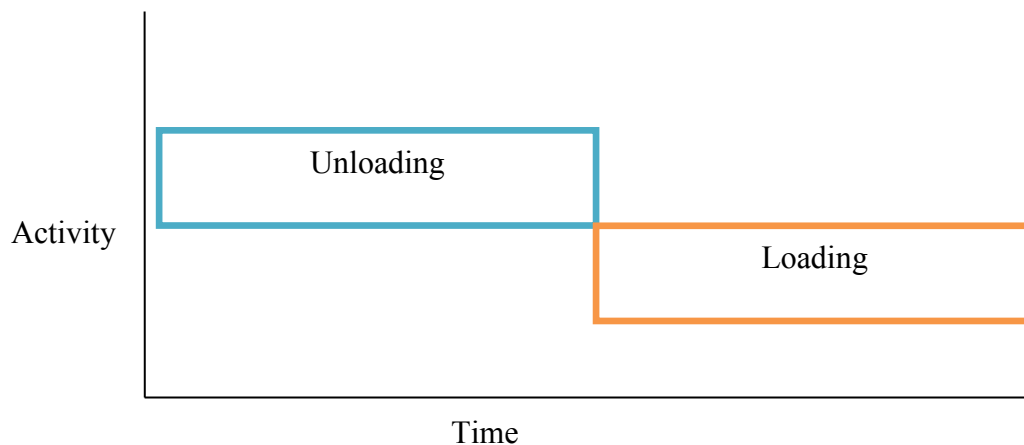
Figure 3- 25: Single cycle container handling timeline

3.7.2 Modeling vessel turnaround time using the double cycling technique

As with single cycling, vessel turnaround time starts with the unloading of the first imported container and ends with the loading of the last exported container. However, in double cycling, loading exported containers can be started at a certain time, in parallel with the container unloading. This time has specific constraints and conditions which have been discussed earlier in this chapter and will be presented in more detail later. When it is time to convert to double cycling, two QCs will work together as a unit to service YTs with different activities (loading and unloading). The overlapping of some of the QCs' cycle time reduces the vessel turnaround time to less than it is in single cycling. This time savings is the main justification for applying the double-cycling technique. A vessel still needs to be loaded with the last exported container before departure. Turnaround time is counted as the sum of the series of single cycle unloading, double cycling and single cycling loading of the imported and exported containers.
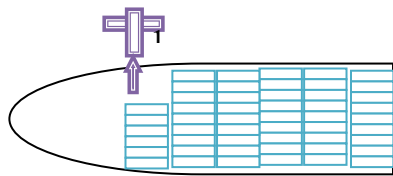
(a) Unloading the first row (turnaround time starts)   (b) Unloading the third row
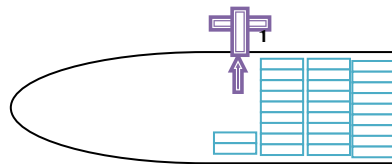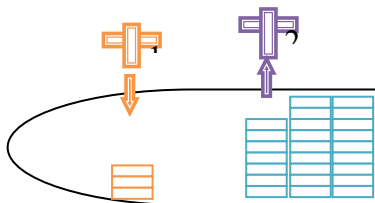
(c) Loading the first row and unloading the fourth row(d) Loading last rows (turnaround time is done)
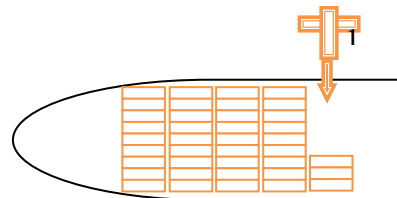
Figure 3- 26: Loading and unloading a vessel using double cycling

. Figure 3- 26 describes the procedure and Figure 3- 27 shows the timeline of the double cycling procedure. The double cycle time modeling optimizes T_D as the objective function to be minimized, where:

T_D = Vessel turnaround time when using the double cycling technique

= time to unload the first 3 rows of imported containers + maximum time to unload the remaining containers and to load the exported containers except for the last 3 rows + time to load the last 3 rows. The number of rows assigned to each pair of QCs depends on the number of holds that a vessel is divided into. Each hold can be occupied by two QCs. Not more than 3 holds of a vessel can be divided, so there will be a maximum of six QCs assigned, in three pairs. The maximum unloading time combined with the maximum loading time is the vessel turnaround time.

$$T_D = w * \{\sum_{i=0}^{n} \sum_{j=1}^{3} Uc\ (i,j) + \max[\sum_{i=0}^{n} \sum_{j=4}^{m} Uc\ (i,j), \sum_{\beta=0}^{s} \sum_{\gamma=1}^{(g-3)} lc\ (\beta,\gamma)] + \sum_{\beta=0}^{s} \sum_{\gamma=(g-2)}^{g} lc\ (\beta,\gamma)\} \qquad \text{(Equation 3.36)}$$

$\omega 1$= average QC unloading cycle time= average time to unload (2TEUs) containers;

$\omega 2$= average QC loading cycle time= average time to load (2TEUs) containers;

Assume $\omega 1 = \omega 2 = w$= average QC cycle time;

Uc = containers to be unloaded; and

Lc = containers to be loaded.

This objective function is subject to the following constraints:

Total number of unloading containers per row=$\sum_{i=1}^{n} Uc\ i$;   (Equation 3.37)

i = Number of containers to be unloaded per row, $1 \leq i \leq n$;

Total number of rows to be unloaded on the vessel =$\sum_{j=1}^{m} j$;   (Equation 3.38)

j = Number of rows on the vessel, $1 \leq j \leq m$;

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Total number of the first rows to be unloaded using single cycle$=\sum_{j=1}^{3} j$; (Equation 3.39)

Number of containers of the first three rows to be unloaded using single cycling

$\sum_{i=0}^{n} \sum_{j=1}^{3} Uc\ (i,j)$; (Equation 3.40)

Number of containers to be unloaded using double cycling =

$\sum_{i=0}^{n} \sum_{j=4}^{m} Uc\ (i,j)$; (Equation 3.41)

Total number of loaded containers $=\sum_{\beta=1}^{s} \beta$; (Equation 3.42)

β Number of containers to be loaded per row, $1 \leq \beta \leq s$;

Total number of rows to be loaded on the vessel$=\sum_{\gamma=1}^{g} \gamma$; (Equation 3.43)

γ = Number of rows to be loaded, $1 \leq \gamma \leq g$;

Number of rows to be loaded using double cycling $=\sum_{\gamma=1}^{(g-3)} \gamma$. (Equation 3.44)

Number of containers to be loaded using double cycling =

$\sum_{\beta=0}^{s} \sum_{\gamma=1}^{(g-3)} lc\ (\beta,\gamma)$; (Equation 3.45)

Number of the last three rows to be loaded using single cycle$=\sum_{\gamma=(g-2)}^{g} \gamma$; and (Equation 3.46)

Number of containers to be loaded using single cycling =

$\sum_{\beta=0}^{s} \sum_{\gamma=(g-2)}^{g} lc\ (\beta,\gamma)$. (Equation 3.47)
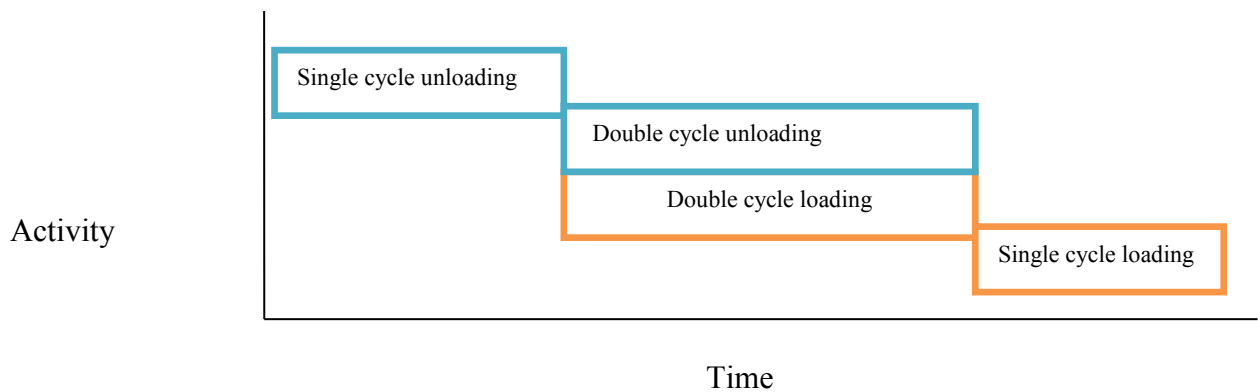
Figure 3- 27 Double cycling timeline

3.7.3 Modeling of possible double cycling scenarios

Three scenarios are possible in real life container handling using double cycling: the number of containers to be unloaded and loaded is equal, there are more containers to unload than to load, and there are less containers to unload than to load.

3.7.3.1 First scenario

Unloading containers U_c = loading containers L_c

In this case the objective function is:

$$T_D = w * \{\sum_{i=0}^{n} \sum_{j=1}^{3} Uc\ (i,j) + [\sum_{i=0}^{n} \sum_{j=4}^{m} Uc\ (i,j), \sum_{\beta=0}^{s} \sum_{\gamma=1}^{(g-3)} lc\ (\beta,\gamma)] +$$
$$\sum_{\beta=0}^{s} \sum_{\gamma=(g-2)}^{g} lc\ (\beta,\gamma)\}. \hspace{2cm} \text{(Equation 3.48)}$$

3.7.3.2 Second scenario

The number of unloading containers (Uc) > the number of loading containers (lc).

The unloading process precedes the loading process. To satisfy this condition, the number of rows that must be unloaded in single-cycling mode to insure the earliest possible start of non-conflict double cycling must be determined.

In addition to these three rows, another, or part of another row must be calculated, according to the difference between the containers to be unloaded and loaded. This scenario is represented in Figure 3- 28.

These rows are described as $\forall j = \left(\frac{Uc-lc}{n}\right)$ \hspace{2cm} (Equation 3.49)

Where: $\forall j$ represents the different rows between the unloading and the loading containers;

Uc = the total number of containers to be unloaded;

lc= the total number of containers to be loaded; and

n= the number of containers per row.

The objective function is then:

$$T_D = w * \{\sum_{i=0}^{n} \sum_{j=1}^{3+\forall j} Uc\,(i,j) + [\sum_{i=0}^{n} \sum_{j=(4+\forall j)}^{m} Uc\,(i,j)] +$$

$$\sum_{\beta=0}^{s} \sum_{\gamma=(g-2)}^{g} lc\,(\beta,\gamma)\}. \hspace{3cm} \text{(Equation 3.50)}$$
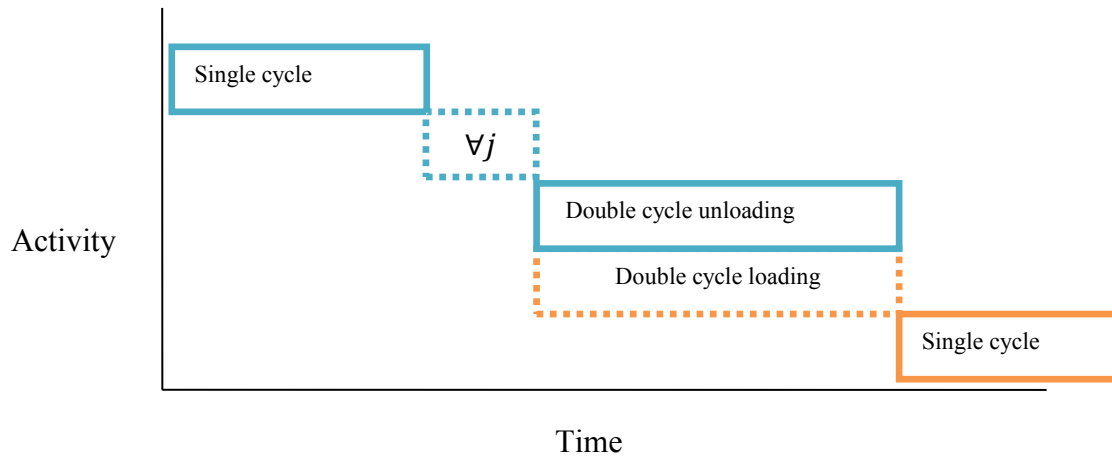
Figure 3- 28 Double cycling timeline where the number of unloaded containers > the number of loaded containers

3.7.3.3 Third scenario

The number of containers to be unloaded (Uc) < the number of containers to be loaded (lc)

In this case, the additional numbers of loading containers are to be added at the end of the procedure to insure the early start of double cycling. This schedule will preclude conflicts (crane use, traffic). Two different cases are implemented to clarify the timeline, presented in Figure 3-29 and Figure 3- 30).

The extra loading containers can be defined as: $\forall j = \left(\dfrac{lc-Uc}{n}\right)$ $\hspace{2cm}$ (Equation 3.55)

The objective function is then:

$$T_D = w * \{\sum_{i=0}^{n} \sum_{j=1}^{3} Uc\,(i,j) + [\sum_{\beta=0}^{s} \sum_{\gamma=1}^{(g-(3+\forall j))} lc\,(\beta,\gamma)] +$$

$$\sum_{\beta=0}^{s} \sum_{\gamma=(g-(3+\forall j))}^{g} lc\ (\beta, \gamma)\}. \hspace{3cm} \text{(Equation 3.56)}$$
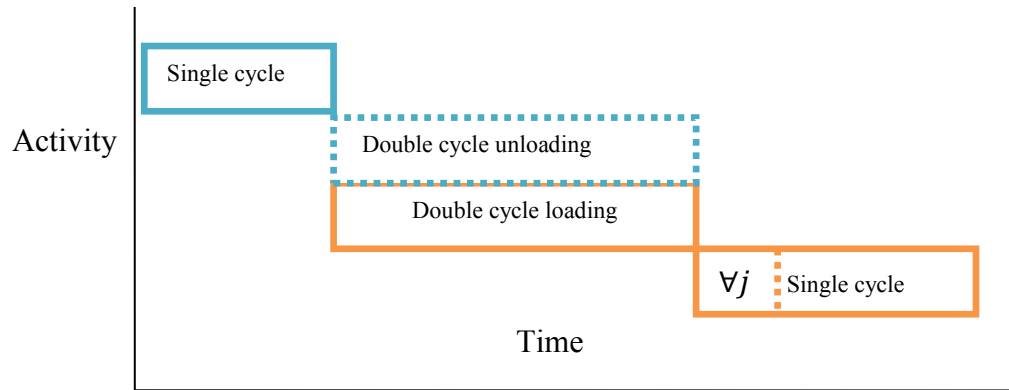
Figure 3- 29 Double cycling timeline where the number of loaded containers > unloaded containers, case 1

Or:

$$T_D = w * \{\sum_{i=0}^{n} \sum_{j=1}^{3} Uc\ (i,j) + [\sum_{i=0}^{n} \sum_{j=4}^{m} Uc\ (i,j)] +$$

$$\sum_{\beta=0}^{s} \sum_{\gamma=(\forall j)}^{g-2} lc\ (\beta, \gamma) + \sum_{\beta=0}^{s} \sum_{\gamma=(g-2)}^{g} lc\ (\beta, \gamma)\}. \hspace{2cm} \text{(Equation 3.57)}$$
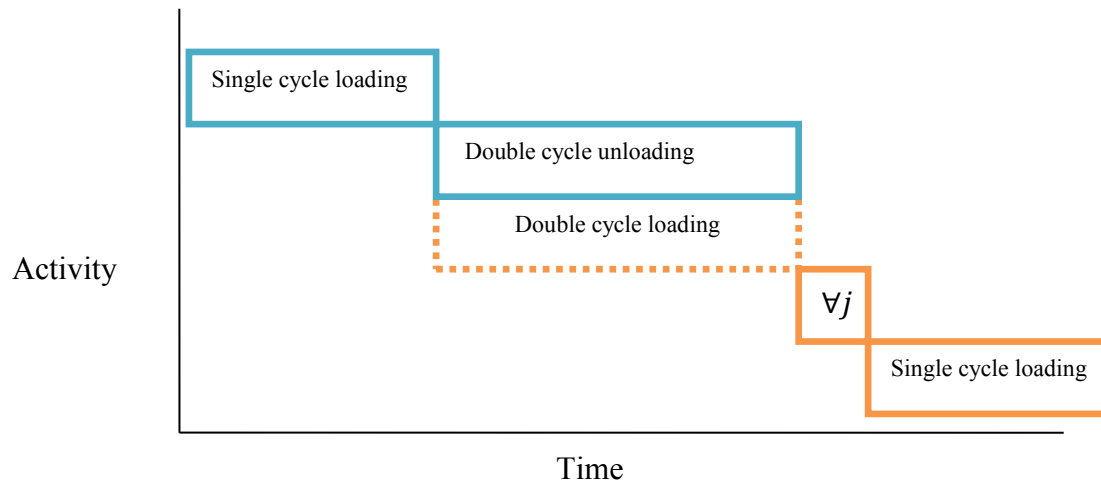
Figure 3- 30: Double cycling timeline where the number of unloaded containers < the number of loaded containers, case 2

3.7.4 Optimization

Optimization is the most important part of this research. Optimizing the fleet size that delivers the handling container tasks with efficient productivity and reasonable cost is what makes it possible to achieve the main objective of the research.   The aim of this optimization is to satisfy the following:

1- Insure the improvement in container terminal productivity when replacing YT single cycling by double cycling.

2- Define the fleet productivity in each activity of the developed strategy (single cycle unloading, double cycle, and single cycle loading) to be able to optimize the fleet size.

3- Define the vessel turnaround time, which is very important for scheduling in both planning and control management.

4- Predict the costs of the operation to help cost managers in building task costs and mark-up.

5- Select the best fleet size, according to the resources' availability, that delivers the job with optimum productivity and reasonable costs.

To optimize container terminal fleet size the two objective functions to minimize vessel turnaround time and hourly cost must be satisfied; maximizing container terminal productivity and minimizing the unit cost. Since there are two objective functions, a multi-objective optimization approach is the best way to proceed. Equation (3.22) and equation (3.58) are the two objective functions to be optimized when using the single cycle strategy. In equation (3.22) the turnaround time T_s is controlled by the maximum time the QC takes to finish the job. The containers and the QC cycle times are defined according to how many holds a vessel is divided

into. It is assumed that a vessel can be divided from one hold into six holds, which means that the vessel can be serviced by up to six QCs. Each QC has its required YTs and their YCs to keep it busy. Using the simulation solution groups and the results of the first objective function, it is possible to define the population, the genes and chromosomes of the second objective function. In double cycling, the time objective function will be one of the following equations (3.46, 3.48, 3.50, 3.56, or 3.57), according to which of the three scenarios stated earlier in this chapter reflects the vessel loading conditions. The second objective function is equation (3.61).

As in single cycling, the vessel is divided into holds. Since each hold can be serviced by a pair of QCs, the vessel can be divided into not more than three holds for six QCs. The hold with the highest number of containers is the hold that controls the vessel turnaround time. Using these results, the second objective function can be optimized. The optimum solution is the one that best satisfies both objectives. Since the developed strategy of double cycling requires the partial use of single cycling unloading before changing to double cycling, and it normally ends by single cycling loading, the three activities are have to be done in sequence: (a) single cycling unloading, (b) double cycling, and (c) single cycling loading. The turnaround time is the summation of those three activities' times, as shown in to Figure 3- 27. To satisfy the two main objectives' optimization and thus the vessel turnaround time and total cost, several sub-objectives have to be optimized in each activity: single cycle unloading productivity, single cycle unloading unit cost, double cycling productivity, double cycle unit cost, single cycle loading productivity and single cycle loading unit cost.

The objective functions are to:

Maximize A1, A2, A3 and Pt, and

Minimize B1, B2, B3, Tt, Ct and Uc,

where:

A1 is the productivity of the chain in the first activity (YT single cycle unloading);

A1= the minimum resource productivity of the chain in this activity; and

$A1 = \min(a_1 x_1, b_1 y_1, c_1 z_1)$;   (Equation 3.58)

where:.

a_1 is the QC Productivity and x_1 is the number of QCs;

b_1 is the YT productivity and y_1 is the number of YTs,

c_1 is the YC productivity and Z_1 is the number of YCs;

A2 is the productivity of the chain in in the second activity (YT Double cycling);

A2 = the minimum resource productivity of the chain in this activity; and

$A2 = \min(a_2 x_2, b_2 y_2, c_2 z_2)$.   (Equation 3.59)

where:

a_2 is the pair of QCs' double cycling productivity and x_2 is the number of pairs of QCs;

b_2 is the YT double cycling productivity and y_2 is the number of YTs;

c_2 is the pair of YCs' double cycling productivity and Z_2 is the number of pairs of YCs;

A3 is the productivity of the chain in the third activity (when single cycle loading);

A3= the minimum resource productivity of the chain in this activity; and

$A3 = \min(a_3 x_3, b_3 y_3, c_3 z_3)$;   (Equation 3.60)

where:

a_3 is the QC loading productivity and x_3 is the number of QCs;

b_3 is the YT single cycle loading productivity and y_3 is the number of YTs;

c_3 is the YC loading productivity and Z_3 is the number of YCs.

Pt is the average productivity of the chain fleet during the task

Pt = number of units to be moved/ the total time of the operation

$Pt = [\sum_{i=1} \sum_{j=1} u(i,j) + \sum_{g=1} \sum_{\gamma} l(g,\gamma)]/ T$.   (Equation 3.61)

B1 is the unit cost in the first activity;

B1= ($\sum$ of resources hourly costs and overhead hourly cost/ single cycle unloading productivity);

B1= [$\sum$ (QCs, YTs and YCs hourly costs) + (overhead hourly cost)]/A1.　　　　(Equation 3.62)

B2 is the unit cost in the second activity.

B2= ($\sum$ of resources hourly costs and overhead hourly cost/ double cycling productivity);

B2= [$\sum$ (QCs, YTs and YCs hourly costs) + (overhead hourly cost)]/A2.　　　　(Equation 3.63)

B3 is the unit cost in the last activity.

B3= ($\sum$ of resources' hourly costs and overhead hourly cost/ single cycle unloading productivity);

B3= [$\sum$ (QCs, YTs and YCs hourly costs) + (overhead hourly cost)]/A3.　　　　(Equation 3.64)

Tt is the vessel turnaround time;

Tt= the total time needed to unload and load the vessel; and

Tt= $\sum$ of the time required to deliver each the three activities.

Adapting equation (3.48)

$$Tt= \{([\textstyle\sum_{i=0}^{n}\sum_{j=1}^{3} Uc\,(i,j)]/A_1) + ([\sum_{i=0}^{n}\sum_{j=4}^{m} Uc\,(i,j) + \sum_{\beta=0}^{s}\sum_{\gamma=1}^{(g-3)} lc\,(\beta,\gamma)]/A_2) +$$

$$([\textstyle\sum_{\beta=0}^{s}\sum_{\gamma=(g-2)}^{g} lc\,(\beta,\gamma)]/A_3\,)\}. \qquad\qquad \text{(Equation 3.65)}$$

Ct is the total cost to finish the task

Ct = $\sum$ each the three activities cost.

Adapting the above equation:

$$Ct= \{B_1[\textstyle\sum_{i=0}^{n}\sum_{j=1}^{3} Uc\,(i,j)] + B_2[\sum_{i=0}^{n}\sum_{j=4}^{m} Uc\,(i,j) + \sum_{\beta=0}^{s}\sum_{\gamma=1}^{(g-3)} lc\,(\beta,\gamma)] +$$

$$B_2[\textstyle\sum_{\beta=0}^{s}\sum_{\gamma=(g-2)}^{g} lc\,(\beta,\gamma)]\}, \qquad\qquad \text{(Equation 3.66)}$$

where:

Uc is the average unit cost using the strategy all over the operation;

Uc = total cost / the number of units to be unloaded and loaded; so that

$Uc = \{C_t/([\sum_{i=0}^{n}\sum_{j=1}^{3} Uc\,(i,j)] + [\sum_{i=0}^{n}\sum_{j=4}^{m} Uc\,(i,j) + \sum_{\beta=0}^{s}\sum_{\gamma=1}^{(g-3)} lc\,(\beta,\gamma)] +$

$[\sum_{\beta=0}^{s}\sum_{\gamma=(g-2)}^{g} lc\,(\beta,\gamma)]\}.$ (Equation 3.67)

The objective functions are subjected to:

A1, A2, A3, Pt, B1, B2, B3, Tt, Ct and Uc> 0

$1 \leq X1, X2, X3 \leq 3$; $1 \leq Y1, Y3 \leq 25$, $1 \leq Y2 \leq 30$ and $1 \leq Z1, Z2, Z3 \leq 5$, when 6 QCs are available;

$1 \leq X1, X2, X3 \leq 2$; $1 \leq Y1, Y2 \leq 20$, $1 \leq Y3 \leq 2\ 5$ and $1 \leq Z1, Z2, Z3 \leq 4$, when only 4 QCs are available;

$X1, X2, X3 = 1$; $1 \leq Y1, Y3 \leq 15$, $1 < Y2 \leq 20$ and $1 \leq Z1, Z2, Z3 \leq 3$, when only 2 QCs are available;

$(X1, X2, X3) \in QCs$; $(Y1, Y2, Y3) \in YTs$ and $(Z1, Z2, Z3) \in YCs$,

X, Y and Z are integers.

The expected results are a set of the near-optimum feasible solutions. As stated earlier, in multi-objective optimization, selecting only one solution involves a conflict in most cases. In such cases, the support of other methods or approaches is crucial. In this research, three approaches and a simulation tool are implemented.

- Pareto frontier: utilized to identify if there is a possibility of visualizing a unique solution that dominates all other alternatives. If not, the other two approaches and the simulation are required.

- TOPSIS: implemented in two scenarios:

The first only considers two main criteria: Total average productivity (Pt), where the highest is best, and Average unit cost (Uc), in which the lowest is the best. The second scenario considers 7 criteria; (P1, P2, P3 and Pt); in which all are judged such that the higher values are better, and (B1, B2, B3, Tt and Uc), evaluated such that lower values are better.

The first scenario is considered more often, as it uses criteria that are usually the preferred comparative criteria in similar problems, while the second scenario is employed because sometimes it provides information that is important for the operation managers to know:

a- The time saved by utilizing the first activity could be invested in the other resources in different areas or activities;

b- The timing of when to start and finish the second activity is difficult, as it is the more challenging activity, where the productivity of the fleet reaches its maximum and the cost is higher. Also, the time for when the activity is completed is important in order to plan to use the un-needed resource in other activities.

- Cost and decision index: a very useful approach which is a concept is close to that of the TOPSIS, except that it compares the cost relatively to the productivity.

- Simulation: here the EZStrobe simulation is used first to verify that the strategy is implementable, beneficial and worthwhile, and second to compare the best-ranked alternatives according to their fleet size. The best fleet size will produce more units in less time and at reasonable cost.

Even though the approaches have shown their powerful ability to select the best solution, sometimes there is a contrast in the results from one approach to another. In this case, one more step is needed to be implemented, evaluating the chosen alternatives from each approach in one table. Those that obtain the best ranks overall are selected as the winning alternative.

Chapter 4: Data collection and case study

4.1 Overview

This chapter introduces the data collection process, illustrated with a case study. The case study has a specific method of data collection related to the lifting or loading of containers. The data will be used in the simulation and optimization models. The collected data is focusing on QCs YC and YT cycle times. The cycle times of these resources includes single cycle loading, single cycle unloading and double cycling strategies. In order to know more about the productivity of these resources, their cycle times are translated to a productivity data measurement based on the postulate of a single movement produced on a forty-foot or two twenty-foot containers, for 2 TEUs/ move in total.It is understood that a reasonable amount of random data for all three types of equipment must be collected and then statistically analyzed to obtain the mean time (μ) and standard deviation (δ) of each type of equipment's cycle time. The result data was collected and analysed using an EasyFit distribution to draw the histogram and to calculate the mean and the standard deviation.

A simulation of container terminal productivity operation has been carried out in the framework of this research. The simulation requires each activity to be run over its complete duration. A means to bring the system closer to the real data by mimicking reality was developed. Two optimization tools were used in the case study. A sensitivity analysis method was employed on the YTs variable only, in order to compare the traditional strategy of handling containers (YT single cycling) to the developed strategy (the combination of YT single and double cycling). Next, a multi-objective optimization was used by employing GA as an optimization tool using two different software approaches.

4.2 Case study description

This section is devoted to collecting the case study data from a transhipment container terminal to verify and calibration the strategy via both the optimization and the simulation models. The terminal is located in the Strait of Gibraltar at Tangier, Morocco, and is operated by APM Terminals S.A., a world-wide container terminal company based in the Netherlands. APM Terminals operates about 181 container terminals in 61 countries. The location of this terminal is characterized as a gateway linking Europe, Africa and the Americas. It links the Mediterranean to the Pacific, which qualifies the port terminal as appropriate for transhipment operations (see Figure 4- 1for its location). This terminal is operated under a 30-year Build Operate Transfer (BOT) contract between the Government of Morocco and the APM Terminals Company that began in July 2007. The capacity of the terminal is about1.8 million TEU/annum and it is mainly operated for transhipment. To date, APM Terminals has made capital investments on the order of €140 million in this terminal. The traffic flow and the layout of APM Terminals Tangier, S.A. are presented in Figure 4- 2 and Figure 4- 3, respectively.
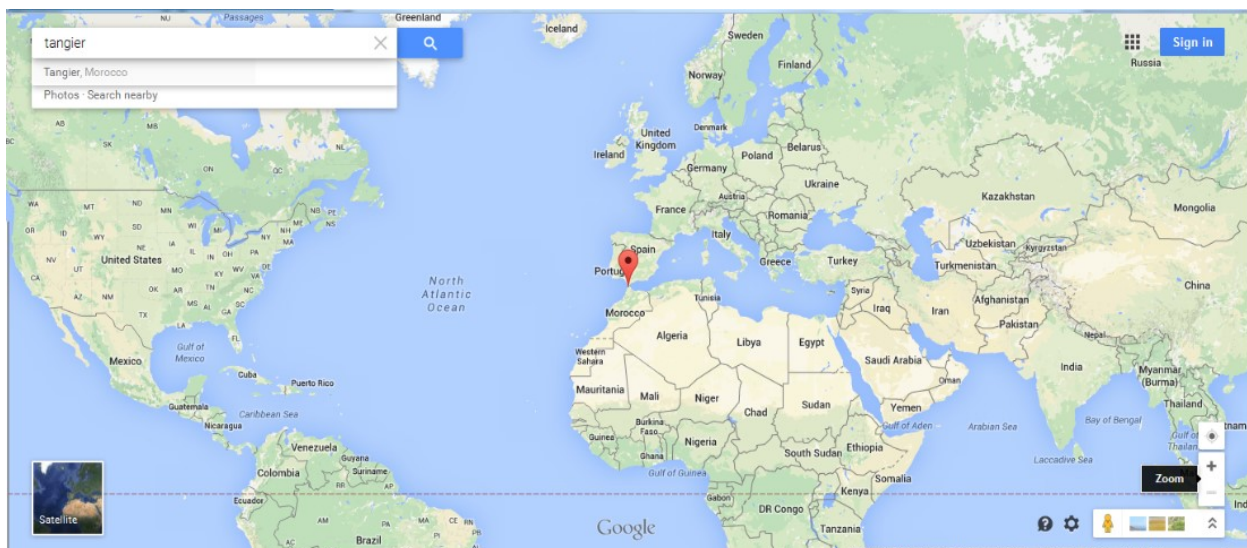
Figure 4- 1: Case study location on the Strait of Gibraltar
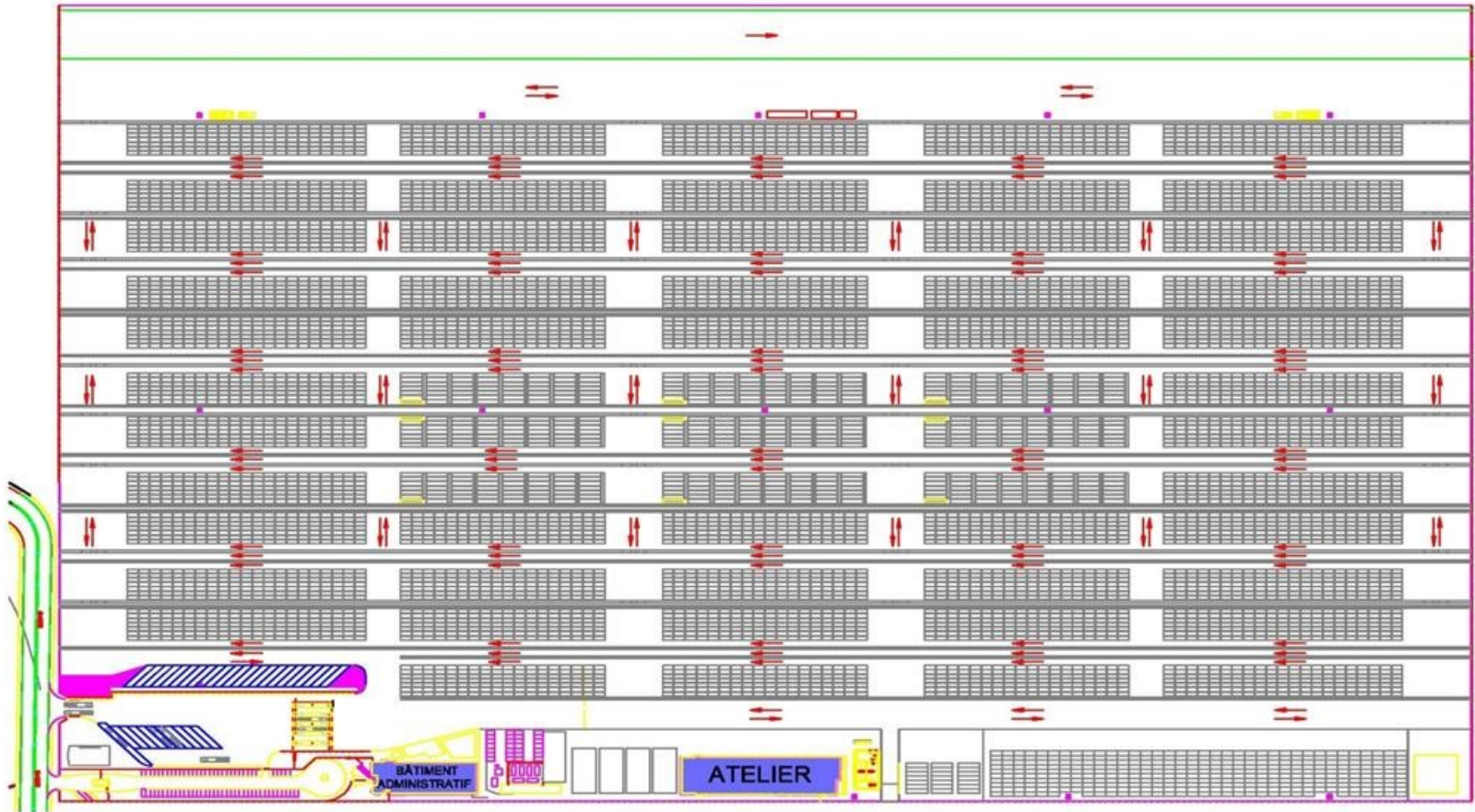
Figure 4- 2: APM Terminals Tangier traffic flow (APM Terminals Tangier indoor data 2014)
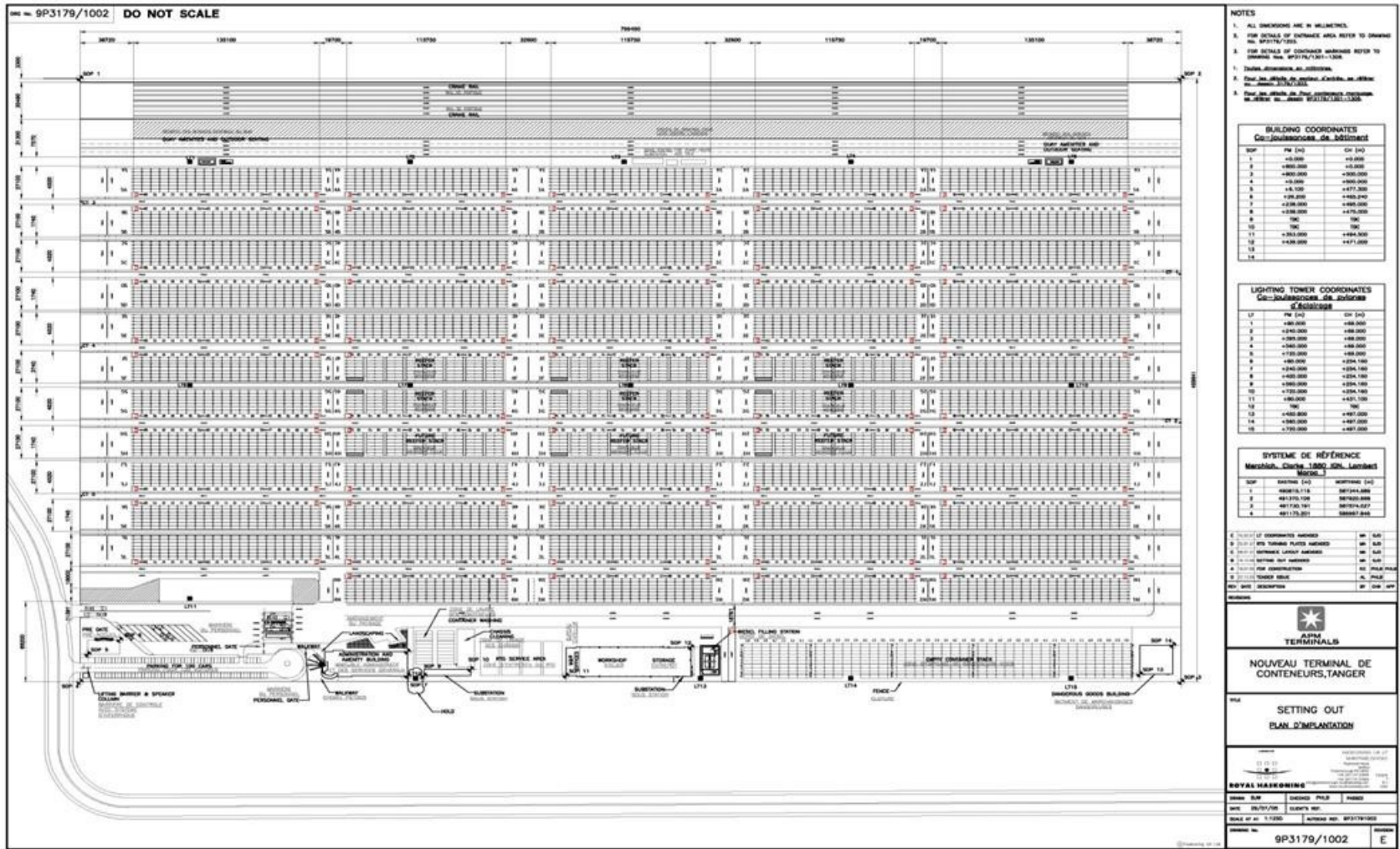
Figure 4- 3: APM Terminal Tangier layout (APM Terminals Tangier indoor data 2014)

In April 2014 a site visit was carried out to expand the understanding and awareness of the container terminal mechanism and performance and to collect data from APM Terminals Tangier. The most important data targeted were: QCs' cycle times, YCs' cycle times, YTs' cycle times, hourly costs, overhead costs and any other information that could help in the research. Fortunately, in addition to the data collected by the visitor, the APM Terminals management provided the visitor with indoor data that had recently been collected for their terminal monitoring and records. Unfortunately, the financial department only provided the hourly costs of the machines; they   excluded the employee wages or salaries. Overall, these data were still adequate to run the simulation and optimization models after cleaning, purification and statistical analyses.

4.3 Case study cycle time data collection

The equipment cycle times were collected from the terminal using both the stopwatch method and from the indoor data furnished by APM Terminals. Fortunately, the company had finished collecting cycle time data for their records and monitoring purposes just one week before the visit. In April, 2014.As specified above, the cost data provided by APM Terminals was only for the hourly costs of their machines. A sample of this raw data can be founded in Table 4-1. The data was then cleaned and re-tabulated to that it could be used and statically analysed for our purposes. The EasyFit distribution was used to analyze the data and the final results of the analysis are summarising at the end of this chapter.

4.3.1 QC cycle times

The QC cycle times (loading and unloading) were divided into four stages starting at the YT lanes, as specified in chapter three.

1- Empty forward moving;

2- Lift or lock the container (discharge the container from the vessel);

3- Loaded backward moving; and

4- Release the container (load the container on the truck).

The QC unloading cycle time = the summation of the four stages' times, see Table 4- 1. This is also termed the QC unloading move (for more details, please refer to

Figure 3- 2).

Table 4- 1: case study QC unloading moves sample

Cycle number	empty move forward (minute)	lift Con from Vessel (minute)	Loaded move backward (minute)	Load Con on YT (minute)	Total cycle time (minute)
1	0.94	0.20	0.60	0.35	2.09
2	0.71	0.31	0.63	0.18	1.83
3	0.87	0.47	0.47	0.27	2.08
4	0.94	0.53	0.73	0.42	2.63
5	0.84	0.58	1.06	0.37	2.85
6	1.01	0.61	0.66	0.29	2.57
7	0.92	1.40	0.74	0.21	3.27
8	0.88	0.41	1.87	1.40	4.55
9	0.92	0.50	0.90	0.66	2.97
10	0.70	0.41	0.42	1.29	2.82
11	0.66	0.56	0.77	0.07	2.06
12	1.19	0.53	1.45	0.42	3.60
13	1.19	0.14	0.81	0.27	2.41
14	0.43	0.30	0.74	0.12	1.59
15	0.64	0.49	0.66	0.07	1.86
16	0.65	0.09	0.63	0.10	1.47
17	0.53	0.04	0.81	0.05	1.43
18	0.71	0.39	0.62	0.18	1.89
19	1.13	0.09	0.76	0.05	2.03
20	1.11	0.03	1.36	0.05	2.55
21	1.12	0.05	0.63	0.05	1.85
22	0.75	0.05	1.10	0.08	1.98
23	0.51	0.10	0.98	0.08	1.68
sum	19.34	8.27	19.39	7.05	54.05
average	0.84	0.36	0.84	0.31	2.35

The statistical analysis results of each stage are represented and summarised in Table 4- 2, where the mean and standard deviations are defined. It is clear that stages with a combination of two resources have a high standard deviation. This reflects the complexity of loading a container to its appropriate position and lifting it from its position onto the other resource. Operator proficiency is very important, as is the readiness of the container to be lifted and the availability of the resource. Two samples of histograms showing QC two-stage statistical analysis are shown in Figure 4- 4Figure 4- 5. It is remarkable to observe how much difference there is between the shortest to the longest durations in lifting containers from the vessel. This shows how critical sharing between two resources becomes during an activity.

Table 4- 2: Case study QC unloading cycle time probability distribution results

Movement direction	Distribution type	Mean (μ)	SD (σ)
Empty forward travel	Normal	0.84	0.22
Lift the container from the vessel	Normal	0.36	0.30
Loaded backward travel	Normal	0.84	0.33
Load the container on the truck	Normal	0.30	0.36

b- *QC loading cycle time stages*

As in unloading activity, the cycle time starts at the YT lanes, but here it begins with lifting the container from the YT. The stages are sequenced as:

1- Lift or lock the container (discharge the container from the YT);

2- Loaded forward moving;

3- Release the container (load the container on the vessel); and

4- Empty back word moving.

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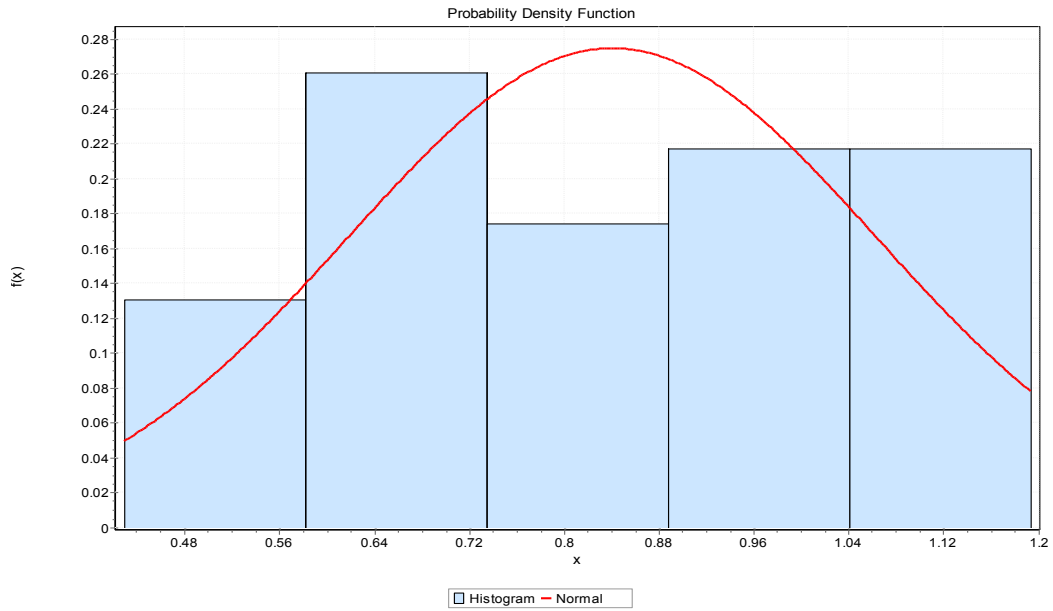
Figure 4- 4: QC Empty forward move travel stage
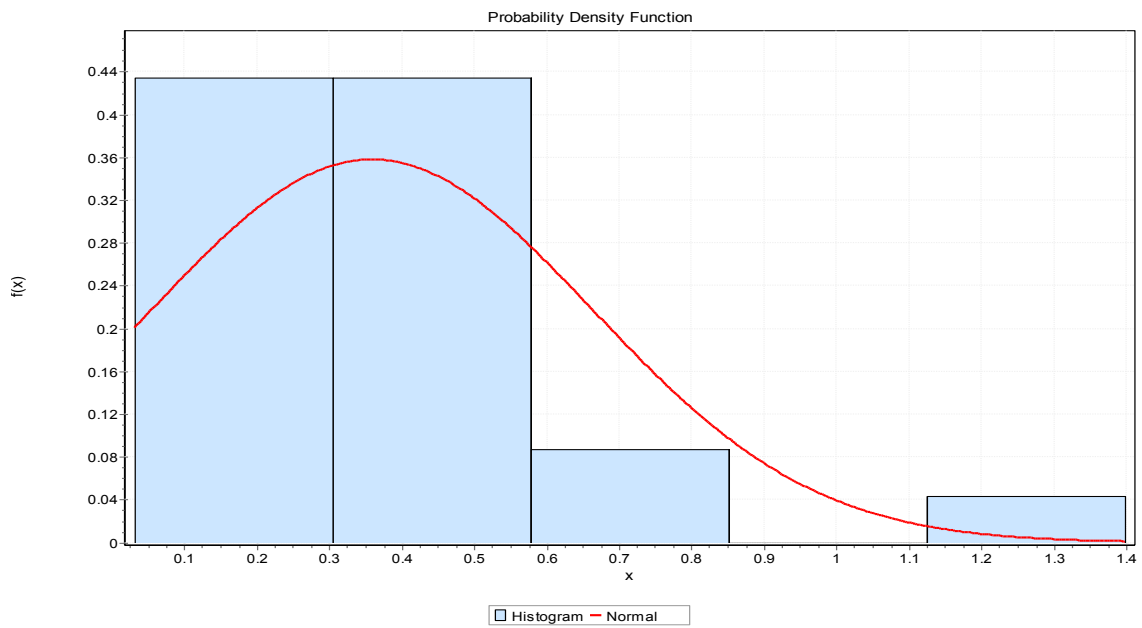
Figure 4- 5: QC lift container from the vessel stage

The QC loading cycle time stages are represented in Table 4- 3. It is clear that the QC loading cycle time is less than it is for unloading. The reasons are that the crane operators are more cautious when unloading the vessel, while the space on vessel is more open for operators when loading. Loading is the terminal operator's responsibility and the container loading process is usually carefully planned by the terminal operators.

Table 4- 3: case study QC loading moves sample

Cycle ID	lift discharge the YT (minute)	loaded move forward (minute)	load the vessel (minute)	empty back move (minute)	Total cycle time (minute)
1	0.12	0.64	0.17	0.70	1.63
2	0.35	0.68	0.14	0.60	1.79
3	0.25	0.93	0.28	0.37	1.84
4	0.04	0.48	0.13	0.83	1.48
5	0.09	1.75	0.07	0.66	2.57
6	0.15	0.61	0.33	0.59	1.69
7	0.23	0.46	0.14	0.59	1.41
8	0.36	0.40	0.10	1.02	1.89
9	0.30	0.67	0.39	0.78	2.14
10	0.43	0.58	0.34	0.79	2.15
11	0.16	0.66	0.49	0.53	1.84
12	0.23	0.58	0.40	0.45	1.65
13	0.25	0.45	0.11	0.97	1.78
14	0.08	0.57	0.20	0.85	1.69
15	0.13	0.83	0.20	0.68	1.84
16	0.10	0.75	0.71	0.19	1.75
17	0.14	0.41	0.17	1.02	1.74
18	0.40	0.62	0.61	0.49	2.13
19	0.15	1.15	0.18	0.39	1.88
20	0.35	0.46	0.11	0.67	1.59
21	0.10	0.50	0.11	0.83	1.54
22	0.25	0.51	0.15	1.41	2.32
23	0.20	0.61	0.16	0.54	1.51
24	0.04	0.48	0.13	0.82	1.47
25	0.18	0.57	0.04	0.92	1.71
Sum	5.12	16.36	5.88	17.67	45.03
Average	0.20	0.65	0.24	0.71	1.80

The QC loading cycle time = the summation of the four stages' times. This is also called the QC loading move.

The statistical analysis results of each stage are represented and summarised in Table 4- 4, which presents the means and standard deviation. As in QC unloading cycles, the stages that involve the sharing other resources (lifting or loading the containers) have higher standard deviation than the empty QC moves (QC forward and backward moves). For further information, samples of histogram figurers and descriptive statics tables can be found in the Appendixes.

Table 4- 4: Case study QC loading cycle time probability distribution results

Movement direction	Distribution type	Mean (μ)	SD (σ)
Lift container from the YT	Normal	0.20	0.11
Loaded forward travel	Normal	0.64	0.25
Load the container on the Vessel	Normal	0.21	0.16
Empty backward travel	Normal	0.66	0.11

4.3.2 YC cycle times

YC cycles times are not different than QC cycle times except that the vessel is replaced by the storage yard, where the unloading and loading starts. The unloading YC cycle time starts by discharging the container from the YT, and the loading cycle time starts by lifting the container from the SY. The final results after statistical analysis of the YC unloading and loading cycle time's data are represented in Table 4- 5 and Table 4- 6, respectively.

4.3.3 YT cycle times

The yard truck (YT) cycles are categorised into three different activities: unloading, loading and double cycling.

a- ***YT unloading cycle time***

The YT unloading cycle time is broken-down to four stages:

1- YT travels empty from the SY to the berth side;

2- YT loading by the QC;

3- Loaded YT travels from the berth to the SY; and

4- Discharging of the YT by the YC.

The YT cycle time is equal to the summation of the four stages' times.

Table 4- 5: Case study YC unloading cycle time probability distribution results

Movement direction	Distribution type	Mean (μ)	SD (σ)
Lift container from the YT	Normal	0.34	0.13
Loaded forward travel	Normal	0.77	0.25
Load the container on SY	Normal	0.28	0.21
Empty backward travel	Normal	0.62	0.28

Table 4- 6: Case study YC loading cycle time probability distribution results

Movement direction	Distribution type	Mean (μ)	SD (σ)
Empty forward travel	Normal	0.67	0.16
Lift the container from SY	Normal	0.18	0.07
Loaded backward travel	Normal	1.12	0.33
Load the container on the	Normal	0.23	0.11

b- ***YT loading cycle time***

As in YT unloading, the cycle time is divided into four stages, replacing the unloading by loading.

1- YT loading by the YC at the storage yard;

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2- Loaded YT travel from the SY to the berth side;

3- YT discharged by the QC; and

4- Empty YT travels from the berth side to the SY.

c- *YT double cycle*

Since the case study terminal does not employ YT double cycling, the author has modified the cycle times to mimic the process as follows:

1- Keep loaded YT travels in both single cycle unloading and single cycle loading;

2- Keep YT discharging and loading by QCs in both unloading and loading single cycling;

3- Keep YT discharging and loading by YCs as in QCs;

4- Add YT empty travel from QC unloading and QC loading; and

5- Add empty travel from YC unloading and YC loading.

This will produce YT double cycling divided into six stages: YT loading at the SY, YT loaded travel from the SY to the berth side, YT discharging at berth side, YT empty travel from the unloading QC to the loading QC, YT loading at berth side, YT loaded travel from berth side to the SY, YT discharging at the SY and YT empty travel from the unloading YC to the loading YC.

The operators that load and discharge the trucks at QCs and YCs need to consider the cranes' loading and the truck's discharging times. These times were previously represented in the cranes' cycle times.

The YT double cycling time is equal to the summation of the six stages. The final results of the YT cycle times in the three activities are summarised in Table 4- 7.

Table 4- 7: case study YT travels probability distribution results

Activity description	Movement direction	Distribution type	Mean (μ)	SD (σ)
Single cycle unloading	Empty travel From SY to QC	Normal	3.26	1.06
	Loaded travel from QC to SY	Normal	2.74	0.53
Single cycle loading	Loaded travel from SY to QC	Normal	2.77	1.04
	Empty travel from QC to SY	Normal	2.68	0.54
Double cycle (Loading and unloading)	Loaded travel from YC1 to QC1	Normal	2.74	0.53
	Empty travel from QC1 to QC2	Deterministic	0.16	-
	Loaded travel from QC2 to YC2	Normal	2.77	1.04
	Empty travel from YC2 to YC1	Deterministic	0.75	-

4. 4 Case study resources' productivities

To determine the resources' productivities, the times were recalculated, based on the assumption that each machine single cycle produces 2TEUs. For example, if the QC makes 27 moves per hour in single cycling, it produces (27). (2)= 54 TEUs per hour. The same thing can be applied for each YC and YT. On double cycling there would be 4 TEUs per cycle for each pair of QCs and YCs and 4 TEUs per cycle for a single YT. For the simulation, the detailed cycle times for each machine were used as input and the productivity is one of the expected outputs. In the optimization, the productivity of each machine is needed to run the model in order to identify the fleet's or the chain's productivity as a whole. The steps for recalculating the QC unloading productivity are given below as an example:

1- Export the total cycle time from Table 4- 1;

2- Calculate the number of moves per hour = 60 (min)/cycle time (min);

3- For QC unloading productivity, multiply the number of moves per hour by 2 TEUs/move; and

4- For QC double cycle productivity based on QC single cycle unloading productivity, take

the result from step 3 and multiply by 2, or repeat step 3, replacing 2 TEUs by 4TEUs.

Table 4- 8: Case study of QC single cycle unloading productivity and double cycling based on number of QC moves/ hour

Cycle ID	total time (min)	Number of Moves/hr	Single cycle unloading Prod. (TEU/hr)	Double cycle Prod. (TEU/hr)
1	2.09	28.74	57.48	114.97
2	1.83	32.85	65.70	131.39
3	2.08	28.90	57.79	115.58
4	2.63	22.82	45.65	91.30
5	2.85	21.05	42.10	84.21
6	2.57	23.39	46.78	93.56
7	3.27	18.37	36.73	73.47
8	4.55	13.17	26.35	52.69
9	2.97	20.19	40.37	80.74
10	2.82	21.30	42.61	85.21
11	2.06	29.12	58.24	116.47
12	3.60	16.67	33.35	66.69
13	2.41	24.90	49.80	99.61
14	1.59	37.62	75.25	150.49
15	1.86	32.29	64.58	129.16
16	1.47	40.69	81.37	162.74
17	1.43	42.04	84.07	168.15
18	1.89	31.71	63.43	126.85
19	2.03	29.50	59.00	118.00
20	2.55	23.51	47.02	94.04
21	1.85	32.48	64.96	129.92
22	1.98	30.35	60.70	121.41
23	1.68	35.78	71.55	143.10
sum	54.05	637.44	1274.88	2549.76
average	2.35	28.97	55.43	110.86
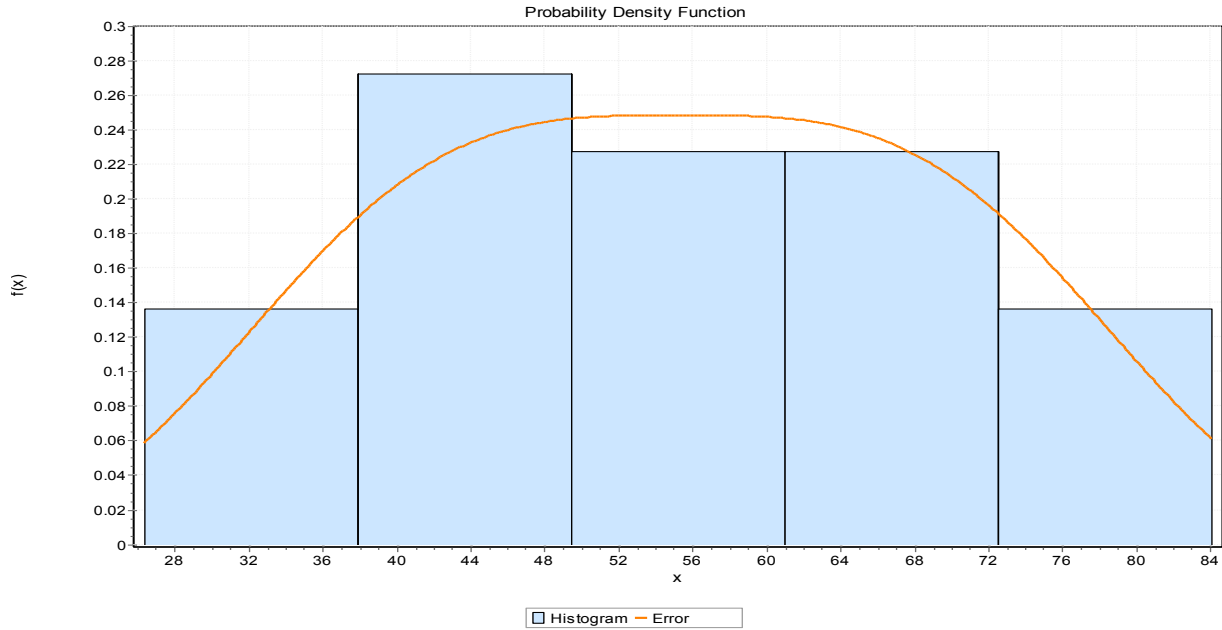
Figure 4- 6: QC unloading productivity histogram
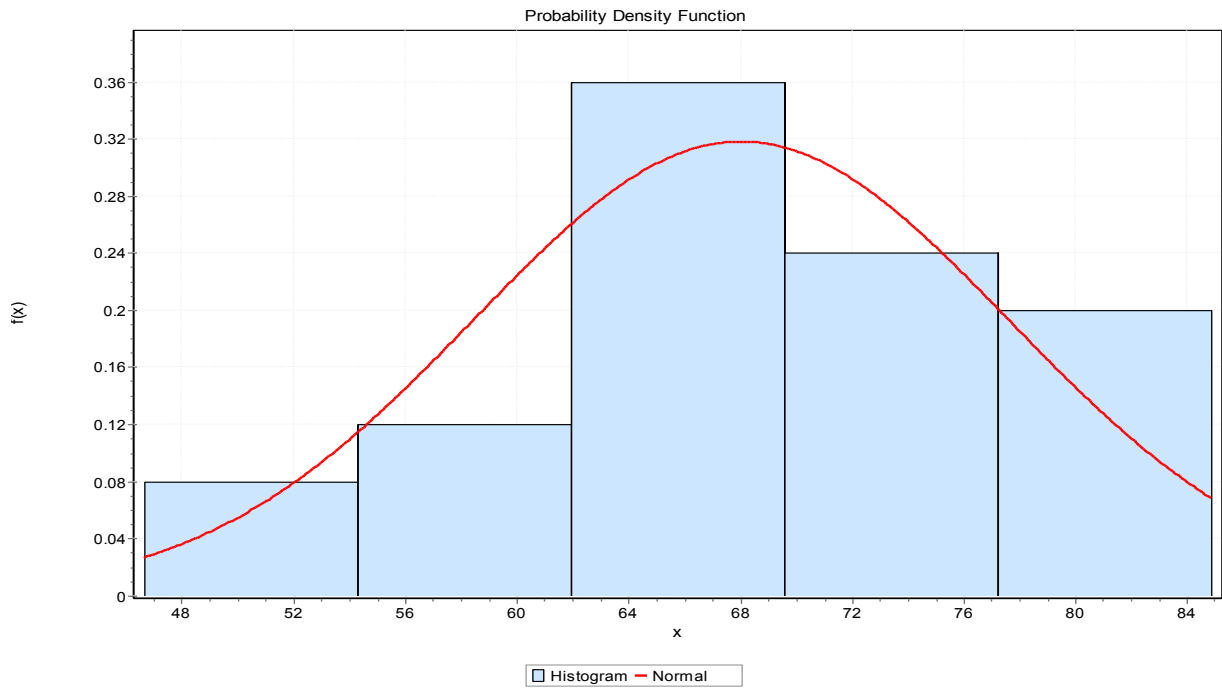
Figure 4- 7: QC loading productivity probability density function histogram

The QC unloading and loading probability functions are represented in Figure 4- 6 and Figure 4-7, respectively.

As in QC productivities, YC productivities are calculated based on the YC cycle times in both unloading and loading cycles. YC double cycling is also abstractive, based on YC single cycle productivity. The lowest YC productivity is adapted to calculate the YC double cycle productivity as a way to control the pairs of YCs, since the YC pairs are dependent on each other. The YC loading productivity is greater than it is in unloading. The adopted productivity for YC double cycling is double that of the YC's unloading productivity.

The YT productivity is calculated using the same principle of cranes with only some modifications. YT single cycle productivities follow the same principles as for cranes. Defining the number of moves per hour and then multiplying that number by 2 TEUs gives the YT single cycle productivity for each activity. For double cycling, the steps given below must be followed:

1- Export the YT double cycle time from section 4.3.3;

2- Define the number of moves per hour= 60 (min)/ double cycle time (min); and

3- Multiply the number of moves per hour by 4 TEUs.

Table 4- 9: Statistic analysis of resources productivity result summary

Resource	Category	Single cycle		Double cycling (TEU/hr)
		Unloading (TEU/hr)	Loading (TEU/hr)	
QC	Mean (μ)	55.33	68.03	110.86
	SD (σ)	15.53	9.58	30.37
YT	Mean (μ)	12.85	13.81	17.84
	SD (σ)	3.43	3.91	4.38
YC	Mean (μ)	61.86	53.59	113.1
	SD(σ)	13.93	13.24	27.85

4.5 Cost data collections

As mentioned earlier, the resources hourly costs are the only data provided by the company. The authors preferred to add 25% of each resource hourly cost as an overhead cost. The equipment base hourly costs provided by the APM terminal are;

QC hourly cost = 63.875 $/hr

YC hourly cost = 10.125 $/hr

 YT hourly cost = 6.75 $/hr

4.6 Summary

Data collection is an important part of any project. Successful data collection will vary according to the type of project, the use and the nature of the data. Data almost always needs to be organized, cleaned and analyzed to fit the format used in the model or project. Data can be qualitative, quantitative or both. In this research most of the data are quantitative, divided into two types: duration data and productivity data. The duration data was collected from APM Terminals container facility at Tangier, Morocco. The productivity was calculated and abstracted from the duration data based on a single move of a resource equal to 2 TEUs/ move and of a double move equal to 4 TEUs/ move. Both types of data were organized, analyzed and summarized. The data is now is ready to be used in implementation as input variables in both simulation and optimization models. The next chapters show how these models were implemented and verified.

Chapter 5: Models implementation and verification

5.1 Overview

In this chapter, both the simulation and optimization models are implemented, using both duration and productivity case study data. The models test the handling strategy's efficiency and assess its improvements. The aims of this implementation and verifications are:

1- To make sure that the strategy can be implemented in real life through the simulation tool;

2- To monitor the movements of the resources during the container handling process and at the turning points of changing from single to double cycling and vice versa;

3- To quantify the improvement in productivity by comparing the introduced strategy with the traditional strategy; and

4- To be able to select the optimum fleet size that will deliver the job with maximum productivity and thus minimize the vessel turnaround time at a minimum cost.

Both the simulation model and optimization model developed in chapter three are implemented, verified and tested, followed by selected approaches to their deployment. First, the simulation model is implemented using the case study duration data. Second, the sensitivity analysis is implemented using the simulation model by changing the number of YTs. The simulation models of both single cycling and double cycling with the results of the sensitivity analysis are then compared. The comparison shows the improvement and benefits achieved by replacing traditional container handling (YT single cycling) by the introduced strategy (YTs double cycling). Third, a multi-objective GA model is implemented using the case study productivity data. Fourth, some selection approaches are implemented to select the best alternative from

results generated by GA optimization. Fifth, the simulation model is implemented again, to evaluate the top-ranked four solutions generated by the GA. Finally, the top solutions are compared and ranked to select the best solution, also called the best chromosome or alternative.

5.2 Simulation model implementation

The case study considers a hatched vessel with a 16000 TEU (8000, 40 feet containers) capacity. The vessel will totally unload and then be loaded with the same number of containers. The containers are estimated to be distributed uniformly on the vessel in 20 rows and 20 stacks. The total number of containers per row is 400. For single cycling, only one QC and one YC will do the job of unloading and loading the vessel, and the loading process will not start until the unloading process is completely finished. However, for double cycling, two QCs and two YCs are needed to do the job. Each activity (loading and unloading) requires one QC and one YC. The same trucks will work as duel loading/unloading trucks to serve the QCs and the YCs. The small movement of QCs between the rows is neglected due its minor time value compared to the total time of unloading each row. The YCs are of the RTG type.

5.2.1 Single cycle simulation inputs

The single cycle model is displayed in detail in chapter three. The simulation model is shown in Figure 5-1 and the simulation process is clarified in detail in section 3-6. The input durations and costs are derived from the data selected and analyzed in chapter 4. The single cycle simulation parameters include the number of resources, the number of containers to be unloaded and loaded and the hourly costs of the equipment cost plus 25% of the total hourly costs to cover overhead and labour.
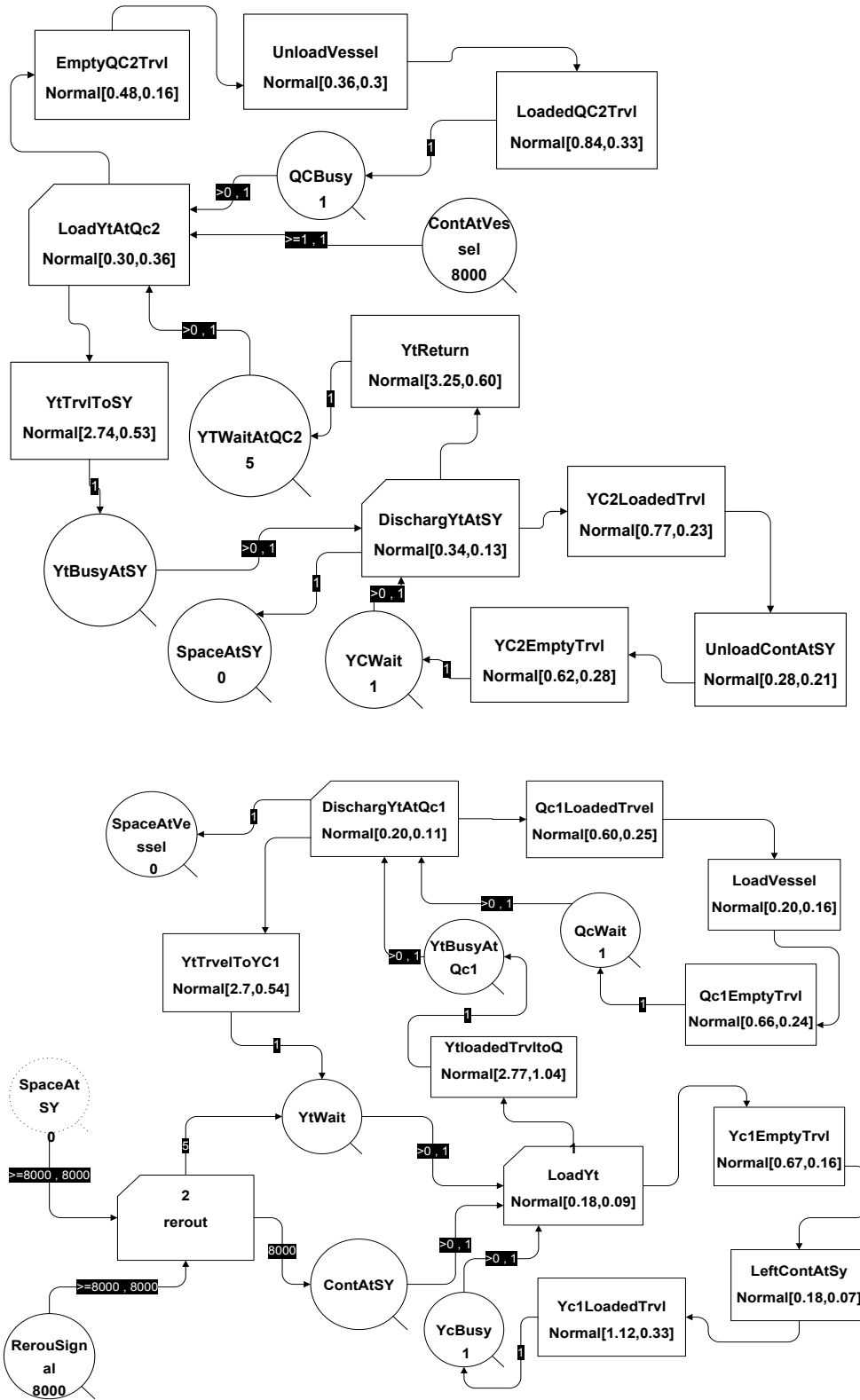
Figure 5- 1: Single cycle simulation model implementation

The parameters used in the implemented single cycle simulation model are listed below and presented in more detail in Figure 5-2.

Containers to be unloaded = 8000, 40-ft (16000 TEUs)

Containers to be loaded = 8000, 40-ft (16000 TEUs)

Number of QCs required = 1

Number of YCs required = 1

Number of trucks for unloading and loading = 5

UnloddContanr	Containers to be Unloaded	8000
LoddContainer	Contaners to be Loaded	8000
nYTs	yard truck	5
nQC	QC loading cranes	1
nYC	YC Loading yard crane	1
QCCst	Loading Quay cranel cost ($/hr)	63.875
YCCst	Loading Yard crane cost ($/hr)	10.125
YTCst	Yard Truc cost ($/hr)	6.75
OHCst	Overhead cost ($/hr)	25% of total hourly cost

Hrs	Hrs needed to unload and load 16000 40` containers (32000 TEUs)	SimTime/60
ProdRate	Productivity rate (TEU)/hr)	(4*SpaceAtVessel.CurCount/Hrs)
HourlyCst	Hourly Cost	(nQC*QCCst+nYC*YCCst+nYTs*YTCst)*1.25
UnitCst	Unit Cost ($/ETU)	HourlyCst/ProdRate

Figure 5- 2: Single cycle simulation parameters

5.2.2 Case of study single cycle outputs

The simulation is targeted to define the four results below, using EZStrobe:

1- Productivity rates;
2- Total hours to complete unloading and loading of 16000 containers (32000 TEUs);

3- Hourly costs; and

4- Unit cost (cost of a single TEU).

These results from theEZStrobe simulation are normally displayed as in Figure 5- 3, where the inputs and important results can be easily observed.

Stroboscope Model 5 trucks single cycle Startigy 16000 containers 1 QC 1YC.vsd (467829248)

** Model input parameters **

yard truck   : 5
QC loading cranes   : 1
YC Loading yard crane   : 1
Loading Quay crane cost ($/hr) : 63.875

Loading Yard crane cost ($/hr) : 10.125

Yard Truck cost ($/hr)   : 6.75

Overhead cost ($/hr)   : 0
Containers to be unloaded : 8000
Containers to be loaded   : 8000

** Calculated results after simulation **

Hrs needed to load and unload 1600 40` containers (32000 TEUs): 567.552
Productivity rate (TEU)/hr)   : 56.3825
Hourly Cost   : 134.688
Unit Cost ($/ETU)   : 2.38882

Statistics report at simulation time 34053.1

Figure 5- 3: Single cycle simulation results

5.2.3 Double cycle simulation inputs

The double cycle model has been designed and is displayed in chapter three. The simulation model is shown in Figure 5- 4. In double cycling, it is expected that unloading the first three rows of 400 containers will be carried out with the single cycling technique, followed by a conversion   to double cycling for 17 rows of 400 containers. The loading is anticipated to go back to a single cycle model for loading the last three rows of 400 containers. The parameters are listed below and shown in detail in Figure 5- 5.

EmptyQC2Trvl
Normal[0.84,0.22]

UnloadVessel
Normal[0.22,0.23]

LoadedQC2Trvl
Normal[0.84,0.33]

QC2Busy
1

ContAtVessel
1200

>0 , 1

>=1 , 1

LoadYtAtQc2
Normal[0.306,0.363]

>0 , 1

YtIdelAtQc2
5

YtReturn
Normal[3.25,0.6]

SpaceAtSY

YtTrvlToSY
Normal[2.74,0.53]

1

DischargYtAtSY
Normal[0.347,0.138]

1

YC2LoadedTrvl
Normal[0.77,0.101]

YtBusyAtSY

>0 , 1

>0 , 1

YC2Wait
1

1

YC2EmptyTrvl
Normal[0.6,0.24]

UnloadContAtSY
Normal[0.28,0.21]

SpceAtVesselDbl
0

1

2
DschrgYtAtQc1Db
Normal[0.206,0.112]

Qc1LoddTrvelDbl
Normal[0.64,0.25]

LoadVesselDbl
Normal[0.208,0.161]

YtTrvelToQC2
0.16

>0 , 1

Qc1WaitDbl
1

1

Qc1EmptyTrvlDbl
Normal[0.66,0.244]

>0 , 1

YtBusyAtQc1

1

YtIdelAtQc2Dbl

YtloddTrvlDbl
Normal[2.77,1.04]

YtWaitDbl
0

>0 , 1

SpaceAtSY

RferuteToDblCycl
0.0001

5

6800

ContAtSYDbl
0

>=1 , 1

LoadYtDbl
Normal[0.233,0.11]

Yc1EmptyTrvlDbl
Normal[0.67,0.16]

>=1200 , 1200

>=1200 , 1200

>0 , 1

SgnlRerutDble
1200

Yc1BusyDbl
1

1

Yc1LodedTrvlDbl
Normal[1.1,0.33]

LeftContAtSyDbl
Normal[0.18,0.07]

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Figure 5- 4: Double cycling simulation model

The double cycle simulation parameters are:

Containers to be unloaded = 8000, 40-ft (16000 TEUs)

Containers to be loaded = 8000, 40-ft (16000 TEUs)

Number of QCs required = 2

Number of YCs required = 2

Number of trucks for unloading and loading = 5

Durations and hourly costs are generated from the data collection, see chapter 4.

UnloddConta	Containers to be Unloaded	8000
LoddContainer	Contaners to be Loaded	8000
nYTs	yard truck	5
nQC1	QC1 loading cranes	1
nQC2	QC2 unloading crane	1
nYC1	YC1 Loading yard crane	1
nYC2	YC2 Unloading Yard crane	1
QC1Cst	Loading Quay cranel cost ($/hr)	63.875
QC2Cst	Unloading Quay crane cost ($/hr)	63.875
YC1Cst	Loading Yard crane cost ($/hr)	10.125
YC2Cst	Unloading Yard crane cost ($/hr)	10.125
YTCst	Yard Truck cost ($/hr)	6.75
OHCst	Overhead cost ($/hr)	25% of total hourly cost

Hrs	Hrs needed to load and unload 16000 40` containers (32000 TEUs)	SimTime/60
ProdRate	Productivity rate (TEU)/hr)	(((26*SpceAtVesselLst.CurCount)+(800))/Hrs)
HourlyCst	Hourly Cost	(nQC1*QC1Cst+nQC2*QC2Cst+nYC1*YC1Cst+nYC2*YC2Cst+nYTs*YTCst)*1.25
UnitCst	Unit Cost ($/TEU)	HourlyCst/ProdRate

Figure 5- 5: Double cycling simulation parameters

5.2.4 Case study of double cycling outputs

The simulation is targeted to define the four results below, using EZStrobe:

1- Productivity rates;

2- Total hours to complete the unloading and loading of 16000 containers (32000 TEUs);

3-Hourly costs; and

4-Unit cost (cost per TEU).

The simulation results are then generated after the EZStrobe simulation run and shown in Figure 5- 6.

```
Stroboscope Model 5 Trucks  new distribution.vsd 16000.vsd YT Tangier.vsd
                          (1381557888)

               ** Model input parameters **

          Description                 : 0
          yard truck                  : 5
          QC1 loading cranes            : 1
          QC2 unloading crane           : 1
          YC1 Loading yard crane         : 1
          YC2 Unloading Yard crane        : 1
     Loading Quay crane cost ($/hr)   : 63.875

     Unloading Quay crane cost ($/hr)   : 63.875

     Loading Yard crane cost ($/hr)     : 10.125

     Unloading Yard crane  cost ($/hr)  : 10.125
          Yard Truck  cost ($/hr)        : 6.75

          Overhead cost ($/hr)          : 0
          Containers to be unloaded     : 8000
          Containers to be loaded       : 8000


               ** Calculated results after simulation **

  Hrs needed to load and unload 16000 40` containers (32000 TEUs): 351.166
          Productivity rate (TEU)/hr)               : 91.1249
            Hourly Cost                             : 227.188
            Unit Cost ($/TEU)                       : 2.49314

          Statistics report at simulation time 21070
```

Figure 5- 6: Double cycling simulation results

It is clear that the productivity has been improved and the vessel turnaround time reduced. These results prove that the use of the YT double cycle is a beneficial and worthwhile. However, this is not yet enough improvement to justify replaces the YT single cycling by double cycling. Furthermore, the number of trucks is not yet optimized to handle containers using double cycling. For the above reasons and more, a sensitivity analysis was carried out to optimize the

fleet size in order to maximize productivity and minimize costs. This optimization also leads to further reducing the vessel turnaround time, the overall aim of this research.

5.3 Sensitivity analysis

The sensitivity analysis is undertaken to evaluate the changes in model resources. For now, only the number of YTs is to be evaluated. The other resources (the number of QCs and YCs) will be assessed in the GA as lower and upper boundaries. To implement the sensitivity analysis on the other resources, a model must be developed to meet the processes. For instance, to add one more YC, another YC cycle must be developed and a probabilistic routing element introduced to connect the process. The number of YTs changes covers from 3 to 14 trucks in both single and double cycle. The resultsare compared and the optimum result can be observed.

5.3.1 Sensitivity analysis result

After applying the sensitivity analysis on one resource, here the number of YTs for both single and double cycling, several results can easily be foreseen. These results vary from one to another in terms of their overall affect. The optimum single cycle productivity rate was almost 57 TEUs/hr when using 6 trucks, and was stable at that rate, while the optimum unit cost was 2.28 $/TEU when using 4 trucks. On the other hand, for double cycling, the optimum productivity rates were almost 92.5 TEUs/hr when using 9 trucks, with an optimum unit cost of about 2.8 $/TEU. It is obvious that the unit costs are not simple to use to decide which strategy is better. This led us to use a cost index to clearly monitor which option is most profitable, based on the productivity. The cost index is the ratio between unit cost and its corresponding productivity. The cost index is much better (lower) when using YT double cycling rather than single cycling. The cost index when using 9 trucks at double cycling is equal to 0.031and it is 0.046 when using 5 trucks in single cycle.

Table 5- 1: Sensitivity analysis comparisons between single and double cycling strategies

Trucks	Single Cycle						Double Cycle					
	Hrs needed to move 1600 Cont.	Productivity rate (TEUs/hr)	Hourly cost ($/hr)	Unit Cost ($/TEU)	Cost Index	Total cost ($)	Hrs needed to move 1600 Cont.	Productivity rate (TEUs/hr)	Hourly cost ($/hr)	Unit Cost ($/TEU)	Cost Index	Total cost ($)
3	644.48	49.65	117.81	2.37	0.048	37920	417.88	76.57	210.31	2.74	0.036	43840
4	579.48	55.22	126.25	2.28	0.041	36480	365.66	87.51	218.75	2.49	0.028	39840
5	567.55	56.38	134.68	2.38	0.042	38080	350.855	91.21	227.188	2.49	0.027	39840
6	563.33	56.8	143.12	2.52	0.044	40320	348.41	91.84	235.62	2.56	0.028	40960
7	560.62	57.08	151.56	2.65	0.046	42400	347.23	92.15	244.06	2.64	0.029	42240
8	561.38	57	160	2.8	0.049	44800	347.02	92.21	252.5	2.73	0.030	43680
9	560.72	57.06	168.43	2.95	0.052	47200	346.28	92.41	260.93	2.82	0.031	45120
10	559.59	57.18	176.8	3.09	0.054	49440	345.46	92.62	269.35	2.9	0.031	46400
11	559.29	57.21	185.231	3.23	0.056	51680	346.73	92.29	277.81	3.01	0.033	48160
12	559.195	57.22	193.75	3.38	0.059	54080	346.07	92.46	286.25	3.09	0.033	49440
13	560.34	57.1	202.18	3.54	0.062	56640	345.94	92.499	294.68	3.18	0.034	50880
14	557.33	57.41	210.62	3.66	0.064	346.82	345.54	92.26	303.12	3.28	0.036	52480

It is expected that clearer optimum results will be generated if the sensitivity analysis can be applied to the other resources (QCs and YTs). Single cycling and double cycling can now be compared in terms of productivity rates and cost savings. Even though more trucks are needed in double cycling, it is preferable to maximize productivity and minimize costs. To provide an integrated perspective, a broad comparison has been made, which includes turnaround time, productivity rate, unit cost and cost index. The quantitative comparisons are shown in Table 5-

1to illuminate the difference between the two strategies. The sensitivity analysis implemented on trucks, varying from 3 to 14 trucks, provides a clear idea of the fluctuations and changes. Graphical comparisons were also developed in Table 5- 1 (a, b, c and d) to cover the most important objectives: turnaround time, productivity rate, unit cost and cost index, respectively. Figure 5-7a shows the differences in vessel turnaround time between single and double cycling strategies. The time savings was more than 214 hours with a percentage of saving of 38%. This time savings is a result of productivity improvement which exceeded 35TEUs/hour in double cycling comparing to using single cycling for feasible solutions (see Figure 5-7b). The unit cost is not as clearly differentiated, but while it is almost the same in the two strategies, sometimes it is less when using single cycling, especially when using less than 7 trucks (see Figure 5-7c). However, this is not an optimal variable to use to compare between the two strategies' unit cost, asthe double cycling strategy delivers higher productivity with the same cost. In other words, YT double cycling delivers the desired results with higher efficiency without increasing the unit cost. Using a cost index makes it easier to compare the cost and efficiency. Figure 5-7d shows that the cost index when using double cycling is lower than it is for single cycling, which supports the above statements.

To summarize the comparisons; YT double cycling is more productive, efficient and economical than YT single cycling. For more confidence in the results and to be more specific, an optimization covering all the scenarios and testing all the probable resource exchanges was carried out and is described in the following sections. The optimum number of YTs is to be the base number for each QC in an optimization algorithm to insure that the QC is kept busy all the time. The number of YCs varies from 1 to 2.5 times the number of QCs, as stated in the literature.
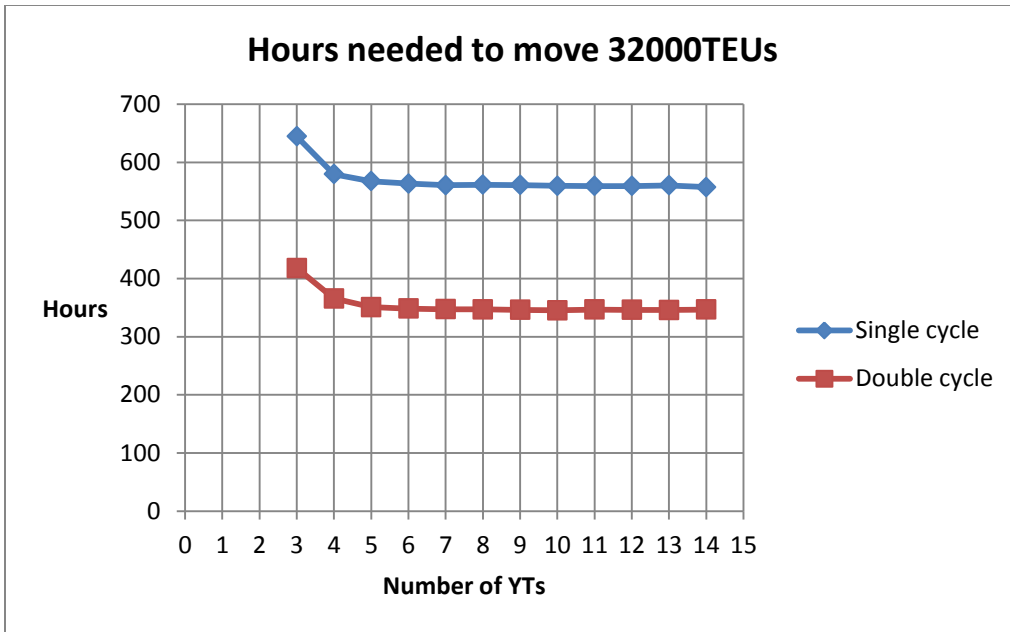
(a) Comparison between single and double cycling hours needed to load and unload (32000 TEUs)
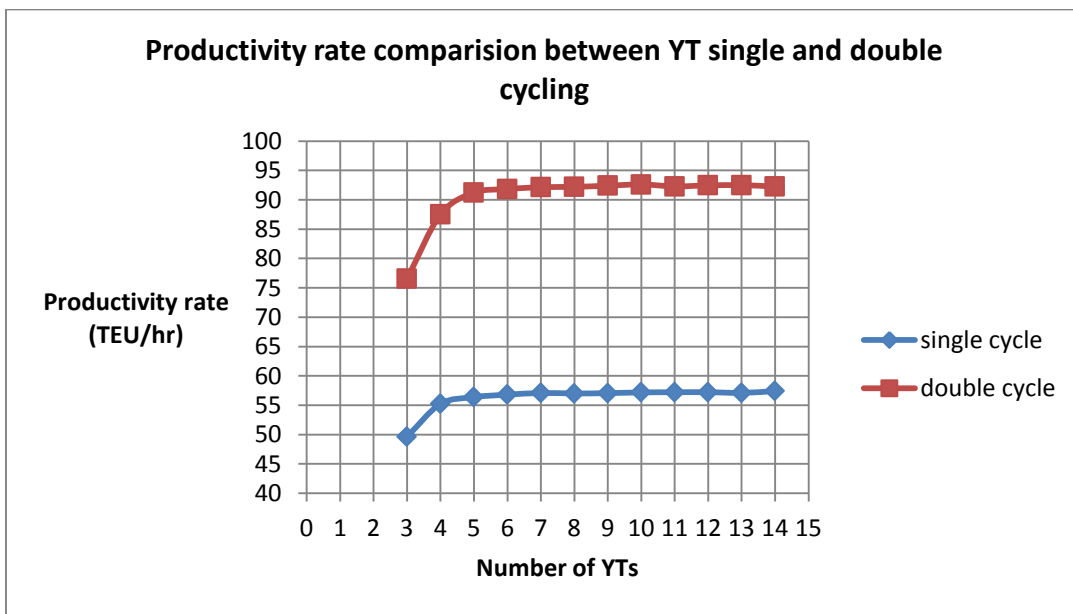
(b) Comparison between single and double cycling productivity rates
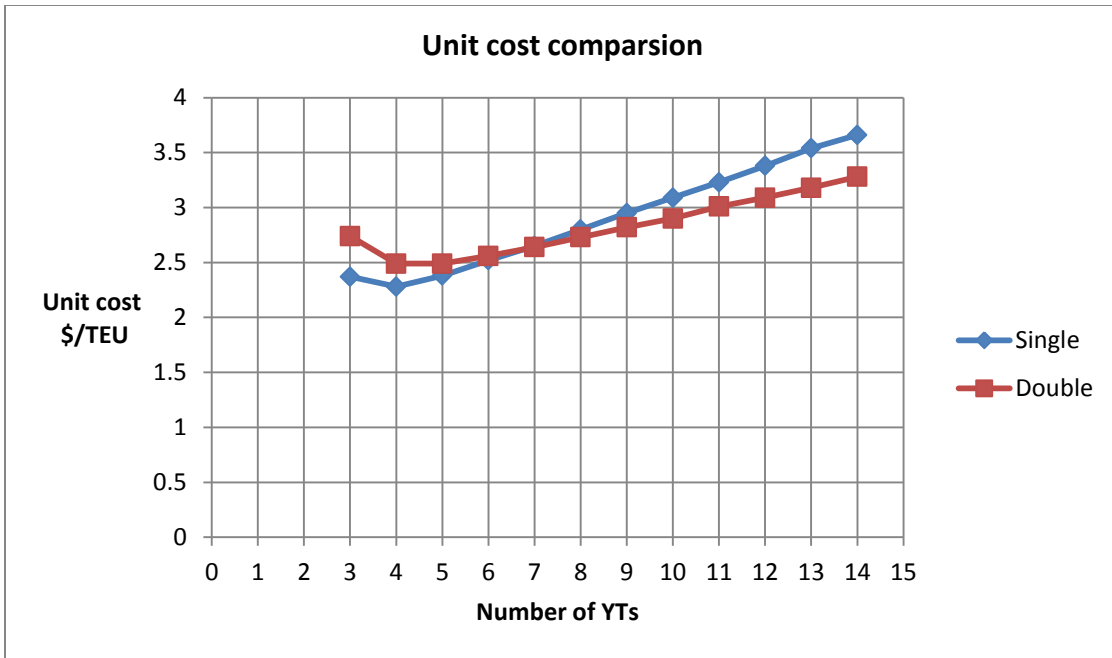
(c) Comparison between single and double cycling unit costs
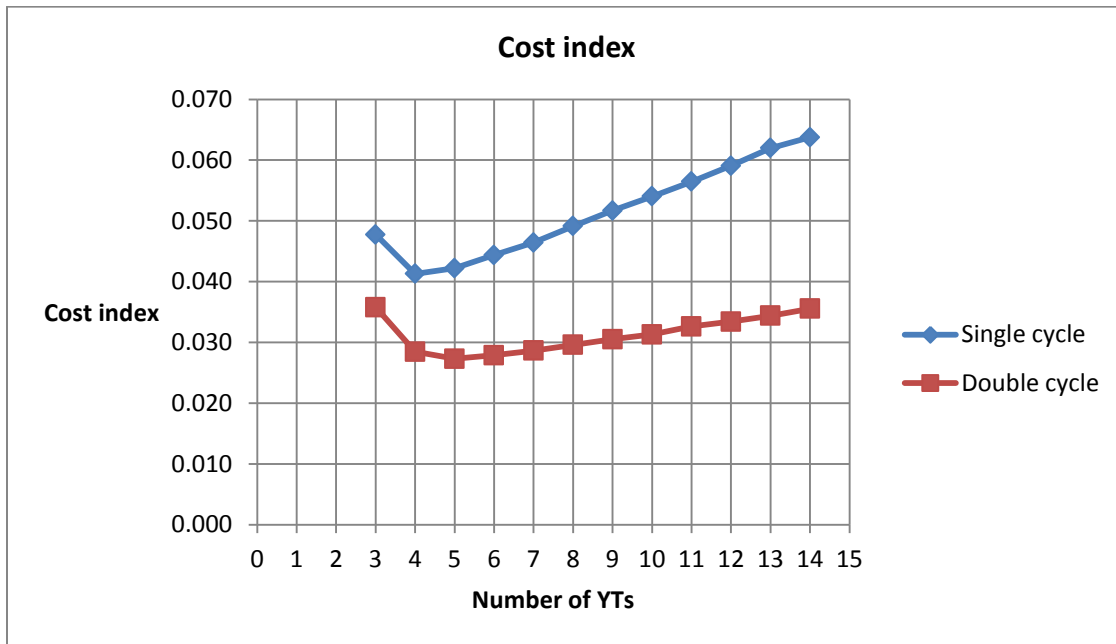
(d) Comparison between single and double cycling cost index

Figure 5- 7: (a, b, c, and d) Sensitivity analysis output comparisons

5.4 Case study optimization model implementation overview

The case study is set to have the same parameters as in the simulation case study in terms of vessel capacity, number of containers to be loaded and unloaded and the handling strategy. Three activities are scheduled to deliver the containers: YT unloading single cycling, YT double cycling and YT single cycling loading. The activities are set to start in sequence. The data (durations and costs) are generated from the case study data collection in chapter 4. Multi-objective GA optimization is implemented, employing two different software applications.

- GANetXL software, developed by a research team in the Water Engineering Department at the University of EXETER, UK (Savić et al. 2011): This software is an add-in for Microsoft Excel that uses GA to solve optimization problems and searches. Due to the inherent complications in selecting an absolute optimum alternative solution, four approaches are used to select the near-optimum solution. The four approaches are: Pareto frontier, TOPSIS, Cost index and re-simulation. Most of the approaches indicated the same alternative solution in each of the three scenarios of QC availability.

- Visual Basic for Applications code (VBA). This code is an algorithm for solving nonlinear problems VBA functions by relying primarily on randomly generated variables. The code randomly generates a value for every variable (between the minimum and maximum variable values) and then calculates both objective functions for that variable's values. The code generates a random answer and then checks if the answer is better than the last best-generated answer. Any improvement on the previous best-answer is determined by calculating the multiplication of the time and cost functions and comparing them to the previous best-answer's objective functions' multiplication. The code adds all the generated answers which improve on the existing optimal answer and

also randomly adds other answers to use in plotting the answer curve. End of editing in this version. New editing starts from here:

5.5 GA optimization

A multi-objective genetic algorithm was applied to verify the near-optimum solution. A population size of 600 was selected to be tested. SolveXL software, which is a commercial version of GANetXl, was used for most of the optimization, but the GANet XL solver was later used to solve the multi-objective optimization. The variables were selected in each activity to be adequate to accomplish the task. The activities were selected to be of start-to-end duration. None of a preceding activity could start before the successor activity had finished. The activities are sequenced as follows:

The YT double cycling activity is preceded by the YT single cycling unloading activity, and the YT single cycling loading activity is the successor activity of the YT double cycling activity. The task ends by loading the last container. The vessel turnaround time starts at minute zero and ends at the minute of loading the last container. The vessel will not depart until the last container is loaded.

5.5.1 GA variables and parameters

Table 5- 2 presents the input parameters for the GA, where: a, b, and c are the resource productivity in each activity, and W1, W2 and W3 are the hourly resource costs in each activity.

Table 5- 3 presents the GA input variables and the objective functions, where

GA variables

X_n, Y_n and Z_n are the number of resources (QCs, YTs, and YCs, respectively) in each activity.

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5.5.2 Objective functions

a) Maximize

1- A_1, A_2, and A_3 are the fleet productivity for each activity, A= min (resource productivity in the chain for each associated activity).

2- Average productivity for the task = [total number of units to be moved (TEUs)/Total time (hr)]= TEU/hr.

b) Minimize

1- B_1, B_2 and B_3 are the unit cost of the activity. B= [(summation hourly cost of each resource). (number of resources) + (overhead hourly cost)]/ (productivity (A)) = ($/hr)/ (TEU/hr)= $/TEU.

- Overhead cost estimated to be 25% of the resources' hourly cost.

2- Total time (T total)

T total = Summation of [(number of TEUs to be moved using single cycling unloading/ A_1), (number of TEUs to be moved using double cycling/ A_2) and (number of TEUs to be moved using single cycling loading/ A_3)] = TEUs/(TEU/hr)= hours.

3- Total cost of the task

= Summation of [(number of units to be moved in each activity (TEUs)) times ((unit cost of each activity ($/TEU))] = TEUs. ($/TEU)= $

4- Average unit cost for the task

Unit cost average= [Total cost ($) / (number of units to be moved (TEUs)]= ($/TEU)

5.5.3 GA constraints

The objective functions are subjected to some constraints. Most of the constraints have been defined in chapter 3 (see section 3.7.4). In addition to those constraints, the following constraints must be considered:

Number of units to be unloaded $\quad Uc = \sum_{i=0}^{n} \sum_{j=1}^{m} Uc\ (i,j) = 16000$ TEU. $\qquad$ (Equation 5.1)

$(i \in n, j \in m)$;

i; Number of units/row n = 0,1,2,3 ….. n and j number of rows to be unloaded j= 1,2,3……m

Number of units to be loaded $\quad lc = \sum_{\beta=0}^{s} \sum_{\gamma=1}^{g} lc\ (\beta,\gamma) = 16000$ TEU. $\qquad$ (Equation 5.2)

$$(\beta \in s, \gamma \in g)$$

β; Number of units/row, $\beta = 0,1,2,3……$ s and γ; number of rows to be loaded $\gamma = 1,2,3…..$ g

5.5.4 Configuration of GA using GANetXL

As mentioned earlier in this chapter, the GA is a multi-objective optimization. To configure the multi objective GA optimization using GANetXL software, several steps must be implemented:

1- Select the type of optimization (single or multi objective);

2- Select the sized of the solution population. In this optimization problem, the population size is selected to be 600 solutions. Steps 1 and 2 are shown in Figure 5-8.

Table 5- 2: GA parameters

Single cycling unloading					Double cycling					Single cycling loading			
Resources productivity		Resources hourly costs			Resources productivity		Resources hourly costs			Resources productivity		Resources hourly costs	
a1	55.33 TEU/QC	W1	63.88 $/hr/QC		a2	110.9 TEU/Pair QCs	2W1	127.8 $/hr/Pair QCs		a3	68.03 $/QCs	W1	63.88 $/hr/QC
b1	61.38 TEU/YC	W2	10.13 $/hr/YC		b2	113.1 TEU/Pair YCs	2W2	20.26 $/Pair YCs		b3	53.59	W2	10.13 $/hr/YC
c1	12.83 TEU/YT	W3	6.75 $/hr/YT		C2	17.84 TEU/YT	W3	6.75 $/hr/YT		c3	13.82 TEU/YT	W3	6.75 $/hr/YT

Table 5- 3: GA variables and objectives

GA optimization Variables									Objective functions										
Single cycling Unloading			Double cycling			Single cycling Loading			Single cycling Unloading		Double cycling		Single cycling Loading		Total task			
									Max	Min	Max	Min	Max	Min	Min	Min	Max	Min
X1	Y1	Z1	X2	Y2	Z2	X3	Y3	Z3	A1 TEU/hr	B1 $/TEU	A2 TEU/hr	B2 $/TEU	A3 TEU/hr	B3 $/TEU	T total hr	C total $	Productivity TEU/hr	Unit Cost $/TEU
2	6	3	1	2	2	3	24	4	76.98	3.23	35.68	6.37	204.09	2.41	805.18	186726.468	39.742	5.835

120
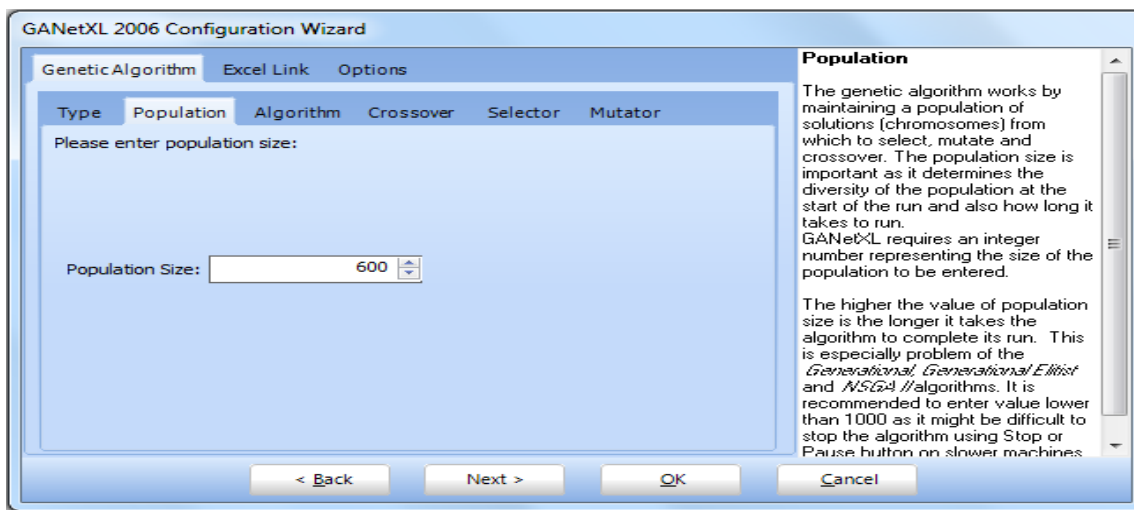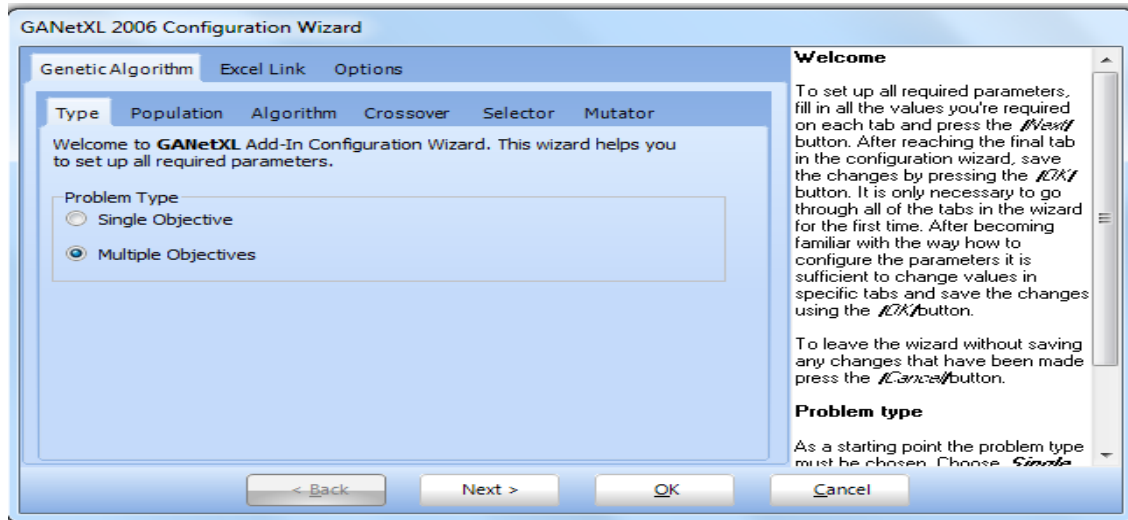
Figure 5- 8: GA configuration (steps 1and 2)

3- Assign a uniform random crossover rate (here it is 95%); and

4- Define the mutation rate, which is defined to be 5%. Figure 5-9 describes steps 3 and 4.
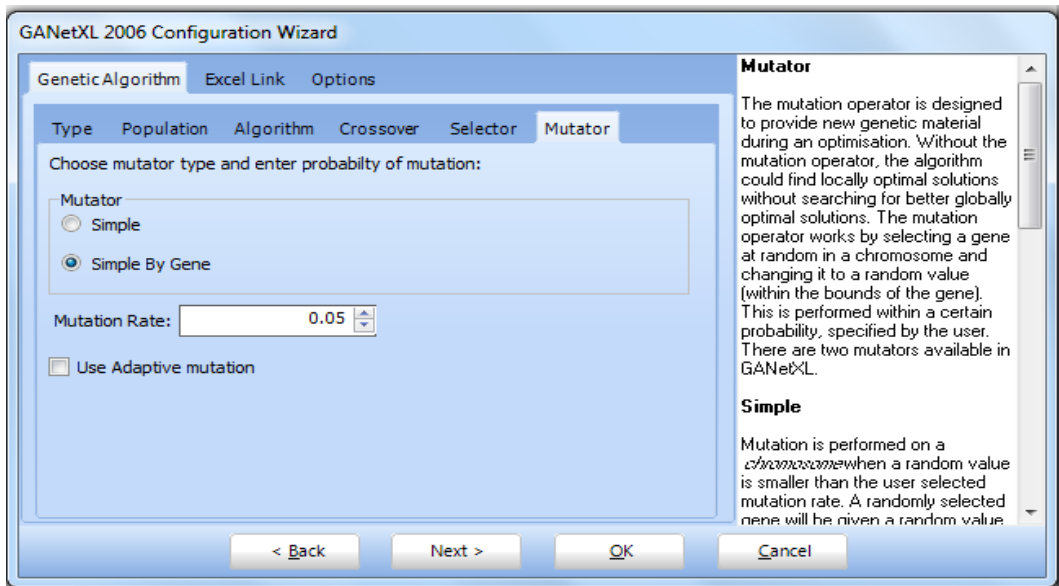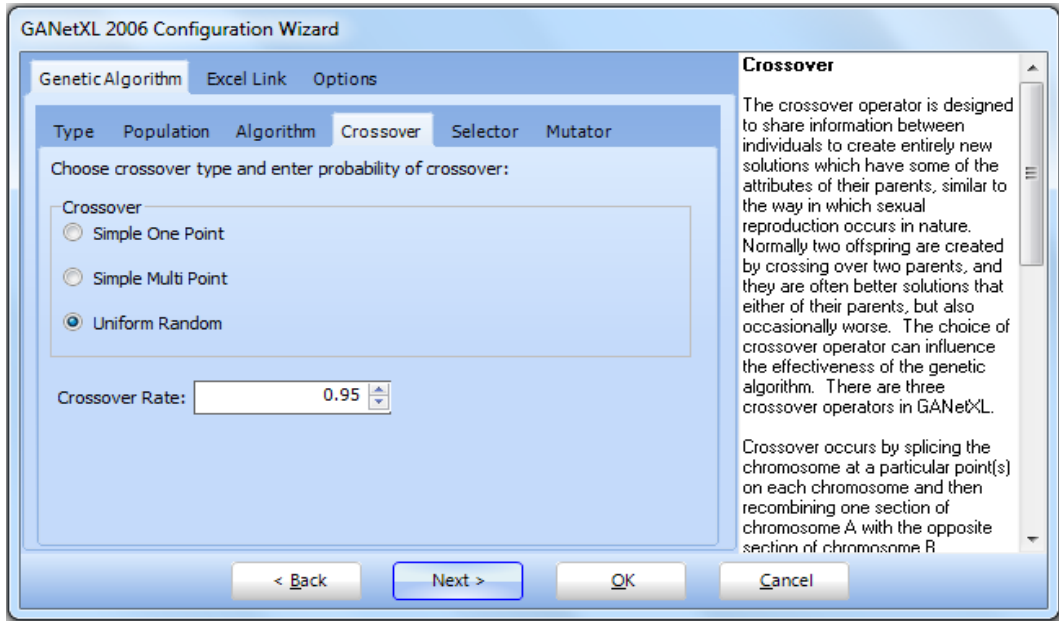
Figure 5- 9: GA configuration (steps 3 and 4)

5.5.5 GA excel sheet linking

By linking to the excel sheet, all the objective functions, the variable functions and the constraints are defined as functions in the excel cells where the variables represented in the selected cells and their boundaries (upper and lower) are defined in the software. The cells represent the assigned objective functions, which have to be defined if they are to be maximized

or minimized. If there are any constraints, they must be assigned excel cells in the software to be considered. For some examples, see Figure 5-10.
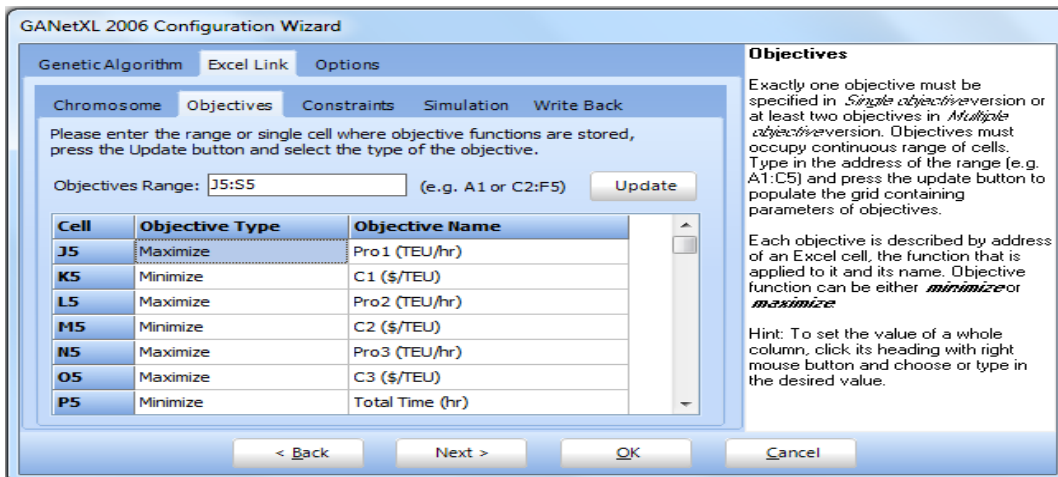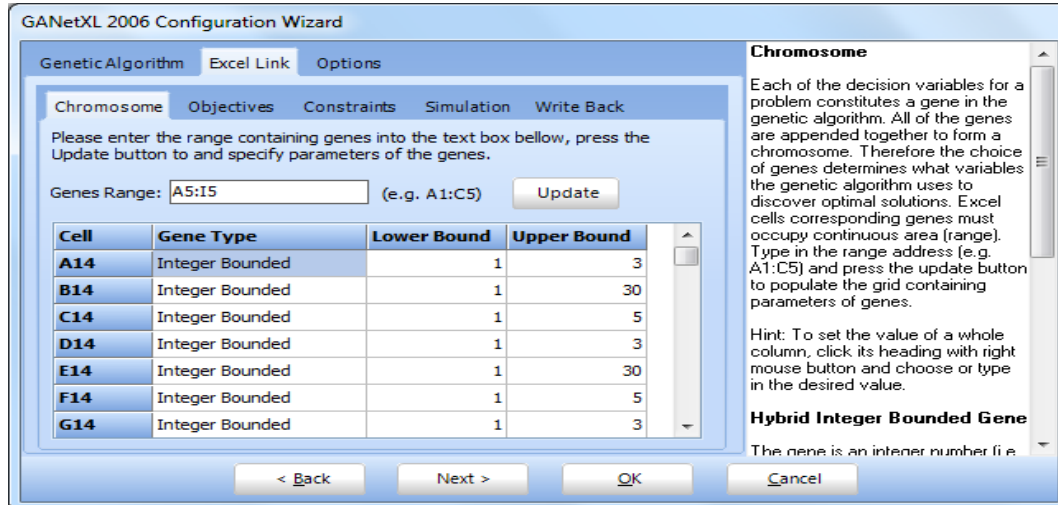
Figure 5- 10: GA configuration, excel sheet linking

Any other options such as the number of runs, the number of generations and the display of the charts can be assigned according to the user requirements(see Figure 5- 11 for two examples).
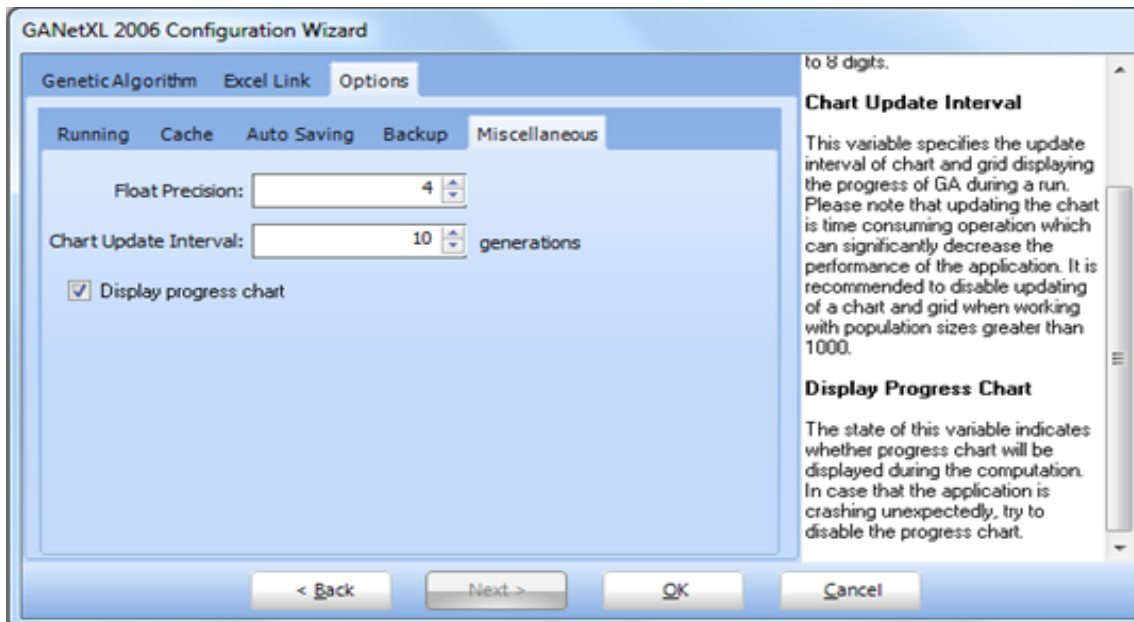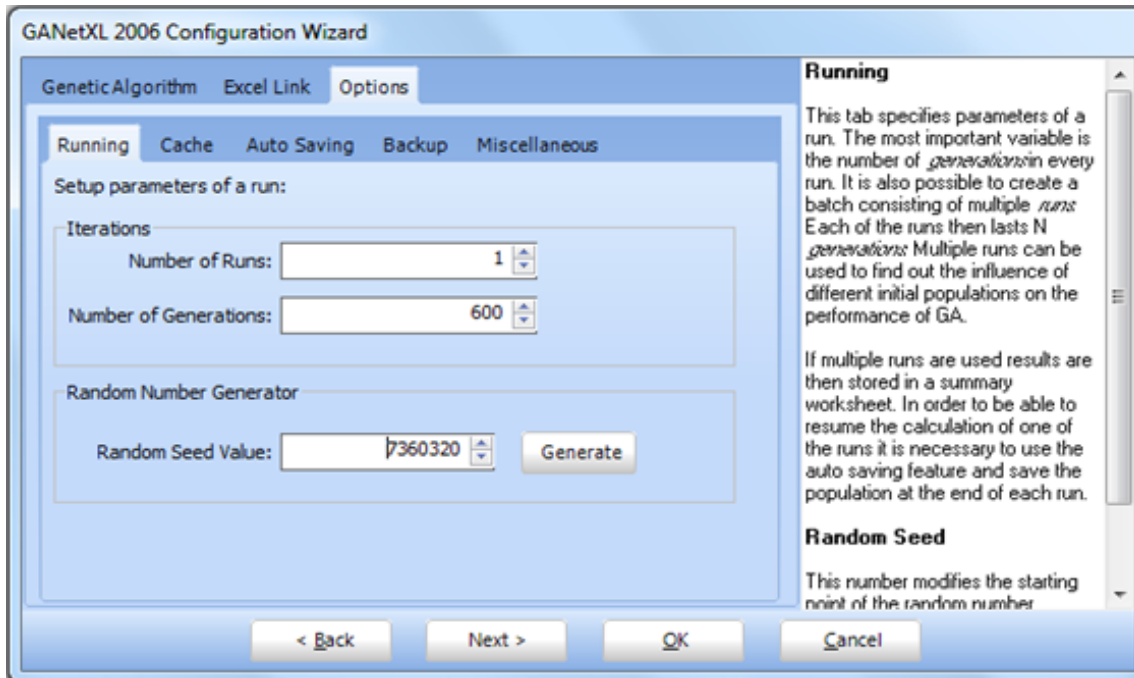
Figure 5- 11: GA configuration, options

5.5.6 GA results

The GA is employed and feasible solutions are tabulated. Each feasible solution is considered as

a chromosome. The numbers of resources in each chromosome are treated as genes. As in any

multi-objective optimization, more than one solution could be considered to be a near-optimum. For instance, some alternatives are near-optimum for productivity and thus the task time, but further from the optimum in costs and vice versa. In conclusion, it is difficult to select the overall nearest-optimum solution without some support from another method or tool. To solve this problem, several approaches are utilized to simplify the conflict or diminish the complexity in order to define the best alternative.

Table 5- 4 represents the GANetXl results where:

ID is the chromosome identification number that represents the individual alternative or solution;

G0, G1, …….., G6 are the genes in each chromosome and represent the number of resources;

G0, G1, G2 are the number of QCs, YTs and YCs used to unload containers in the first activity (YT single cycling unloading);

G2, G3, and G4 are the number of pairs of QCs, YTs and YCs used to load and unload containers in the second activity (YT double cycling);

G5, G6 and G7 are the number of QCs, YTs and YCs used to unload containers in the third/ last activity (YT single cycling loading);

Pro 1, Pro2 and Pro 3 represent the fleet productivity in each activity mentioned earlier as A1, A_2 and A_3; and

Unit cost 1, 2 and 3represent each activity unit cost, mentioned earlier as B_1, B_2 and B_3.

The results are then ranked in order with the largest productivity first, which insures that the minimum vessel turnaround time is the first result that is feasible. Even though it is the manager who chooses the best alternative according to the organisation's perspective, it is still not easy to decide which chromosome or alternative is to be selected. More work is needed to be able to

select the best alternative. The next section contains of some approaches implemented for selection support. These approaches are implemented on a set of 20 chromosomes or alternatives from alternatives A to T. These alternatives are ordered in productivity criterion order with the higher productivity firs. For GA set alternatives details see Table 5- 6.

5.6 Best alternative selection

In this section, three different approaches are employed to identify the best solution: Pareto frontier, TOPSIS, cost index or decision index, utilized with EZStrobe simulation.

5.6.1 Pareto frontier

The first approach is to invest the Pareto chart provided by the GANetXl software. Figure 5-12 show the results in Pareto frontier. Unfortunately, the feasible solutions are close to each other and it is difficult to decide which alternative is the best. For example, in Figure 5- 12, the maximum productivity alternative, of (296.37 TEU/hr), has the lowest time with 107.9 hours but it does not offer the minimum unit cost. Meanwhile another alternative has the minimum unit cost at 2.16 \$/TEU, and total cost, but a lower productivity rate of 281 TEU/hr and a longer the time to deliver the job, at about 113 hours compared to the other alternatives. In this case, if the manager's has the authorization to make a decision, it can be made so as to achieve the highest-priority aims. For example, a manager may need to finish the task early regardless of the cost, and so selects the most productive alternative, while if time is not an issue, then inevitably, the costs merit more attention. Therefore, Pareto alone is not sufficient to determine the preference alternative without priorities, which invites us to investigate other approaches.

Table 5- 4: 1600 TEU vessel GA result sample ordered higher productivity first (16000 TEUs vessel)

ID	G0	G1	G2	G3	G4	G5	G6	G7	G8	Pro1 (TEU/hr)	Unit cost 1 ($/TEU)	Pro2 (TEU/hr)	Unit cost 2 ($/TEU)	Pro3 (TEU/hr)	Unit cost 3 ($/TEU)	Total time (hr)	Total Cost ($)	Productivity total (TEU/hr)	Unit cost average ($/TEU)
251202	3	30	5	3	30	5	3	30	5	165.990	3.349	332.700	2.581	204.090	2.724	107.974	84789	296.369	2.650
360770	3	14	5	3	30	5	3	14	5	165.990	2.536	332.700	2.581	193.424	2.177	108.622	81522	294.600	2.548
351227	3	12	4	3	29	5	3	27	4	153.960	2.542	332.700	2.556	204.090	2.538	109.103	81716	293.300	2.554
450978	3	22	5	3	20	3	3	13	5	165.990	2.943	332.700	2.175	179.608	2.297	109.576	71748	292.033	2.242
322627	3	11	3	3	26	4	3	23	4	141.130	2.624	332.700	2.404	204.090	2.373	110.520	77375	289.539	2.418
594609	3	11	4	3	21	4	3	14	4	141.130	2.714	332.700	2.277	193.424	2.111	111.169	73513	287.850	2.297
386183	3	20	4	3	23	5	3	11	4	165.990	2.765	332.700	2.404	151.976	2.520	112.006	78068	285.699	2.440
333347	3	12	4	3	19	3	3	23	3	153.960	2.542	332.700	2.150	160.770	2.933	112.272	71625	285.022	2.238
575511	3	10	5	3	30	5	3	14	5	128.300	3.018	332.700	2.581	193.424	2.177	112.869	82679	283.513	2.584
253649	3	24	2	3	24	4	3	26	4	122.760	3.807	332.700	2.353	204.090	2.497	113.065	79132	283.023	2.473
490939	3	16	5	3	21	4	3	10	3	165.990	2.638	332.700	2.277	138.160	2.620	113.585	74551	281.727	2.330
296285	3	14	3	3	19	3	2	10	3	165.990	2.383	332.700	2.150	136.060	2.073	113.853	69179	281.063	2.162
394764	3	9	2	3	26	5	3	19	4	115.470	2.951	332.700	2.480	204.090	2.207	114.299	79834	279.966	2.495
317135	3	22	2	3	20	3	3	13	5	122.760	3.670	332.700	2.175	179.608	2.297	114.668	73493	279.066	2.297
549337	2	27	5	3	25	3	3	30	4	110.660	4.074	332.700	2.302	204.090	2.662	115.203	78788	277.771	2.462
532089	3	25	4	3	20	3	2	9	4	165.990	3.019	332.700	2.175	124.344	2.302	115.515	71944	277.020	2.248
590558	3	25	2	3	21	4	3	24	3	122.760	3.876	332.700	2.277	160.770	2.986	116.234	78402	275.307	2.450
578845	3	8	5	3	24	5	3	19	4	102.640	3.608	332.700	2.429	204.090	2.207	116.898	80030	273.744	2.501
291653	3	9	3	3	19	3	3	18	3	115.470	3.061	332.700	2.150	160.770	2.671	117.468	72240	272.414	2.258
608453	3	10	4	3	23	5	2	19	4	128.300	2.919	332.700	2.404	136.060	2.724	118.101	78928	270.955	2.467

Table 5- 5: 16000 TEU vessel GA set of twenty best alternatives selected (16000 TEUs vessel)

ID	G0	G1	G2	G3	G4	G5	G6	G7	G8	Pro1 (TEU/hr)	Unit cost 1 ($/TEU)	Pro2 (TEU/hr)	Unit cost 2 ($/TEU)	Pro3 (TEU/hr)	Unit cost 3 ($/TEU)	Total time (hr)	Total Cost ($)	Productivity total (TEU/hr)	Unit cost average ($/TEU)
A	3	30	5	3	30	5	3	30	5	165.990	3.349	332.700	2.581	204.090	2.724	107.974	84789	296.369	2.650
B	3	14	5	3	30	5	3	14	5	165.990	2.536	332.700	2.581	193.424	2.177	108.622	81522	294.600	2.548
C	3	12	4	3	29	5	3	27	4	153.960	2.542	332.700	2.556	204.090	2.538	109.103	81716	293.300	2.554
D	3	22	5	3	20	3	3	13	5	165.990	2.943	332.700	2.175	179.608	2.297	109.576	71748	292.033	2.242
E	3	11	3	3	26	4	3	23	4	141.130	2.624	332.700	2.404	204.090	2.373	110.520	77375	289.539	2.418
F	3	11	4	3	21	4	3	14	4	141.130	2.714	332.700	2.277	193.424	2.111	111.169	73513	287.850	2.297
G	3	20	4	3	23	5	3	11	4	165.990	2.765	332.700	2.404	151.976	2.520	112.006	78068	285.699	2.440
H	3	12	4	3	19	3	3	23	3	153.960	2.542	332.700	2.150	160.770	2.933	112.272	71625	285.022	2.238
I	3	10	5	3	30	5	3	14	5	128.300	3.018	332.700	2.581	193.424	2.177	112.869	82679	283.513	2.584
J	3	24	2	3	24	4	3	26	4	122.760	3.807	332.700	2.353	204.090	2.497	113.065	79132	283.023	2.473
K	3	16	5	3	21	4	3	10	3	165.990	2.638	332.700	2.277	138.160	2.620	113.585	74551	281.727	2.330
L	3	14	3	3	19	3	2	10	3	165.990	2.383	332.700	2.150	136.060	2.073	113.853	69179	281.063	2.162
M	3	9	2	3	26	5	3	19	4	115.470	2.951	332.700	2.480	204.090	2.207	114.299	79834	279.966	2.495
N	3	22	2	3	20	3	3	13	5	122.760	3.670	332.700	2.175	179.608	2.297	114.668	73493	279.066	2.297
O	2	27	5	3	25	3	3	30	4	110.660	4.074	332.700	2.302	204.090	2.662	115.203	78788	277.771	2.462
P	3	25	4	3	20	3	2	9	4	165.990	3.019	332.700	2.175	124.344	2.302	115.515	71944	277.020	2.248
Q	3	25	2	3	21	4	3	24	3	122.760	3.876	332.700	2.277	160.770	2.986	116.234	78402	275.307	2.450
R	3	8	5	3	24	5	3	19	4	102.640	3.608	332.700	2.429	204.090	2.207	116.898	80030	273.744	2.501
S	3	9	3	3	19	3	3	18	3	115.470	3.061	332.700	2.150	160.770	2.671	117.468	72240	272.414	2.258
T	3	10	4	3	23	5	2	19	4	128.300	2.919	332.700	2.404	136.060	2.724	118.101	78928	270.955	2.467

Figure 5- 12: Pareto frontier sample results (16000 TEUs vessel)

5.6.2 TOPSIS

As mentioned above, ranking the alternatives in productivity order makes it possible to monitor the set of best solutions. It is obvious that the best set alternatives are from A to T in alphabetical order. Subsequent alternatives offer no improvement or have less productivity and more unit cost than the selected alternative set. The TOPSIS approach is implemented on a set of alternative in two scenarios.

Table 5- 6: TOPSIS first scenario results (16000 TEUs vessel)

ID	$C_i^a = [S_i^b / (S_i^b + S_i^a)]$	Ranking
A	0.307	18
B	0.369	13
C	0.352	15
D	0.834	1
E	0.516	9
F	0.712	4
G	0.456	10
H	0.777	3
I	0.224	20
J	0.382	11
K	0.614	8
L	0.792	2
M	0.324	17
N	0.643	6
O	0.366	14
P	0.685	5
Q	0.374	12
R	0.279	19
S	0.635	7
T	0.329	16

a- First scenario

In this scenario, only two criteria (average productivity and average unit cost) were selected and were fairly equal weights of 50% each. The alternative (B) was the furthest from the NOS and would be considered the winning alternative. These TOPSIS scenario results are shown in Table 5- 7.

b- Second scenario

The targeted criteria in the second scenario are structured to include all eight objectives. These objectives are considered as the main criteria that affect the choice of the near optimum solutions.

Table 5- 7: TOPSIS second scenario results (16000 TEUs vessel)

ID	$C_i^a = [S_i^b /(S_i^b + S_i^a)]$	Ranking
A	0.420	15
B	0.524	11
C	0.500	12
D	0.799	1
E	0.605	7
F	0.735	3
G	0.534	10
H	0.695	4
I	0.401	16
J	0.433	14
K	0.611	6
L	0.739	2
M	0.457	13
N	0.577	8
O	0.396	17
P	0.631	5
Q	0.353	20
R	0.387	18
S	0.573	9
T	0.374	19

Different weights are distributed among the criteria in a way that agrees with the author's opinion. Alternative (B) was ranked the nearest to the POS and considered the winner. To more fully inform the decision, other approaches are implemented on the set of best solutions. Table 5-8 shows the results of the second scenario of TOPSIS approach.

5.6.3 Cost and decision index

A decision index approach was implemented on the set of twenty top-ranked productivity-ordered alternatives from A to T. According to the results, alternative (D) was ranked with the lowest index, which can win in the competition for the best alternative. Table 5-9 shows the results.

Table 5- 8: Cost index results

ID	Average Productivity (TEU/hr)	Average unit cos ($/TEU	cost index	Decision index	Ranking
A	296.369	2.650	0.009	1.162	17
B	294.600	2.548	0.009	1.124	11
C	293.300	2.554	0.009	1.132	12
D	292.033	2.242	0.008	0.998	1
E	289.539	2.418	0.008	1.086	9
F	287.850	2.297	0.008	1.038	4
G	285.699	2.440	0.009	1.110	10
H	285.022	2.238	0.008	1.021	3
I	283.513	2.584	0.009	1.185	19
J	283.023	2.473	0.009	1.136	13
K	281.727	2.330	0.008	1.075	7
L	281.063	2.162	0.008	1	2
M	279.966	2.495	0.009	1.159	16
N	279.066	2.297	0.008	1.070	6
O	277.771	2.462	0.009	1.152	14
P	277.020	2.248	0.008	1.055	5
Q	275.307	2.450	0.009	1.157	15
R	273.744	2.501	0.009	1.188	20
S	272.414	2.258	0.008	1.077	8
T	270.955	2.467	0.009	1.183	18

5.6.4 EZStrobe simulation tool

To save time, an EZStrobe simulation was applied to a set of four solutions ranked the highest from both the TOPSIS and Cost index results. Using the genes (G0, G1, G2,……G8) of each of the selected alternatives, and data collected and analysed from the r terminal (resources' cycle times), the EZStrobe simulation is re-run and the results of the simulation are summarised in Table 5-10. Alternative (L) ranked the best solution.

Table 5- 9: EZStrobe Simulation results (16000 TEUs vessel)

Alternative	Total time	Total cost	Productivity	Unit cost	Rank
D	112.9	89332.13	283.416	2.792	**2**
F	118.84	90021.3	269.268	2.813	**4**
H	118.36	90157.18	270.34	2.817	**3**
L	118.36	84664.45	270.351	2.645	**1**

5.7 Alternative ranking and final decision selection

After carrying out the above simulations, a summary table ranking the best alternatives in each approach was created and is presented in table 5-11. It is obvious that alternative (D) is the winner in three approaches, which allow it to be the selected alternative. The fleet size of this solution is distributed over the three activities as shown in Table 5-6This crew or fleet size is able to deliver the best performance, with the following results:

Vessel turnaround time reduced to 109.57 hours;

The unit cost reduced to 2.24 $/ TEU; and

The terminal productivity increased to 292.03 TEU/hr.

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It is also able to maximize the productivity of single cycle unloading up to 165 TEU/hr, of double cycling up to 332 TEU/hr and of YT single cycle loading up to 179 TEU/hr, while minimizing the unit cost of single cycle unloading activity down to 2.9 $/TEU, of double cycling down to 2.17 $/TEU and of single cycle loading to 2.3 $/TEU when 6 QCs are available.

Table 5- 10: Selected approaches: comparative and ranking (for a 16000 TEU vessel)

Approach	Pareto frontier	TOPSIS scenario 1	TOPSIS Scenario 2	Cost decision index	EZStrobe simulation	Final rank
D	-	1	1	1	2	1
F	-	4	3	4	4	4
H	-	3	4	3	3	3
L	-	2	2	2	1	2

The same procedure is implemented in other two QC-availability scenarios (for 4and 2 QCs available). The results are summarized in Table 5-12.

5.8 GA using stochastic productivity values

Stochastic productivity is randomly determined using probability distributions that are statistically analyzed but are not always accurate predictors. The parameters are taken from the case study data analysis in chapter 4. The resources' productivities in each activity considered the mean (μ) and its standard deviation (σ) (see Table 4-14).

The GA algorithm and its procedure is implemented again, here on the productivities' stochastic values instead of the productivities' deterministic values; or the mean values of the resources' productivities.

The results reveal more productive alternatives (in terms of fleet size) and better values of unit costs compared to the deterministic productivity values. A sample of the best alternatives is shown in Table 5-13 for a scenario with 6 QCs available and vessel capacity of 16000 TEUs.

The results show that more than one output productivity value of time and unit cost can be generated from the same fleet solution (chromosome). For instance, solutions B, C, I, O, P and T have the same crew but different results. The same conflicting results occur with group solutions (A, K and N) and (D, L and R). This situation makes selecting the best solution more complicated. All of the results are true because of the probability distribution of resource productivity. Even though it is more optimistic to adapt the stochastic productivity results, only the deterministic productivity is considered in the verification and calibration of the developed strategy, the models and algorithms. The verification and calibration are discussed in the next chapter and will show the benefits and the improvement achieved by replacing YT single cycling with double cycling.

The same procedure has been implemented on 12000 TEU-capacity vessels. The model outputs are summarized in the following tables in the same order as for the previous procedure, which includes the results, ranking, selecting approaches and final-decision selected alternative. These tables are labeled as: Table 5-14 to Table 5-12 and Figure 5-13. For more details, please see the appendix.

Table 5- 11: GA best alternative solutions according to QC availability and deterministic productivity values (16000 TEU vessel)

QCs Availability	Fleet size									performance									
	Single cycling Unloading			Double cycling			Single cycling Loading			Single cycling Unloading		Double cycling		Single cycling Loading		Total task			
										Max	Min	Max	Min	Max	Min	Min	Min	Max	Min
	QCs	YTs	YCs	Pairs QCs	YTs	Pairs YCS	QCs	YTs	YCs	A1 TEU/hr	B1 $/TEU	A2 TEU/hr	B2 $/TEU	A3 TEU/hr	B3 $/TEU	T total hr	C total $	Productivity TEU/hr	Unit Cost $/TEU
6 QCs	3	22	5	3	20	3	3	13	5	165.990	2.943	332.700	2.175	179.608	2.297	109.576	71748	292.033	2.242
4 QCs	2	9	2	2	13	2	2	13	3	110.66	2.358	221.8	2.1628	136.06	2.259	161.960	69909	197.579	2.184
2 QCs	1	5	1	1	7	1	1	5	2	55.33	2.434	110.9	2.200	68.03	2.166	323.920	70904	98.789	2.215

Table 5- 12: GA results using stochastic productivity values for 6 QCs availability and 12000 TEUs vessel capacity

ID	G0	G1	G2	G3	G4	G5	G6	G7	G8	Pro1 (TEU/hr)	Unit cost 1 ($/TEU)	Pro2 (TEU/hr)	Unit cost 2 ($/TEU)	Pro3 (TEU/hr)	Unit cost 3 ($/TEU)	Total time (hr)	Total Cost ($)	Productivity total (TEU/hr)	Unit cost average ($/TEU)
A	3	18	5	3	24	5	3	24	3	205.71	2.21	459.99	1.76	221.04	2.17	79.38	46855	302.35	1.95
B	3	25	5	3	25	5	3	25	3	209.92	2.45	401.11	2.04	229.41	2.13	82.17	51587	292.07	2.15
C	3	25	5	3	25	5	3	25	3	227.70	2.26	402.60	2.03	206.32	2.37	82.68	51742	290.29	2.16
D	3	21	5	3	20	4	3	21	3	183.53	2.62	445.95	1.68	206.00	2.21	85.24	48215	281.57	2.01
E	3	18	3	3	22	4	3	20	3	189.17	2.27	457.22	1.68	192.37	2.32	85.49	46898	280.75	1.95
F	3	17	5	3	23	4	3	21	3	209.53	2.13	433.70	1.79	181.66	2.50	85.93	48587	279.28	2.02
G	3	23	4	3	20	4	3	22	3	233.85	2.07	386.33	1.94	186.35	2.49	86.24	50198	278.30	2.09
H	3	17	5	3	23	5	3	17	3	193.12	2.31	392.95	2.04	217.13	1.94	86.42	49812	277.70	2.08
I	3	25	5	3	25	5	3	25	3	219.69	2.34	406.43	2.01	179.74	2.72	87.10	53825	275.54	2.24
J	3	21	3	3	20	4	3	22	3	179.32	2.54	424.80	1.76	203.95	2.27	87.66	49232	273.77	2.05
K	3	18	5	3	24	5	3	24	3	206.68	2.20	396.70	2.04	188.61	2.54	88.03	52515	272.62	2.19
L	3	21	5	3	20	4	3	21	3	196.35	2.44	394.87	1.90	195.76	2.32	88.52	50785	271.14	2.12
M	3	25	5	3	25	5	3	25	3	193.05	2.66	457.94	1.78	165.58	2.95	89.41	53839	268.43	2.24
N	3	18	5	3	24	5	3	24	3	187.33	2.43	437.12	1.85	176.89	2.71	89.55	52166	268.00	2.17
O	3	25	5	3	25	5	3	25	3	216.63	2.37	438.49	1.86	154.26	3.17	90.04	54488	266.56	2.27
P	3	25	5	3	25	5	3	25	3	199.77	2.57	429.00	1.90	166.23	2.94	90.29	54881	265.82	2.29
Q	3	19	5	3	20	3	3	17	3	225.37	2.05	321.58	2.25	208.74	2.02	90.88	51695	264.09	2.15
R	3	21	5	3	20	4	3	21	3	233.15	2.06	377.53	1.98	162.42	2.80	91.37	52427	262.66	2.18
S	3	22	5	3	24	4	3	24	3	247.46	1.97	390.78	2.00	149.25	3.22	91.78	54469	261.49	2.27
T	3	25	5	3	25	5	3	25	3	187.68	2.74	453.97	1.80	158.68	3.08	91.88	55148	261.21	2.30

Table 5- 13: GA result sample ordered higher productivity first (12000 TEU vessel)

ID	G0	G1	G2	G3	G4	G5	G6	G7	G8	Pro1 (TEU/hr)	Unit cost 1 ($/TEU)	Pro2 (TEU/hr)	Unit cost 2 ($/TEU)	Pro3 (TEU/hr)	Unit cost 3 ($/TEU)	Total time (hr)	Total Cost ($)	Productivity total (TEU/hr)	Unit cost average ($/TEU)
1374623	3	13	3	3	21	3	3	15	4	165.99	2.33	332.70	2.20	204.09	2.04	98.66	52674	243.24	2.19
1283820	3	16	3	3	18	4	3	22	4	165.99	2.48	321.15	2.28	204.09	2.33	100.09	56105	239.77	2.33
1247482	3	15	5	3	21	5	3	14	4	165.99	2.58	332.70	2.35	193.42	2.11	100.12	56429	239.69	2.35
1222384	3	12	4	3	21	5	3	28	5	153.96	2.54	332.70	2.35	204.09	2.64	101.20	59053	237.13	2.46
1123565	3	17	5	3	18	3	3	14	4	165.99	2.68	321.15	2.20	193.42	2.11	101.55	54972	236.33	2.29
1161760	3	15	3	3	25	3	3	13	4	165.99	2.43	332.70	2.30	179.60	2.226	102.27	55558	234.66	2.31
1291549	3	12	3	3	18	3	3	18	4	153.96	2.46	321.15	2.20	204.09	2.166	102.63	54036	233.84	2.25
1321351	3	17	5	3	17	3	3	14	5	165.99	2.68	303.31	2.30	193.42	2.177	103.96	56668	230.83	2.36
1367840	3	11	3	3	30	3	3	19	4	141.13	2.62	332.70	2.42	204.09	2.207	104.39	58153	229.89	2.42
1122788	3	27	3	3	25	3	3	12	4	165.99	3.04	332.70	2.30	165.79	2.361	104.77	59579	229.05	2.48
1133589	3	21	3	3	16	4	3	16	4	165.99	2.73	285.47	2.50	204.09	2.083	105.23	59120	228.07	2.46
1088567	3	19	3	3	19	3	3	19	3	165.99	2.63	332.70	2.15	160.77	2.723	105.79	57331	226.85	2.38
1379157	3	15	3	3	17	4	3	13	4	165.99	2.43	303.31	2.38	179.60	2.226	106.11	56667	226.16	2.36
1219935	3	13	4	3	16	4	3	14	4	165.99	2.40	285.47	2.50	193.42	2.111	106.68	57485	224.95	2.39
1171109	3	17	3	3	18	4	3	15	3	165.99	2.53	321.15	2.28	160.77	2.514	107.22	57363	223.83	2.39
1178361	3	17	3	3	24	3	3	11	3	165.99	2.53	332.70	2.27	151.97	2.437	107.73	56909	222.76	2.37
1220890	3	21	3	3	17	4	3	12	4	165.99	2.73	303.31	2.38	165.79	2.361	108.62	59041	220.94	2.46
1382531	3	15	3	3	18	3	3	11	5	165.99	2.43	321.15	2.20	151.97	2.604	109.16	56259	219.85	2.34
1132615	3	18	3	3	17	3	3	17	3	165.99	2.58	303.31	2.30	160.77	2.618	109.64	58505	218.89	2.43
1109864	3	22	2	3	21	3	3	15	5	122.76	3.67	332.70	2.20	204.090	2.104	110.12	60229	217.93	2.51

Table 5- 14: GA set of twenty best alternative selected (12000 TEU vessel)

ID	G0	G1	G2	G3	G4	G5	G6	G7	G8	Pro1 (TEU/hr)	Unit cost 1 ($/TEU)	Pro2 (TEU/hr)	Unit cost 2 ($/TEU)	Pro3 (TEU/hr)	Unit cost 3 ($/TEU)	Total time (hr)	Total Cost ($)	Productivity total (TEU/hr)	Unit cost average ($/TEU)
A	3	13	3	3	21	3	3	15	4	165.990	2.333	332.700	2.201	204.090	2.042	98.666	52674	243.244	2.195
B	3	16	3	3	18	4	3	22	4	165.990	2.485	321.156	2.280	204.090	2.331	100.093	56105	239.778	2.338
C	3	15	5	3	21	5	3	14	4	165.990	2.587	332.700	2.353	193.424	2.111	100.125	56429	239.699	2.351
D	3	12	4	3	21	5	3	28	5	153.960	2.542	332.700	2.353	204.090	2.642	101.208	59053	237.135	2.461
E	3	17	5	3	18	3	3	14	4	165.990	2.688	321.156	2.201	193.424	2.111	101.552	54972	236.333	2.291
F	3	15	3	3	25	3	3	13	4	165.990	2.434	332.700	2.302	179.608	2.226	102.273	55558	234.666	2.315
G	3	12	3	3	18	3	3	18	4	153.960	2.460	321.156	2.201	204.090	2.166	102.634	54036	233.840	2.252
H	3	17	5	3	17	3	3	14	5	165.990	2.688	303.314	2.303	193.424	2.177	103.969	56668	230.837	2.361
I	3	11	3	3	30	3	3	19	4	141.130	2.624	332.700	2.429	204.090	2.207	104.397	58153	229.892	2.423
J	3	27	3	3	25	3	3	12	4	165.990	3.044	332.700	2.302	165.792	2.361	104.778	59579	229.055	2.482
K	3	21	3	3	16	4	3	16	4	165.990	2.739	285.472	2.506	204.090	2.083	105.230	59120	228.071	2.463
L	3	19	3	3	19	3	3	19	3	165.990	2.638	332.700	2.150	160.770	2.723	105.796	57331	226.852	2.389
M	3	15	3	3	17	4	3	13	4	165.990	2.434	303.314	2.386	179.608	2.226	106.117	56667	226.166	2.361
N	3	13	4	3	16	4	3	14	4	165.990	2.409	285.472	2.506	193.424	2.111	106.689	57485	224.952	2.395
O	3	17	3	3	18	4	3	15	3	165.990	2.536	321.156	2.280	160.770	2.514	107.222	57363	223.835	2.390
P	3	17	3	3	24	3	3	11	3	165.990	2.536	332.700	2.277	151.976	2.437	107.739	56909	222.760	2.371
Q	3	21	3	3	17	4	3	12	4	165.990	2.739	303.314	2.386	165.792	2.361	108.622	59041	220.949	2.460
R	3	15	3	3	18	3	3	11	5	165.990	2.434	321.156	2.201	151.976	2.604	109.166	56259	219.850	2.344
S	3	18	3	3	17	3	3	17	3	165.990	2.587	303.314	2.303	160.770	2.618	109.640	58505	218.899	2.438
T	3	22	2	3	21	3	3	15	5	122.760	3.670	332.700	2.201	204.090	2.104	110.123	60229	217.939	2.510
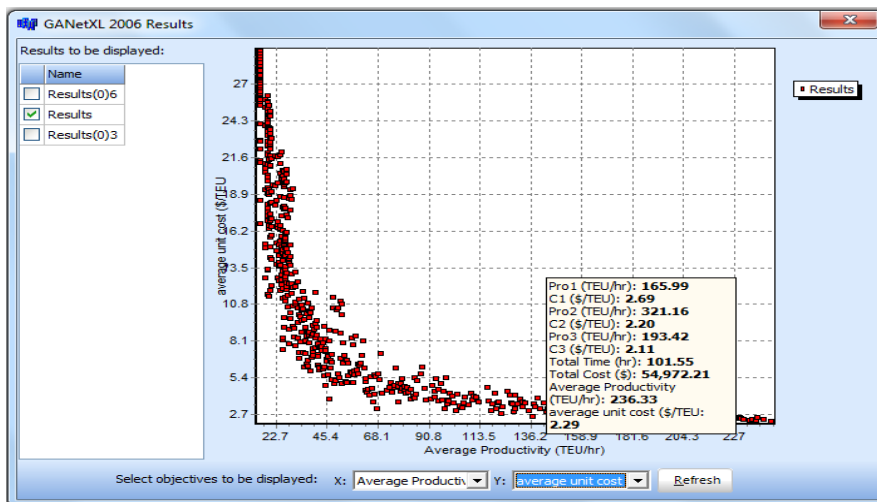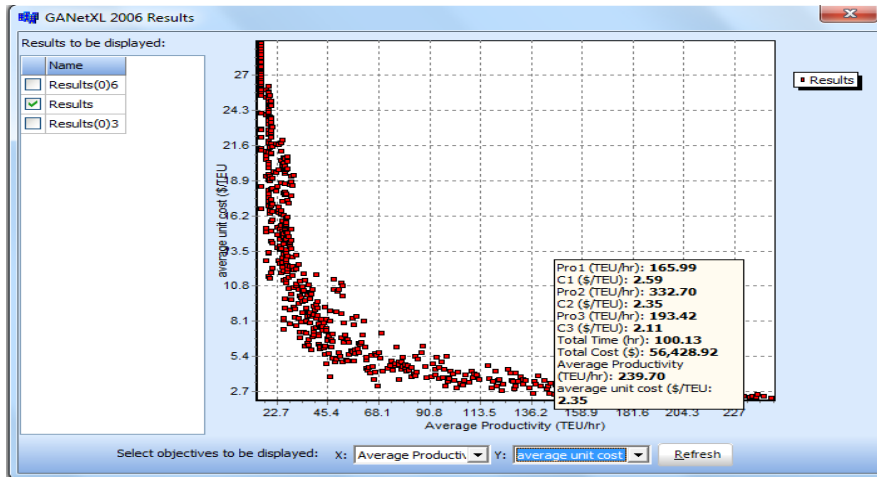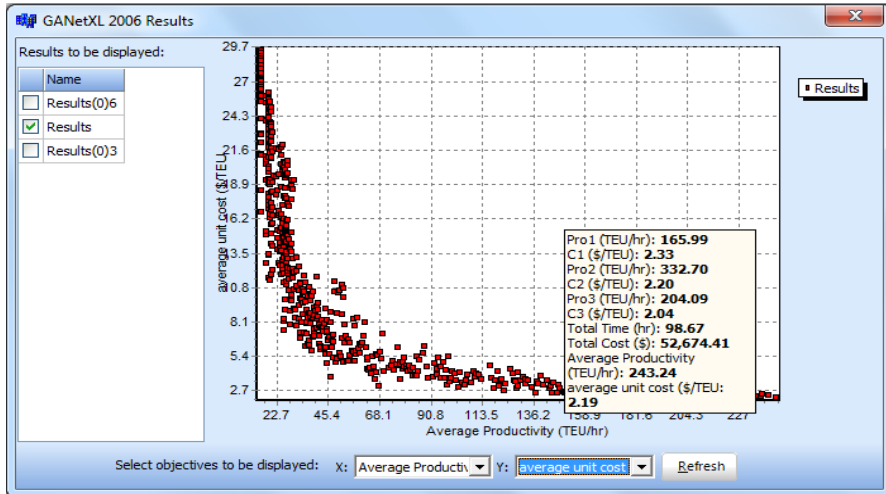
Figure 5- 13: Pareto Frontier simple results (12000 TEUs vessel)

Table 5- 15 : TOPSIS first scenario results (12000 TEU vessel)

ID	$C_i^a = [S_i^b / (S_i^b + S_i^a)]$	Ranking
A	1	1
B	0.65865	4
C	0.631867	6
D	0.428862	8
E	0.708349	3
F	0.63556	5
G	0.73065	2
H	0.487147	7
I	0.361545	12
J	0.268305	17
K	0.26952	16
L	0.370815	10
M	0.41325	9
N	0.329256	14
O	0.323457	15
P	0.347436	13
Q	0.142553	18
R	0.368805	11
S	0.17136	10
T	0	20

Table 5- 16: TOPSIS second scenario results (12000 TEU vessel)

ID	$C_i^a = [S_i^b / (S_i^b + S_i^a)]$	Ranking
A	0.964657	1
B	0.717618	4
C	0.696264	6
D	0.542146	8
E	0.748575	3
F	0.700432	5
G	0.774054	2
H	0.582522	7
I	0.520718	10
J	0.427194	17
K	0.445016	16
L	0.512759	11
M	0.537571	9
N	0.489715	14
O	0.484421	15
P	0.500376	12

Q	0.373439	19
R	0.497472	13
S	0.389235	18
T	0.344157	20

Table 5- 17: Cost index results (12000 TEU vessel)

ID	Average Productivity (TEU/hr)	Average unit cos ($/TEU	cost index	Decision index	Ranking
A	243.244	2.195	0.00902	1.0000	1
B	239.778	2.338	0.00975	1.0805	4
C	239.699	2.351	0.00981	1.0871	5
D	237.135	2.461	0.0103	1.1500	8
E	236.333	2.291	0.00969	1.0741	3
F	234.666	2.315	0.00986	1.0933	6
G	233.840	2.252	0.00963	1.0671	2
H	230.837	2.361	0.01023	1.1336	7
I	229.892	2.423	0.01054	1.1681	11
J	229.055	2.482	0.01084	1.2011	17
K	228.071	2.463	0.01080	1.1970	16
L	226.852	2.389	0.01053	1.1671	10
M	226.166	2.361	0.01044	1.1570	9
N	224.952	2.395	0.01065	1.1801	13
O	223.835	2.390	0.01068	1.1834	15
P	222.760	2.371	0.01064	1.1797	12
Q	220.949	2.460	0.01113	1.2340	18
R	219.850	2.344	0.01066	1.1817	14
S	218.899	2.438	0.01114	1.2342	19
T	217.939	2.510	0.01151	1.2762	20

Table 5- 18: EZStrobe Simulation results (12000 TEU vessels)

Alternative	Total time	Total cost	Productivity	Unit cost	Rank
A	101.93	75640	235.45	3.16	3
B	101.47	77760	236.51	3.24	4
E	101.47	75600	236.5	3.15	2
G	102.07	73440	235.13	3.06	1

Table 5- 19: Selecting approaches comparison and ranking (12000 TEU vessels)

Approach	Pareto frontier	TOPSIS scenario 1	TOPSIS Scenario 2	Cost decision index	EZStrobesimulation	Final rank
A	1	1	1	1	3	1
B	-	4	4	4	4	4
E	-	3	3	3	2	3
G	-	2	2	2	1	2

5.9 GA Visual Basic for Applications

The optimization problem was solved using the Excel Visual Basic for Applications (VBA). A macro coding for the GA process was applied using visual basic language. The problem is solved and coded using the same inputs, variables, upper and lower variables boundaries, constrains and objective functions as were used in the GANetXL. A population size of 1024 was selected to be tested. The designed problem and its upper and lower boundaries are shown in Table 5-22. The solutions were then generated by clicking on the solve button that appears on the Excel page. Some examples are presented in Figure 5-14. The software will show all of the possible solutions and the operator can rank these solutions according to the maximum productivity or minimum unit cost. The solutions are then selected in the same way as when using the GANetXL software. A sample of the best solutions can be found in Table 5- 23. The nearest-optimum solution provides a vessel turnaround time of about 108 hours and near-optimum productivity of 296 TEU/hr. The code utilized to for solve the problem using VBA Excel is presented next.

Table 5- 20: GA best alternative solutions according to QCs availability and deterministic productivity values (12000 TEU vessel)

QCs Availability	Fleet size									performance									
	Single cycling Unloading			Double cycling			Single cycling Loading			Single cycling Unloading		Double cycling		Single cycling Loading		Total task			
										Max	Min	Max	Min	Max	Min	Min	Min	Max	Min
	QCs	YTs	YCs	Pairs QCs	YTs	Pairs YCS	QCs	YTs	YCs	A1 TEU/hr	B1 $/TEU	A2 TEU/hr	B2 $/TEU	A3 TEU/hr	B3 $/TEU	T total hr	C total $	Productivity TEU/hr	Unit Cost $/TEU
6 QCs	3	13	3	3	21	3	3	15	4	165.99	2.332	332.7	2.200	204.09	2.042	98.66	52674	243.244	2.194
4 QCs	2	9	3	2	13	2	2	10	3	110.66	2.47	221.8	2.162	136.06	2.073	134.7	52698	178.127	2.195
2 QCs	1	5	1	1	7	1	1	5	2	55.33	2.43	110.9	2.200	68.03	2.166	242.9	53178	98.789	2.215

Table 5- 21: GA-designed problem using VBA Excel software for 6 QCs availability and 16000 TEUs vessel capacity

QCs Availability	Fleet size									performance									
	Single cycling Unloading			Double cycling			Single cycling Loading			Single cycling Unloading		Double cycling		Single cycling Loading		Total task			
										Max	Min	Max	Min	Max	Min	Min	Min	Max	Min
	QCs	YTs	YCs	Pairs QCs	YTs	Pairs YCS	QCs	YTs	YCs	A1 TEU/hr	B1 $/TEU	A2 TEU/hr	B2 $/TEU	A3 TEU/hr	B3 $/TEU	T total hr	C total $	Productivity TEU/hr	Unit Cost $/TEU
Max.	3	30	5	3	30	5	3	30	5	165.99	3.35	332.70	2.58	204.09	2.72	107.97	83586	243.24	3.48
Min.	1	1	1	1	1	1	1	1	1	12.83	7.87	17.84	10.84	13.82	7.31	1885.27	281318	15.47	11.72

Top parameter block:

U1	55.33	U2	110.9	U3	68.03
k1	61.38	k2	113.1	k3	53.59
j1	12.83	j2	17.842	j3	13.816
S1	63.875	S1	127.75	S1	63.875
g1	10.125	g2	20.26	g2	10.125
f3	6.75	f2	6.75	f3	6.75

T6 = 107.97

Solve (button)

Main data table:

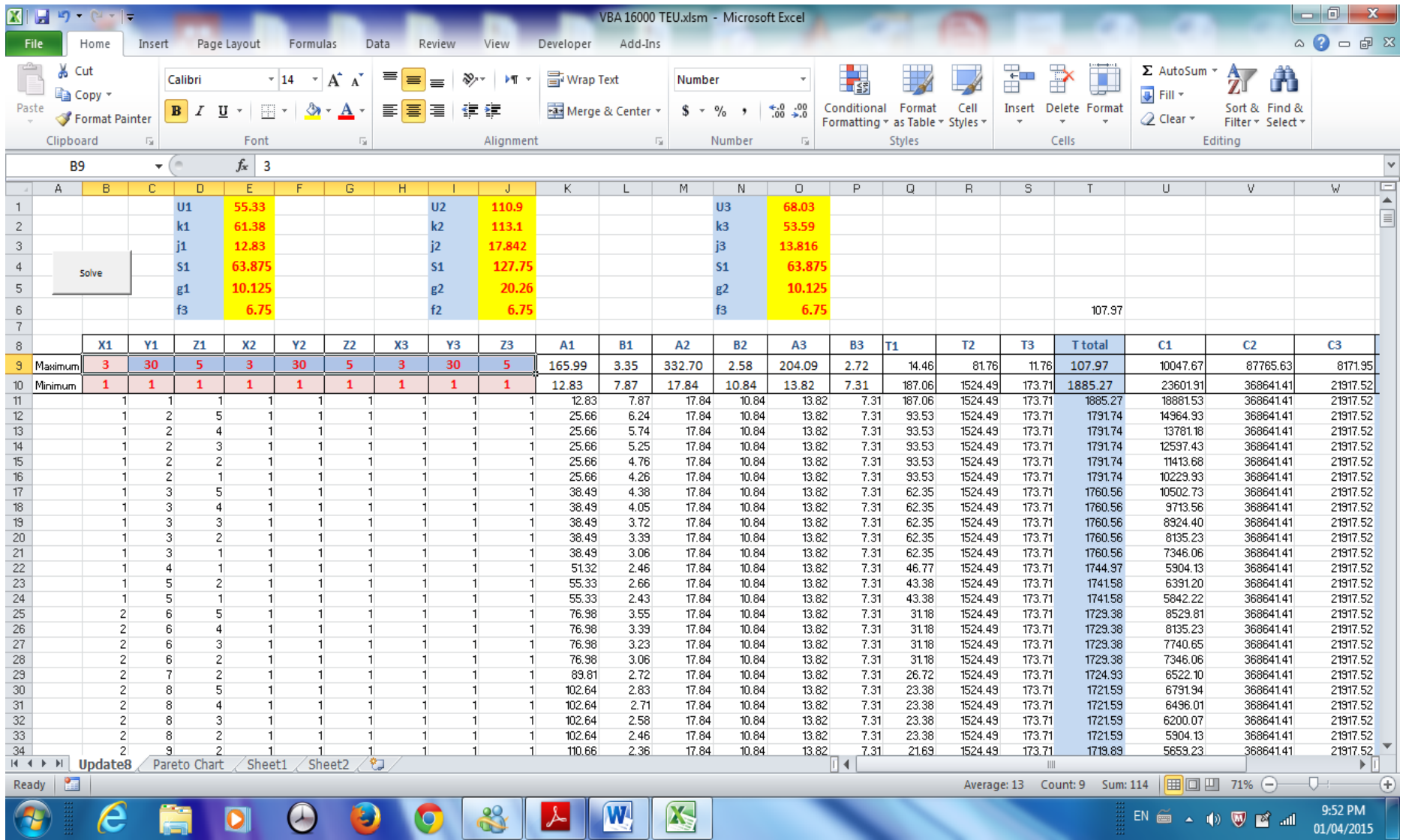|	X1	Y1	Z1	X2	Y2	Z2	X3	Y3	Z3	A1	B1	A2	B2	A3	B3	T1	T2	T3	T total	C1	C2	C3
Maximum	3	30	5	3	30	5	3	30	5	165.99	3.35	332.70	2.58	204.09	2.72	14.46	81.76	11.76	107.97	10047.67	87765.63	8171.95
Minimum	1	1	1	1	1	1	1	1	1	12.83	7.87	17.84	10.84	13.82	7.31	187.06	1524.49	173.71	1885.27	23601.91	368641.41	21917.52
	1	1	1	1	1	1	1	1	1	12.83	7.87	17.84	10.84	13.82	7.31	187.06	1524.49	173.71	1885.27	18881.53	368641.41	21917.52
	1	2	5	1	1	1	1	1	1	25.66	6.24	17.84	10.84	13.82	7.31	93.53	1524.49	173.71	1791.74	14964.93	368641.41	21917.52
	1	2	4	1	1	1	1	1	1	25.66	5.74	17.84	10.84	13.82	7.31	93.53	1524.49	173.71	1791.74	13781.18	368641.41	21917.52
	1	2	3	1	1	1	1	1	1	25.66	5.25	17.84	10.84	13.82	7.31	93.53	1524.49	173.71	1791.74	12597.43	368641.41	21917.52
	1	2	2	1	1	1	1	1	1	25.66	4.76	17.84	10.84	13.82	7.31	93.53	1524.49	173.71	1791.74	11413.68	368641.41	21917.52
	1	2	1	1	1	1	1	1	1	25.66	4.26	17.84	10.84	13.82	7.31	93.53	1524.49	173.71	1791.74	10229.93	368641.41	21917.52
	1	3	5	1	1	1	1	1	1	38.49	4.38	17.84	10.84	13.82	7.31	62.35	1524.49	173.71	1760.56	10502.73	368641.41	21917.52
	1	3	4	1	1	1	1	1	1	38.49	4.05	17.84	10.84	13.82	7.31	62.35	1524.49	173.71	1760.56	9713.56	368641.41	21917.52
	1	3	3	1	1	1	1	1	1	38.49	3.72	17.84	10.84	13.82	7.31	62.35	1524.49	173.71	1760.56	8924.40	368641.41	21917.52
	1	3	2	1	1	1	1	1	1	38.49	3.39	17.84	10.84	13.82	7.31	62.35	1524.49	173.71	1760.56	8135.23	368641.41	21917.52
	1	3	1	1	1	1	1	1	1	38.49	3.06	17.84	10.84	13.82	7.31	62.35	1524.49	173.71	1760.56	7346.06	368641.41	21917.52
	1	4	1	1	1	1	1	1	1	51.32	2.46	17.84	10.84	13.82	7.31	46.77	1524.49	173.71	1744.97	5904.13	368641.41	21917.52
	1	5	2	1	1	1	1	1	1	55.33	2.66	17.84	10.84	13.82	7.31	43.38	1524.49	173.71	1741.58	6391.20	368641.41	21917.52
	1	5	1	1	1	1	1	1	1	55.33	2.43	17.84	10.84	13.82	7.31	43.38	1524.49	173.71	1741.58	5842.22	368641.41	21917.52
	2	6	5	1	1	1	1	1	1	76.98	3.55	17.84	10.84	13.82	7.31	31.18	1524.49	173.71	1729.38	8529.81	368641.41	21917.52
	2	6	4	1	1	1	1	1	1	76.98	3.39	17.84	10.84	13.82	7.31	31.18	1524.49	173.71	1729.38	8135.23	368641.41	21917.52
	2	6	3	1	1	1	1	1	1	76.98	3.23	17.84	10.84	13.82	7.31	31.18	1524.49	173.71	1729.38	7740.65	368641.41	21917.52
	2	6	2	1	1	1	1	1	1	76.98	3.06	17.84	10.84	13.82	7.31	31.18	1524.49	173.71	1729.38	7346.06	368641.41	21917.52
	2	7	2	1	1	1	1	1	1	89.81	2.72	17.84	10.84	13.82	7.31	26.72	1524.49	173.71	1724.93	6522.10	368641.41	21917.52
	2	8	5	1	1	1	1	1	1	102.64	2.83	17.84	10.84	13.82	7.31	23.38	1524.49	173.71	1721.59	6791.94	368641.41	21917.52
	2	8	4	1	1	1	1	1	1	102.64	2.71	17.84	10.84	13.82	7.31	23.38	1524.49	173.71	1721.59	6496.01	368641.41	21917.52
	2	8	3	1	1	1	1	1	1	102.64	2.58	17.84	10.84	13.82	7.31	23.38	1524.49	173.71	1721.59	6200.07	368641.41	21917.52
	2	8	2	1	1	1	1	1	1	102.64	2.46	17.84	10.84	13.82	7.31	23.38	1524.49	173.71	1721.59	5904.13	368641.41	21917.52
	2	9	2	1	1	1	1	1	1	110.66	2.36	17.84	10.84	13.82	7.31	21.69	1524.49	173.71	1719.89	5659.23	368641.41	21917.52

Sheet tabs: Update8 / Pareto Chart / Sheet1 / Sheet2

Figure 5- 14: VBA optimization screen shot

Table 5- 22: GA sample results using VBA Excel software for 6 QCs availability and 16000 TEUs vessel capacity

QCs Availability	Fleet size									performance									
	Single cycling Unloading			Double cycling			Single cycling Loading			Single cycling Unloading		Double cycling		Single cycling Loading		Total task			
										Max	Min	Max	Min	Max	Min	Min	Min	Max	Min
	QCs	YTs	YCs	Pairs QCs	YTs	Pairs YCS	QCs	YTs	YCs	A1 TEU/hr	B1 $/TEU	A2 TEU/hr	B2 $/TEU	A3 TEU/hr	B3 $/TEU	T total hr	C total $	Productivity TEU/hr	Unit Cost $/TEU
1	3	30	5	3	30	5	3	30	5	165.99	3.35	332.70	2.58	204.09	2.72	107.97	105985.2	296.37	3.312
2	3	13	3	3	19	3	3	30	4	165.99	2.33	332.70	2.15	204.09	2.66	107.97	70470.63	296.37	2.202
3	3	13	3	3	19	3	3	29	4	165.99	2.33	332.70	2.15	204.09	2.62	107.97	70371.41	296.37	2.199
4	3	13	3	3	19	3	3	28	4	165.99	2.33	332.70	2.15	204.09	2.58	107.97	70272.19	296.37	2.196
4	3	13	3	3	19	3	3	27	4	165.99	2.33	332.70	2.15	204.09	2.54	107.97	70172.97	296.37	2.193
6	3	13	3	3	19	3	3	26	4	165.99	2.33	332.70	2.15	204.09	2.50	107.97	70073.75	296.37	2.190
7	3	13	3	3	19	3	3	25	4	165.99	2.33	332.70	2.15	204.09	2.46	107.97	69974.53	296.37	2.187
8	3	13	3	3	19	3	3	24	4	165.99	2.33	332.70	2.15	204.09	2.41	107.97	69875.31	296.37	2.184
9	3	13	3	3	19	3	3	23	4	165.99	2.33	332.70	2.15	204.09	2.37	107.97	69776.09	296.37	2.181
10	3	13	3	3	19	3	3	22	4	165.99	2.33	332.70	2.15	204.09	2.33	107.97	69676.87	296.37	2.177
11	3	13	3	3	19	3	3	21	4	165.99	2.33	332.70	2.15	204.09	2.29	107.97	69577.64	296.37	2.174
12	3	13	3	3	19	3	3	20	4	165.99	2.33	332.70	2.15	204.09	2.25	107.97	69478.42	296.37	2.171
13	3	13	3	3	19	3	3	19	4	165.99	2.33	332.70	2.15	204.09	2.21	107.97	69379.20	296.37	2.168
14	3	13	3	3	19	3	3	18	4	165.99	2.33	332.70	2.15	204.09	2.17	107.97	69279.98	296.37	2.165
15	3	13	3	3	19	3	3	17	4	165.99	2.33	332.70	2.15	204.09	2.12	107.97	69180.76	296.37	2.162
16	3	13	3	3	19	3	3	16	4	165.99	2.33	332.70	2.15	204.09	2.08	107.97	69081.54	296.37	2.159
17	3	13	3	3	19	3	3	15	4	165.99	2.33	332.70	2.15	204.09	2.04	107.97	68982.32	296.37	2.156
18	1	1	5	3	30	1	3	30	5	12.83	11.81	113.10	6.70	204.09	2.72	107.97	70619.46	296.37	2.207

5. 9.1 VBA Excel coding

As introduced earlier in section 5.4, VBA code is Excel-based software-designed to solve non-linear problems. To build the algorithm, the parameters and the objective functions are located in the Excel cells then the constraints are defined as upper boundaries, termed maximums, and lower boundaries termed minimums. According to the written code, the software will solve the problem by testing all of the probable solutions according to the pre-defined population. A special thank you is extended to Mr. Mohammad Kbeili for helping the author in writing this code. A sample of the code is represented on this page, and the rest of the code can be found in Appendix X.

```vba
1.  Sub FindSolution()
2.  ' This code aims to solve a Non-Linear programming problem.
3.
4.  ' Definte variables. Lastrow: stores the value of the last row, b: binary value used to
      determine for loop direction and step
5.  ' l,m,n,o: Variables used in Looping between values
6.  Dim Lastrow, b, i, l, m, n, o As Integer
7.
8.  ' Define Variables. Obj: Stores the temporary objective function values. Sol: Stores th
      e current optimal solution
9.  ' u,j,k,s,g,f: Store problem parameters, Min/Max: Store the lowest and highest bounds o
      f each variable
10. Dim Obj(23), Sol(23), u(3), j(3), k(3), s(3), g(3), f(3) As Double
11. Dim Min(), max() As Variant
12.
13. ' Turn off automatic formulat recalculation in the spreadsheet (To improve processing s
      peed)
14. Application.Calculation = xlCalculationManual
15.
16. ' Turn off screen updating (To improve processing speed)
17. Application.ScreenUpdating = False
18.
19. ' Clear all cells below row (11) to make room for new answer
20. With Rows(11 & ":" & Rows.Count).Delete
21. End With
22.
23. ' Identify last row with data in the spreadsheet
24. Lastrow = ActiveSheet.Range("B" & Rows.Count).End(xlUp).Row + 1
25.
26. ' Store all minimum variable values (constraints) into array
27. Min = Range("B10:X10")
28. ' Store all maximum variable values (constraints) into array
```

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5.10 Summary

This chapter detailed the implementations of the simulation model and the GA multi-objective optimization based on the developed strategy. The simulation model was applied on a theoretical case study, and a sensitivity analysis using that simulation was then applied to that theoretical case study. The simulation shows that the model contributes to a powerful analysis and has the ability to solve the problem. A GA multi-objective optimization was applied to a real case study via two different software applications (SolveXL in its GANetXL version and VBA Excel). The GANetXL solver was applied using both deterministic and stochastic productivity data. A conflict in selecting the nearest-optimum solution using multi-objective optimization was identified. Several approaches were employed to assist in making the best decision in selecting the nearest-optimum solution. The best solutions were then assigned and the fleet size or crew that most improves the container terminal was defined. This optimum crew will minimize vessel turnaround time with the most reasonable cost and near optimum-productivity.

Chapter 6: Benefits, Verification and Calibration

6.1 Benefits of using YT double cycling strategy

It is clear that there are many advantages to be gained by replacing YT single cycling by double cycling. These benefits can be realised by comparing the two strategies' productivity improvement, measured in terms of time saving, cost saving and resource deployment and scheduling (see Table 6- 1). These benefits are summarized in the following seven points:

1- Productivity improvements

The proposed strategy shows productivity improvements of between 89 and 243 TEUs/hr when using YT double cycling, while productivity ranges between 61 and 178 TEUs/hr when using single cycling. The range of productivity improvement depends on the QC availability for vessels of 12000 TEUs, and it is more pronounced for larger vessels.

2- Vessel turnaround time reduction of more than 33% in most cases.

3- Unit cost savings of a maximum of 10%, regardless of the cost savings resulting from time reduction.

4- Another financial benefit is the saving of vessel idle time. From the perspective of shipping companies and based on her study of (Notteboom 2004); Goodchild states that "*Intercontinental freight rates are estimated at $.045 per TEU-km. At this rate, each hour of idle vessel time costs the ship operator $10,000*" (Goodchild & Daganzo 2005).

5- As the double cycling improves the costs, the benefits listed above are improved even more if the number of double cycles is maximized.

6- The number of cycles of YTs is decreased compared to those of the YT single cycle, where YT empty journeys are minimized.

7- Some resources can be scheduled for another job when not needed. For instance, some YTs are not needed when using single cycle loading and unloading. This also applies to the number of QCs and YCs.

6.2 Model Verification and Calibration

QC productivity is one of the methods to measure container terminal productivity, unit and its unit of measurement are the number of TEUs/hr or Lifts/hr. Another method is the vessel turnaround time; the time a vessel spends at berth to fully exchange its targeted containers. This is equal to the summation of time the QCs take to discharge and load the vessel. The relation between vessel turnaround time and QC productivity is expressed in Table 6- 2, Bartošek & Marek (2013) and in Table 6- 3(Jordan 2002). The tables built on the variables and coefficients according to Bartošek & Marek data and imperical calculations. Bartošek & Marek data includes the follwoing:

1- Post-Panamax QCs can produce 1.75 TEU per lift;

2- All terminals are able to produce from 70% to 80% of the maximum computed productivity;

3- There is a loss of QC productivity that must be considered;

4- Transhipment vessels (large vessels) can be served by 6-8 QCs; and

5- Feeders (smaller vessels) can be served by only 1-2 QCs.

Table 6- 1: YT double cycling improvements compared to single cycling(12000 TEUs vessel capacity)

YT double cycling strategy

QCs Availability	Fleet size									performance									
	Single cycling Unloading			Double cycling			Single cycling Loading			Single cycling Unloading		Double cycling		Single cycling Loading		Total task			
										Max	Min	Max	Min	Max	Min	Min	Min	Max	Min
	QCs	YTs	YCs	Pairs QCs	YTs	Pairs YCS	QCs	YTs	YCs	A1 TEU/hr	B1 $/TEU	A2 TEU/hr	B2 $/TEU	A3 TEU/hr	B3 $/TEU	T total hr	C total $	Productivity TEU/hr	Unit Cost $/TEU
6 QCs	3	13	3	3	21	3	3	15	4	165.99	2.33	332.7	2.200	204.09	2.04	98.66	52674	243.24	2.19
4 QCs	2	9	3	2	13	2	2	10	3	110.66	2.47	221.8	2.162	136.06	2.07	134.7	52698	178.12	2.19
2 QCs	1	5	1	1	7	1	1	5	2	55.33	2.43	110.9	2.200	68.03	2.16	242.9	53178	98.78	2.21

YT single cycling strategy

QCs Availability	Fleet size									performance									
	Single cycling Unloading			Double cycling			Single cycling Loading			Single cycling Unloading		Double cycling		Single cycling Loading		Total task			
										Max	Min	Max	Min	Max	Min	Min	Min	Max	Min
	QCs	YTs	YCs	Pairs QCs	YTs	Pairs YCS	QCs	YTs	YCs	A1 TEU/hr	B1 $/TEU	A2 TEU/hr	B2 $/TEU	A3 TEU/hr	B3 $/TEU	T total hr	C total $	Productivity TEU/hr	Unit Cost $/TEU
3 QCs	3	13	3	-	-	-	3	15	4	165.99	2.33	-	-	204.09	2.04	131.0911	52495	183.07	2.18
2 QCs	2	9	2	-	-	-	2	10	3	110.66	2.35	-	-	136.06	2.07	196.63	53173	122.05	2.21
1 QC	1	5	1	-	-	-	1	5	2	55.33	2.43	-	-	68.03	2.16	393.27	55204	61.02	2.30

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Table 6- 2: Comparison of quay crane productivity (Bartošek& Marek, 2013)

Vessel size (TEU)	Lifts per hour			Cranes
	30	40	50	
	Vessel turnaround time (hours)			
8,000	69	51	41	5
10,000	71	53	43	6
12,000	86	64	51	6

Table 6- 3: Vessel Turnaround Time vs- Lifts per Hour (Jordan, 2002)

Vessel size (TEU)	6,000	8,000	10,000	12,000
Cranes	4	5	6	6
Lifts per hour	Vessel turnaround time (hours)			
20	96	103	107	129
30	64	69	71	86
40	48	51	54	64
50	39	41	43	51
60	32	34	36	43

6.2.1 Counting vessel turnaround time

To implement the theory to compute the vessel turnaround time for a vessel, the following steps can be followed:

1- Quay crane per lifts per hour = Q_l lift/hr;

2- QC productivity per lift = Qp TEU/lift;

3- QC productivity per hour= Qhp = (Q_l) * (Qp)= TEU/hr;

4- QCs productivity per vessel= nQ * Qhp;

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5- Vessel turnaround time V_{tt}= time to unload imported TEUs + time to load exported TEUs, where:

a) Time to unload imported TEUs = number of TEUs / (nQ * Qhp); and

b) Time to load exported TEUs= number of exported TEUS/ (nQ * Qhp);

Then, Vtt = (imported TEUs +exported TEUs)/ (nQ * Qhp), when unloading QCs productivity = loading QCs productivity;

6- C_g = percentage of vessel exchange containers; and

7- I_g = percentage of maximum Qhp that QCs can make

6.2.2 Example

To prove the results summarized in Table 6- 2 and Table 6- 3, the following steps and calculations based on the previous method were carried out.

In the above tables, the details required for implementation:

Vessel capacity = 12000 TEU

Vessel exchanges 75% of its containers = I_g * (12000+12000)

Units to be exchanged = 24000*0.75= 18000 TEU.   (Equation 6.1)

Q_l = 30 lifts/hr

Qp= 1.75 TEU/lif

QhP= 30* 1.75=52.5 TEU/hr.   (Equation 6.2)

Gross Qhp = I_g * Qhp= 0.7 * 52.5 = 36.75 TEU/hr/QC.   (Equation 6.3)

Number of QCs =6 cranes

V_{tt}= 18000/(6*36.75)= 81.63.   (Equation 6.4)

Adding 5% to the total time to adjust for QC productivity loss (such as delays, moves between rows etc…),

Adjusted turnaround time = 81.63* 1.05= 85.71 hours ~ 86 hours

For QCs to achieve 40 lifts/hr:

Adjusted turnaround time = [(24000*0.75)/(40*1.75*0.7*6)]* 1.05

$$= 64.2 \text{ hours.} \hspace{3cm} \text{(Equation 6.5)}$$

For QCs to achieve 50 lifts/hr

Adjusted turnaround time = [(24000*0.75)/(50*1.75*0.7*6)]* 1.05

$$= 51.4 \text{ hours.} \hspace{3cm} \text{(Equation 6.6)}$$

Table 6- 4 shows how Bartošek (2013) and Jordan (2002) summarized and calculated the vessel turnaround times.

6.3 Vessel turnaround time Verification and Calibration

Now, we are able to verify and calibrate our work using the previous theory to calculate the vessel turnaround time and compare it with the simulation- optimization model results.

This research applies the developed strategy on two vessel capacity types: large vessels of 12000 TEUs and mega vessels with 16000 TEU capacity.

Since we are not able to use more than 3 pairs of QCs to serve a vessel, we recalculate the target vessel turnaround time by replacing the 6QCs by 3QCs.

The QCs will be distributed on the vessel as; 3 QCs to discharge and 3 QCs to load the vessel. We are able to verify our work using the previous theory to theoretically calculate the vessel turnaround time and compare it with the simulation- optimization models results. The calculation procedure is given below:

Adjust for the number of QCs

Turnaround time = [(24000*0.75)/(30*1.75*0.7*3)]* 1.05 = 128.4 hours.   (Equation 6.7)

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However, the QC productivity per lift = 2 TEUs according to the case study data..

Next, adjust for QCp= 2:

Turnaround time = [(24000*0.75)/(30*2*0.7*3)]* 1.05 = 112.4 hours.   (Equation 6.8)

We can also calculate the QC lifts per hour= 27.66 lifts/hour, and so the next step is to

adjust for QC lifts per hour:

Turnaround time = [(24000*0.75)/(27.66*2*0.7*3)]* 1.05 = 121.6 hours.   (Equation 6.9)

We assume that the terminal reaches 100% of its productivity.

Table 6- 4: Calculated vessel turnaround times based on Bartošek 2013 and Jordan 2002

Vessel capacity (TEU)	TEU exchange %	QCs	QC productivity per lift (TEU/lift)	QC lifts per hour	terminal productivity %	QC productivity lose %	Vessel turn-around time (hours)
12000	75	6	1.75	20	70	5	128.57
12000	75	6	1.75	30	70	5	85.71
12000	75	6	1.75	40	70	5	64.28
12000	75	6	1.75	50	70	5	51.42
12000	75	6	1.75	60	70	5	42.85
10000	75	6	1.75	20	70	5	107.14
10000	75	6	1.75	30	70	5	71.42
10000	75	6	1.75	40	70	5	53.57
10000	75	6	1.75	50	70	5	42.85
10000	75	6	1.75	60	70	5	35.71
8000	75	5	1.75	20	70	5	102.85
8000	75	5	1.75	30	70	5	68.57
8000	75	5	1.75	40	70	5	51.42
8000	75	5	1.75	50	70	5	41.14
8000	75	5	1.75	60	70	5	34.28
6000	75	4	1.75	20	70	5	96.42
6000	75	4	1.75	30	70	5	64.28
6000	75	4	1.75	40	70	5	48.21
6000	75	4	1.75	50	70	5	38.57
6000	75	4	1.75	60	70	5	32.14

Turnaround time = [(24000*0.75)/(27.66*2*1*3)]* 1.05 = 85.11 hours.   (Equation 6.10)

And finally, we assume the exchanging of containers to be 100%; so that

Turnaround time = [(24000*1)/(27.66*2*1*3)]* 1.05 = 151.48 hours.   (Equation 6.11)

Two scenarios are deployed to verify and calibrate the models; one considers the QC lifts limit as the limit to its unloading lifts/hr (see Table 6- 5).and the other is limited to its loading lifts/hr (see Table 6- 6).

Table 6- 5: Model Verification and Calibration (QC lifts limit to its unloading lifts/hr)

Vessel capacity (TEU)	TEU exchange (%)	No. QCs	QC product. per lift (TEU/lift)	QC lifts per hour	Terminal product. (%)	QC product. lose (%)	Calculated turn-around time (hr)	Model turn-around time (hr)	Time improvement (%)
16000	100	3	2	27.66	100	5	202.46	109.576	46
16000	100	2	2	27.66	100	5	303.69	161.96	47
16000	100	1	2	27.66	100	5	607.38	323.92	45
12000	100	3	2	27.66	100	5	151.84	98.66	35
12000	100	2	2	27.66	100	5	227.77	134.7	41
12000	100	1	2	27.66	100	5	433.84	242.9	44

Table 6- 6: Model Verification and Calibration (QC lifts limit to its loading lifts/hr)

Vessel capacity (TEU)	TEU exchange (%)	No. QCs	QC product. per lift (TEU/lift)	QC lifts per hour	Terminal product. (%)	QC product. lose (%)	Calculated turn-around time (hr)	Model turn-around time (hr)	Time improvement (%)
16000	100	3	2	34.02	100	5	164.61	109.576	33
16000	100	2	2	34.02	100	5	246.91	161.96	34
16000	100	1	2	34.02	100	5	493.83	323.92	45
12000	100	3	2	34.02	100	5	123.46	98.66	20
12000	100	2	2	34.02	100	5	185.19	134.7	27
12000	100	1	2	34.02	100	5	370.37	242.9	34

6.4 Summary

This chapter verified the benefits of replacing YT single cycling by double cycling. It is clear that the use of YT double cycling improves the productivity and minimizes the cost associated with container handling by minimizing vessel turnaround time. Investing the unused resources in a predefined time is an indirect benefit that can be added to the direct benefits. For verify and calibrate of the developed strategy, simulation and optimization models were utilized, as well as the optimization algorithm. Using the vessel turnaround time and QC productivity as the results to compare is a flawed approach, because the saving on time can be achieved only by increasing productivity and optimizing the fleet size. The introduced strategy and the developed models proved that reasonable time savings can be achieved, as proved by comparisons with some previous findings and studies.

Chapter 7: Conclusion and future work

7.1Summary

This research sets forth the following main points:

Global trade is growing exponentially, especially for goods transported across the seas. This has driven the shipbuilding industry to accelerate the development of transport vessels. To keep pace with developments in the shipbuilding industry in terms of speed and capacity, container terminals must also improve their productivity.

Container terminal customers (shipping companies) believe that "**Vessels do not make money while berthing**", which means that minimizing vessel turnaround time is crucial to satisfy these customers. It is clear that improving the productivity of any container terminal's resources leads to the improvement of the other elements' productivity and of terminal productivity as a whole. QC double cycling has been introduced recently to improve container terminal productivity and minimize vessel turnaround time.

This work introduces a new strategy that implements double cycling on YTs to improve container terminal productivity. This new strategy for handling containers has been modeled, tested and verified. The simulation indicates that a reasonable improvement in maximizing productivity while minimizing hourly and unit costs can be achieved. A sensitivity analysis, performed as a part of the simulation and feasibility assessment, revealed the efficiency of the new strategy. Multi-objective optimization is part of the research focused on optimizing fleet sizes, based on the objective functions of time and cost. Gas were used as the optimization tool for implementing and verifying this handling strategy, based on the investigation to date. Some selection approaches, based on the GA results, were implemented to provide decision makers a

degree of confidence in selecting the nearest optimum solution. The results were verified based on some previous findings, revealing the effectiveness of the strategy and the efficiency of the simulation model and optimization algorithm.

7.2 Conclusion

A set of conclusions can be drawn from developing the YT double cycling in container handling, using simulation modeling and a GA optimization algorithm.

- Reducing vessel turnaround time can be achieved by improving one or more resources, factors or handling strategies in container terminals.

- Implementing YT double cycling with the conditions that two (or each pair of) QCs are linked to work together, that there is a start-up period with YT single cycling to create enough space on the vessel before switching to double cycling, and linking the functioning of two (or each pair of) YCs eliminates YT empty journeys and accelerates vessel turnaround time.

- To be able to mimic the realty of implementing YT double cycling, a simulation model was developed using EZStrobe simulation. The simulation model reveals a productivity improvement of about 38% overall and about 19% per QC. In terms of cost index (cost/productivity), savings of about 29% could be achieved by utilizing optimum alternatives in most cases.

- Based on the model's verification and comparisons with previous published findings, the optimization model indicates that YT double cycling improves the productivity and saves vessel turnaround time in a range of 26% to 38% compared to traditional YT single cycling for large vessel of 12000 TEU capacity, and this improvement will be even higher for mega vessels of 16000 TEU capacity The optimization model and algorithm

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allows terminal management to select the most effective fleet size to be assigned in each of the three activities: YT single cycle unloading start-up, YT double cycling and YT single cycle loading activities.

- Increasing the number of double cycles is key to guarantee the best results and thus the greatest improvements in container terminal productivity, vessel turnaround time and cost savings.

- Employing a multi-objective GA is worthwhile, but in some situations other supporting approaches are required to select the optimum solution. Pareto frontier, TOPSIS, and Cost Index are powerful approaches that can solve the multi-objective problem with the EZStrobe simulation tool.

- Comparisons with previous YT double cycling results how that this method can improve productivity to achieve minimum 16000 TEUs vessel turnaround times of 109.5, 161.9 and 323.9 hours, depending on QC availability, which are more than 45% shorter than previous achievements. Productivity is thus improved accordingly, achieving a minimum 12000 TEUs vessel turnaround time of 98.66-242.9 hours depending on QC availability for a time savings of about 35%-44% compared to other approaches.

- Fleet size optimization offers the opportunity to invest any un-needed resources – they can be rescheduled to do another job. This can be considered as an extra gain and benefit, one that may contribute to reducing another vessel's turnaround time and thus improving terminal productivity.

7.3 Research limitations

The research has some weaknesses and limitations which should be overcome to allow this method to be even more beneficial:

1- The research does not cover the impact of the developed strategy on other resources and areas such as YC, SY and the terminal's land side (the gate and land transportation).

2- The data was collected from only one container terminal; more data collection from other terminals is needed to make the research more reliable.

3- The cost data collected does not cover all data associated with container handling and so does not reflect an accurate overview of the benefits of the strategy and developed models.

4- In the implementation of TOPSIS approach, the parameter weights are suggested by the author's desire for fairness and reasonability. A survey or experts' questionnaire will add value to the TOPSIS results.

5- The research does not consider the SY truck road congestion and how this would affect the use of the maximum number of trucks.

6- It would be more efficient if the research could evaluate the benefits of the time savings achieved, the cost savings results from this time reduction, the percentage of the increases of containers transhipped and the benefits of early vessel departure.

7.4 Research Contribution

This research is considered to be of practical value in modeling the container handling process and in understanding the impacts of various factors on container terminal productivity in terms of time and cost. One aspect of its practicality is that the model will be able to be simulated using a simple simulation tool. The model will contribute to optimizing fleet sizes to maximize productivity and thereby minimize vessel turnaround time and the associated hourly costs. Both the simulation and its resulting optimization will provide managers and decision makers with

obvious criteria for selecting the optimal container handling method. The following are the most important research contributions:

- An improved understanding of each factors' impact on container terminal productivity;

- Replacing the single cycle strategy by double cycling to reduce vessel turnaround time by reducing the empty yard truck journeys;

- Providing decision makers in the scheduling and planning stages with a simulation of the handling container process that closely mimics reality;

- Optimizing fleet sizes to achieve the maximum productivity and lower hourly costs;

- Providing easy and effective models in both simulation and optimization to enable container terminal mangers to determine the best solutions for the most time and cost-efficient handling of containers; and

- The developed strategy will add value on global trade supply chain. The time reduction contributes to accelerate and increase the sales volume in general. Most reputable suppliers will accrue the benefits from this time reduction which will motivate suppliers to improve their productivity to meet the global trade demands.

7.5 Recommendation for future work

The research introduced a new strategy for container handling. The strategy is simulated and optimized to verify the improvements in container terminal productivity. The simulation model and the optimization algorithm are powerful enough to solve the multi-objective problem and a tangible productivity improvement is achieved. This work solves the problem but it does not cover all the needs in container terminal productivity improvement. There is room for more work

to compliment and reinforce the robustness of this strategy; some suggested research avenues are listed below:

1- This research focuses only on the sea side. To be more affective, adding the land side to this strategy with be necessary to more completely achieve the objective of this research. A container terminal is divided into three areas, the waterside, the storage yard and the gate. Two-directional transportation linking those areas is divided into two types: transportation between the waterside and the storage yard, and transportation between the gate and the storage yard. Container terminal productivity is influenced by the productivity of each area. Improving one area's productivity will impact positively on the other areas. To fully assess the optimum benefit of employing YT double cycling, the impact of the developed strategy on the other areas and the accumulated benefits in both productivity and cost savings must be evaluated.

2- This research requires more complete cost data to be collected to cover the objective cost optimization in a standard and efficient manner. The costs associated with handling containers are multiple and vary from one terminal to another, as well as from one season to another. Direct and indirect costs should be included to assist decision makers in deciding which strategy is most profitable.

3- Every type of productive work is associated with risks. Risks can impact the developed strategy depending on their type, value and indirect impacts. For instance, a resource collapse, especially of resource with limited availability, may affect to possibility of employing the YT double cycle strategy, which needs more resources to be working at a time than single cycling. Adding risk assessment and evaluation will make the research more realistic.

4- Large and mega vessels are fed by small vessels called feeders. It is more challenging to handle containers from and into feeders instead of the temporarily storing the containers in the SY. Managing the handling of containers directly from feeders to a large or mega vessel is a complicated process. If this process can be implemented, the value of the associated cost savings and time reduction is expected to be significant compared to the practice of storing the containers temporarily in a storage yard. These benefits would include:

a- No need for YCs, saving highly-skilled labour and resource costs;

b- Provides more space in SY and reduces SY costs, even reducing SY size – a major benefit to space-constrained port cities;

c- Reduces YT cycle times due to shorter distances to travel on the shore line rather than trips to the SY. This could accelerate the vessel turnaround time and cut the associated costs.

d- Containers can be delivered to customers immediately upon arrival, accelerating global trade compared to the initial storing of containers.

5- The research would be more effective if it could translate the time savings to cost savings and profits, especially for the shipping companies. It can be concluded that the time savings when using YT double cycle strategy is greater than the cost reduction. In the economic sector "Time is money". Translating the saved time into cost savings will provide a clear vision of how beneficial the developed strategy could be. Furthermore, the time reduction affects the shipping companies' profits and accelerates the global trades in general. Many other suppliers in the global trade supplier chains will gain

profits and improve their productivity as a result of this time reduction and accompanying acceleration.

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Appendix A

Table A- 1: YC discharging cycle and productivity

	lift the cont. from the YT	loaded forward move to SY	Load the Cont. on SY	Empty back word move to the YT	Total time (min)	Number of Moves/hr	Productivity TEU/hr
1	0.332	1.247	0.620	0.883	3.082	19.465	38.930
2	0.305	0.740	0.242	1.248	2.535	23.672	47.344
3	0.481	0.681	0.276	0.466	1.904	31.512	63.024
4	0.228	0.790	0.150	1.006	2.174	27.593	55.186
5	0.229	0.965	0.144	0.520	1.858	32.290	64.579
6	0.151	0.878	0.127	0.847	2.003	29.959	59.919
7	0.340	0.558	0.514	0.850	2.262	26.524	53.049
8	0.172	0.357	0.198	0.602	1.329	45.136	90.272
9	0.654	0.967	0.137	1.056	2.815	21.316	42.632
10	0.133	0.800	0.315	0.646	1.894	31.682	63.363
11	0.379	0.569	0.150	0.214	1.313	45.704	91.408
12	0.274	0.642	0.155	0.491	1.561	38.437	76.874
13	0.305	0.771	0.288	0.384	1.748	34.326	68.651
14	0.567	0.761	0.166	0.611	2.104	28.513	57.025
15	0.381	1.205	0.370	0.623	2.579	23.267	46.534
16	0.364	0.889	0.196	0.392	1.840	32.607	65.213
17	0.374	0.752	0.156	0.527	1.809	33.160	66.321
18	0.474	0.807	0.312	0.323	1.917	31.301	62.603
19	0.458	0.333	0.987	0.257	2.034	29.498	58.996

Table A- 2: YC cycle times and productivity

Cycle ID	empty forward move to the SY	Lift the container from SY	Loaded backward move to the YT	Load the container on the YT	Total cycle time (min)	Number of moves/ cycle	Productivity (TEU/hr)
1	0.92	0.25	1.30	0.22	2.70	22.2129	44.42581
2.00	0.99	0.24	0.87	0.20	2.31	26.02798	52.05596
3.00	1.34	0.12	0.82	0.30	2.59	23.19382	46.38764
4.00	1.01	0.12	0.80	0.14	2.07	29.02884	58.05768
5.00	0.93	0.16	1.25	0.74	3.08	19.50378	39.00757
6.00	1.06	0.18	1.12	0.37	2.73	21.97842	43.95683
7.00	0.63	0.29	1.24	0.20	2.37	25.31306	50.62611
8.00	0.49	0.17	0.58	0.14	1.38	43.34979	86.69957
9.00	0.46	0.15	0.55	0.21	1.36	43.98251	87.96503
10.00	0.57	0.10	0.71	0.16	1.54	38.86404	77.72809
11.00	0.98	0.17	0.80	0.27	2.21	27.09423	54.18847
12.00	0.59	0.17	0.78	0.15	1.70	35.33422	70.66843
13.00	0.75	0.15	1.03	0.19	2.12	28.30919	56.61837
14.00	0.70	0.13	0.90	0.26	1.99	30.08436	60.16872
15.00	1.81	0.12	0.65	0.13	2.71	22.12369	44.24738
16.00	0.62	0.13	0.74	0.18	1.66	36.05523	72.11045
17.00	0.71	0.22	1.67	0.19	2.79	21.51631	43.03262
18.00	0.62	0.28	1.31	0.11	2.32	25.86787	51.73574
19.00	0.69	0.12	1.72	0.11	2.64	22.71408	45.42816
20.00	0.62	0.11	1.47	0.13	2.33	25.70708	51.41416
21.00	0.88	0.17	1.58	0.13	2.76	21.76056	43.52111
22.00	1.01	0.17	1.59	0.15	2.93	20.50818	41.01637
23.00	0.49	0.11	1.70	0.12	2.41	24.8578	49.7156
24.00	0.89	0.11	1.32	0.16	2.49	24.10836	48.21672
25.00	0.90	0.13	1.11	0.12	2.26	26.54861	53.09722
26.00	0.77	0.26	1.61	0.13	2.77	21.68495	43.36989
27.00	0.74	0.13	0.92	0.13	1.92	31.25512	62.51025
28.00	1.13	0.14	1.22	0.23	2.71	22.12718	44.25436
29.00	0.43	0.12	1.06	0.13	1.74	34.50018	69.00036
30.00	1.24	0.23	1.29	0.15	2.90	20.68306	41.36613
31.00	0.60	0.13	1.64	0.18	2.55	23.54211	47.08421
32.00	1.32	0.23	1.67	0.11	3.34	17.98267	35.96534
33.00	0.88	0.17	1.06	0.16	2.27	26.48229	52.96457

Table A- 3: YT unloading cycle time and productivity

Cycle ID	Loading the truck at QC2	Loaded move from QC2-YC2	Discharge the truck at YC2	Empty back move from YC2 to QC2	Total cycle time	Number of cycles/hr	Productivity (TEU/hr)
1	0.779	2.481	0.905	2.106	6.271	9.567	19.135
2	1.926	2.062	2.288	2.416	8.693	6.902	13.805
3	1.581	2.498	0.701	1.486	6.267	9.575	19.149
4	1.181	2.301	2.032	3.389	8.904	6.739	13.478
5	1.145	2.245	1.205	3.193	7.789	7.703	15.407
6	1.197	2.753	5.588	3.318	12.856	4.667	9.334
7	1.598	3.256	0.707	3.995	9.556	6.279	12.557
8	1.453	2.653	3.032	2.252	9.391	6.389	12.779
9	4.910	3.768	0.466	2.857	12.000	5.000	10.000
10	5.381	3.245	2.446	4.029	15.100	3.973	7.947
11	1.729	2.505	0.804	5.341	10.380	5.780	11.561
12	1.807	3.536	1.639	4.619	11.601	5.172	10.344
13	1.058	2.409	3.517	3.422	10.405	5.767	11.533

Table A- 4: YT loading cycle time and productivity

	Load the YT at YC1	Loaded move to QC1	Discharge the YT at QC1	Empty` back move YC1	Total cycle time	Number of cycles/hr	Productivity (TEU/hr)
1	3.963	4.363	1.951	3.486	13.762	4.360	8.719
2	0.945	2.092	0.778	2.943	6.758	8.878	17.757
3	1.761	3.060	4.610	2.698	12.128	4.947	9.894
4	5.612	3.208	1.602	2.151	12.572	4.772	9.545
5	0.715	3.985	1.697	2.577	8.975	6.686	13.371
6	3.879	4.073	1.000	1.845	10.797	5.557	11.114
7	0.929	1.388	0.460	3.534	6.310	9.509	19.017
8	1.920	1.686	0.585	2.350	6.541	9.172	18.345
9	1.068	2.169	0.942	2.477	6.656	9.015	18.029
10	2.098	1.734	4.134	2.307	10.273	5.841	11.681
11	1.890	2.747	0.420	3.218	8.275	7.251	14.502

Table A- 5: YT double cycle, cycle times and productivities

| cycle ID	Load the YT at YC1	Loaded move to QC1	Discharge the YT at QC1	Empty move from QC1 to QC2	Loading the truck at QC2	Loaded move to YC2	Discharge the truck at YC2	empty back move from YC2 to YC1	Total cycle time	Number of cycles/hr	Productivity (TEU/hr)
1	3.963	4.363	1.951	0.167	0.779	2.481	0.905	0.750	15.358	3.907	15.627
2	0.945	2.092	0.778	0.167	1.926	2.062	2.288	0.750	11.008	5.450	21.801
3	1.761	3.060	4.610	0.167	1.581	2.498	0.701	0.750	15.127	3.966	15.866
4	5.612	3.208	1.602	0.167	1.181	2.301	2.032	0.750	16.853	3.560	14.241
5	0.715	3.985	1.697	0.167	1.145	2.245	1.205	0.750	11.909	5.038	20.152
6	3.879	4.073	1.000	0.167	1.197	2.753	5.588	0.750	19.407	3.092	12.367
7	0.929	1.388	0.460	0.167	1.598	3.256	0.707	0.750	9.255	6.483	25.933
8	1.920	1.686	0.585	0.167	1.453	2.653	3.032	0.750	12.246	4.900	19.598
9	1.068	2.169	0.942	0.167	4.910	3.768	0.466	0.750	14.239	4.214	16.855
10	2.098	1.734	4.134	0.167	5.381	3.245	2.446	0.750	19.954	3.007	12.028
11	1.890	2.747	0.420	0.167	1.729	2.505	0.804	0.750	11.012	5.448	21.794
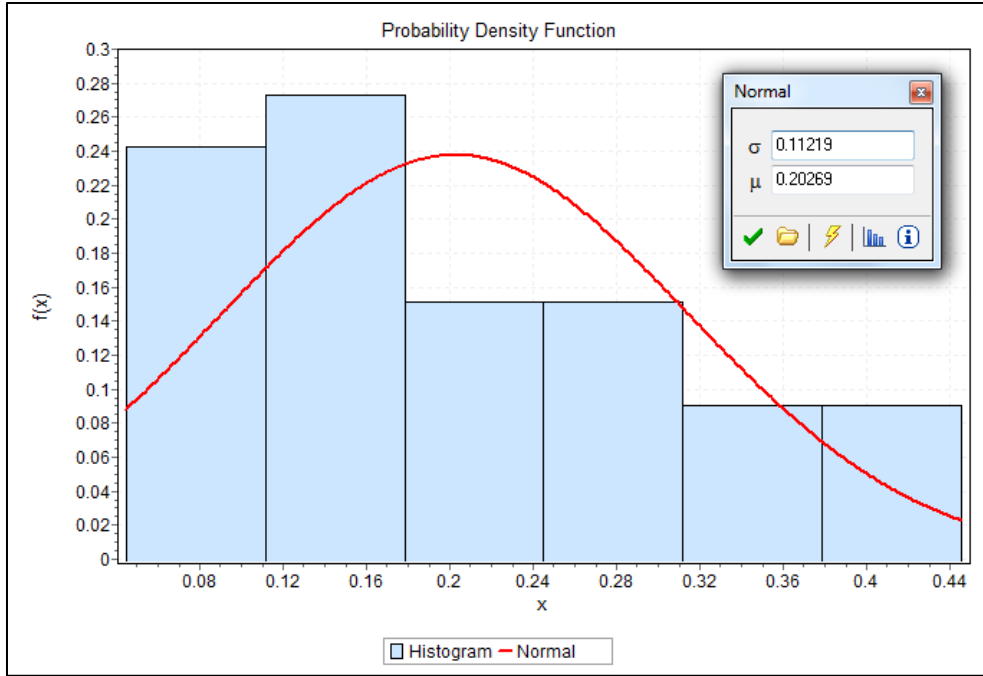
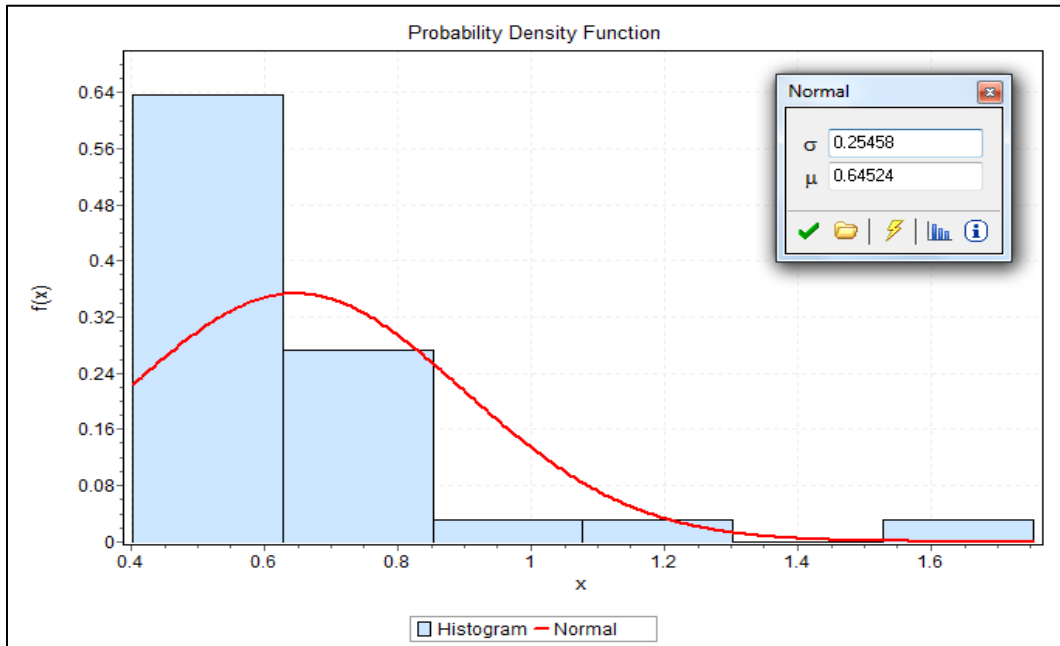Figure A- 1: QC loading Discharge the YT
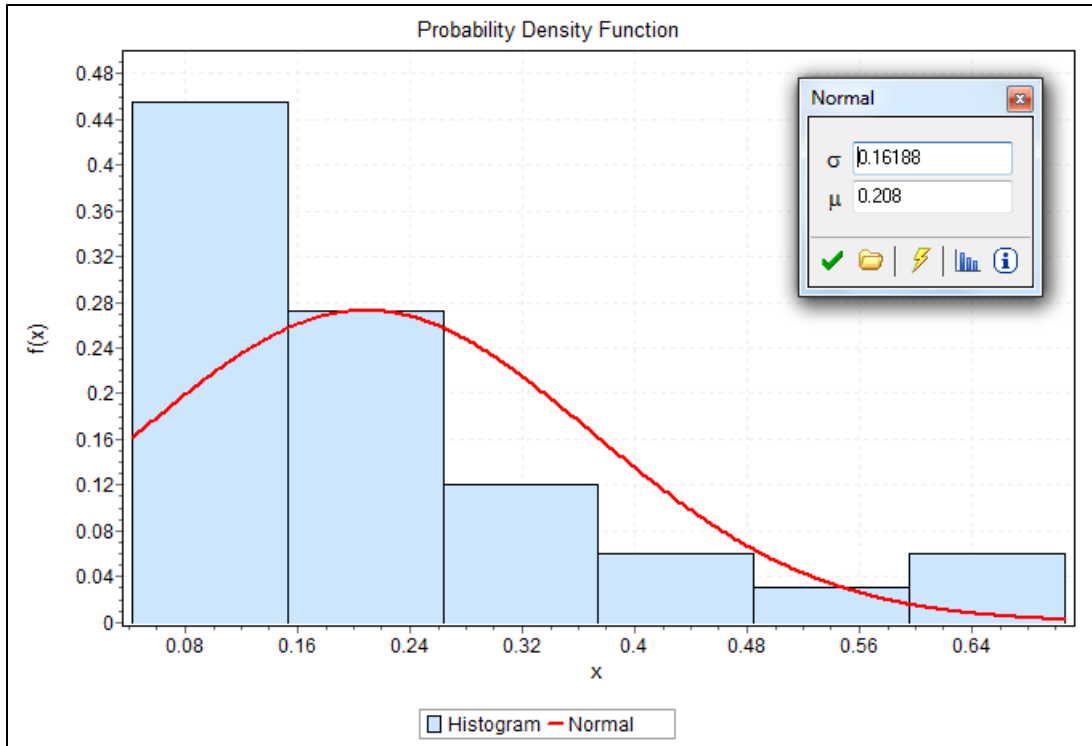

Figure A- 2: QC loading forward loaded move

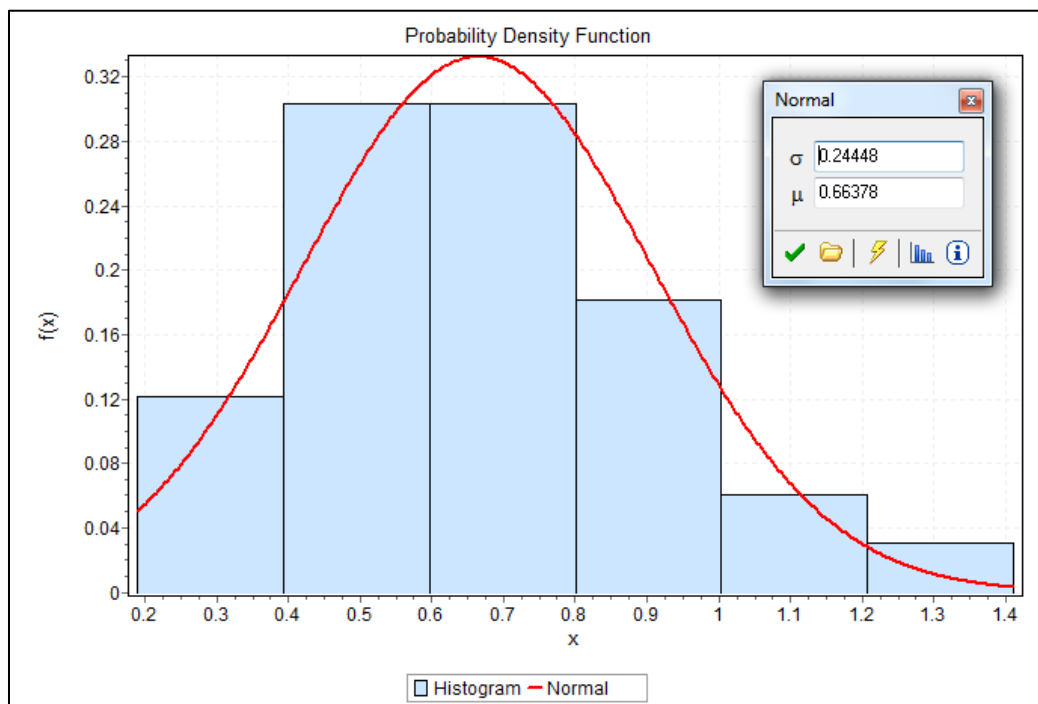Figure A- 3: QC loading Load the container on vessel

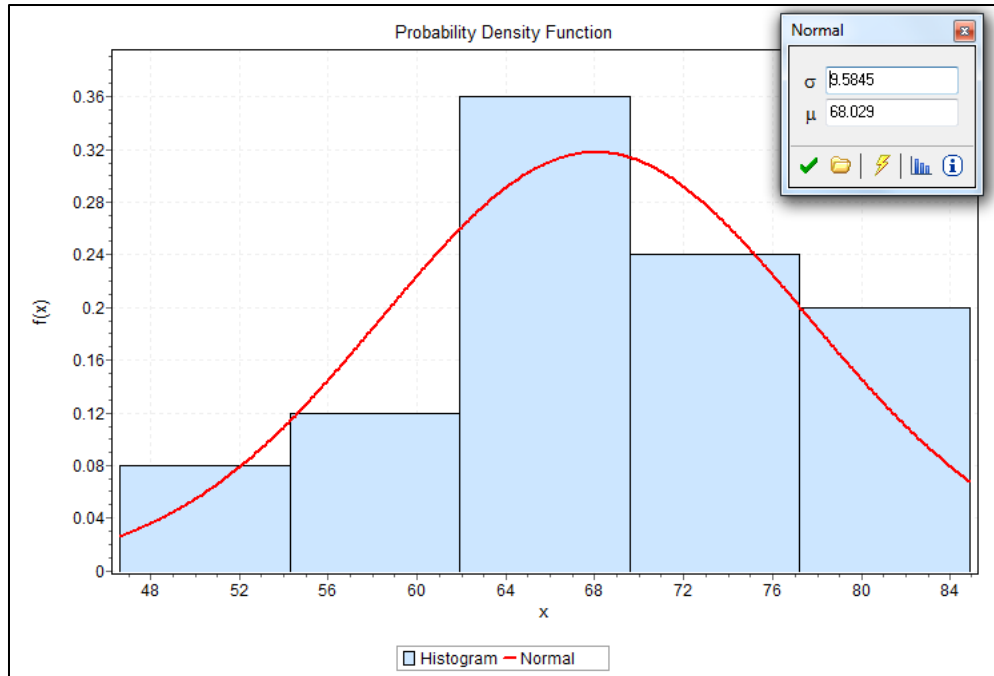Figure A- 4: QC loading, empty back move
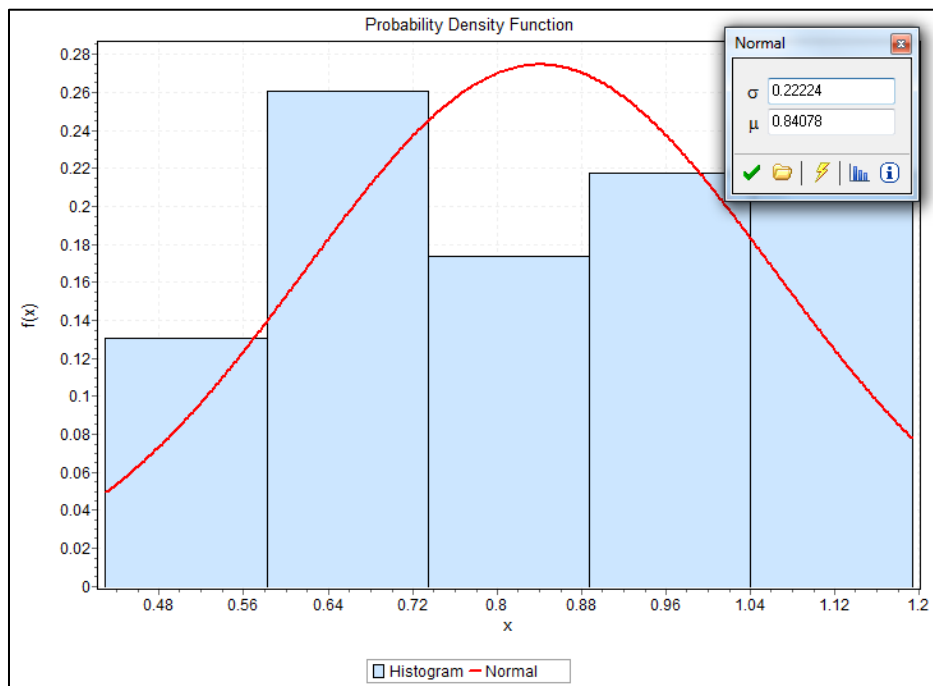
Figure A- 5: QC loading productivity

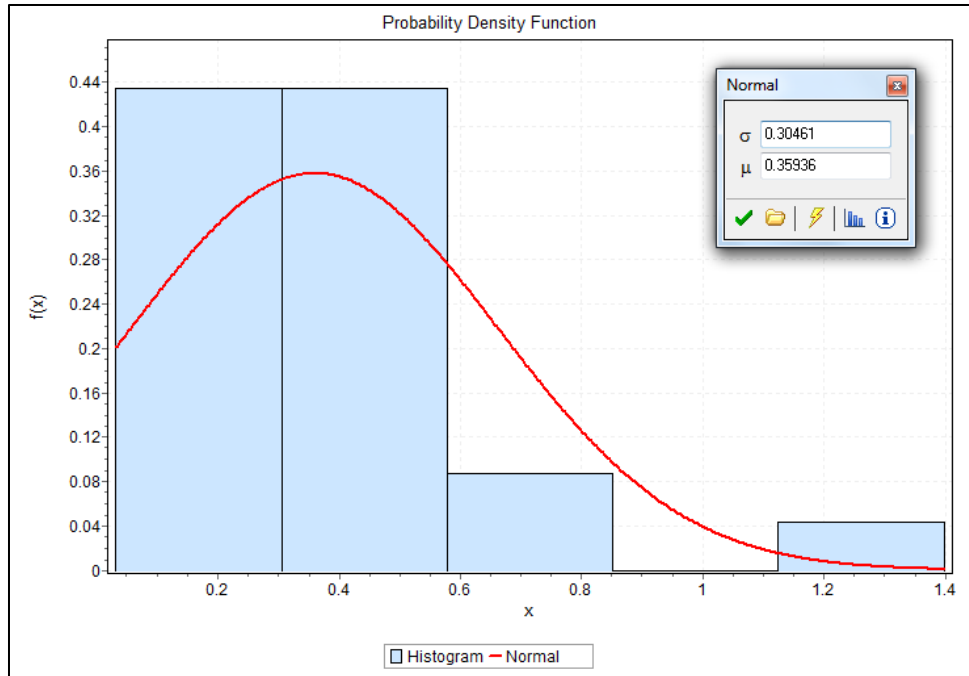Figure A- 6: QC discharging empty forward move

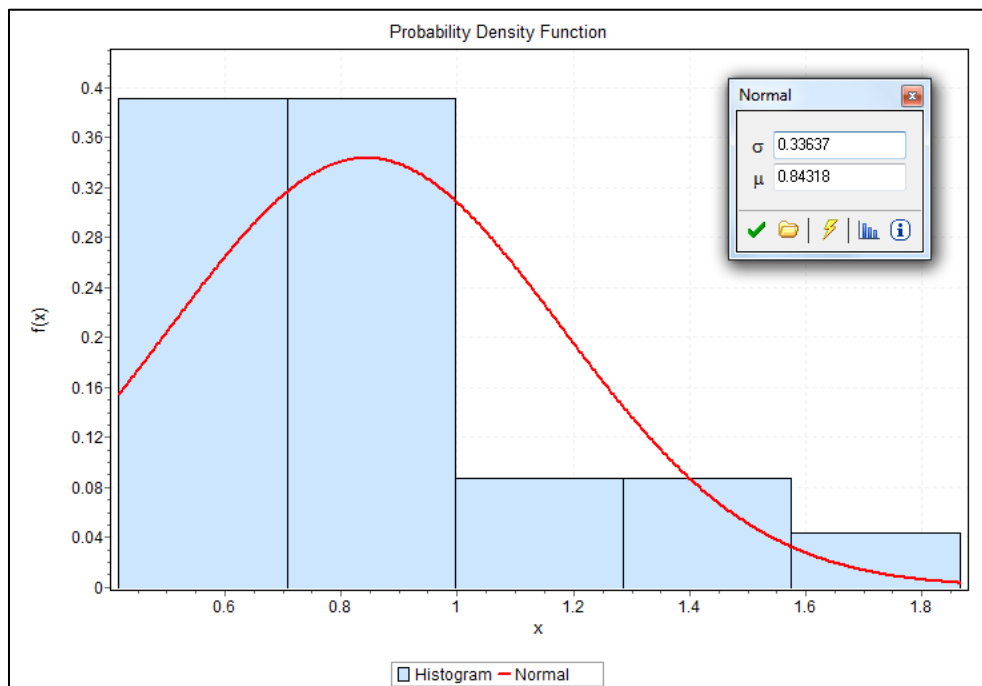Figure A- 7: QC discharging lift container from vessel

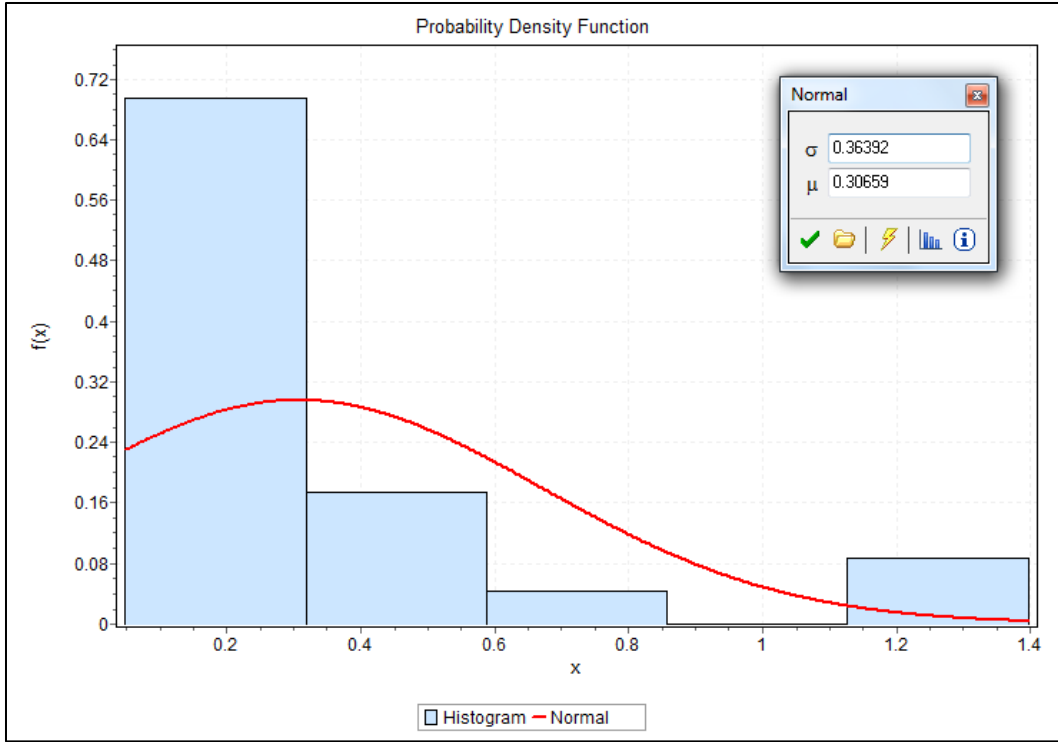Figure A- 8: QC discharging loaded back move

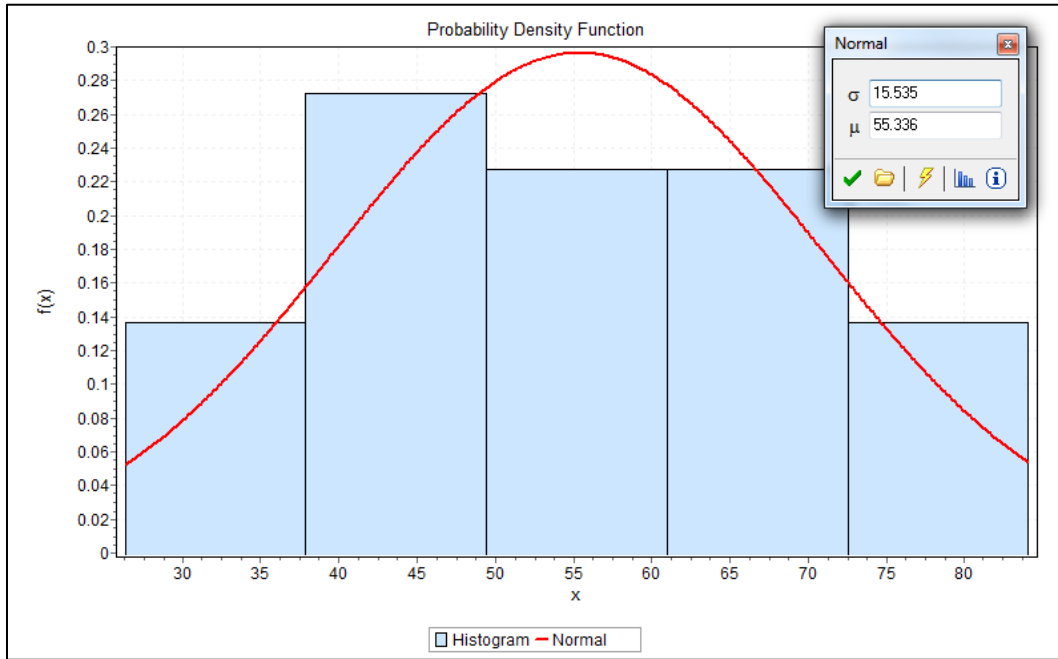Figure A- 9: QC discharging Load container on YT

Figure A- 10: QC discharging productivity
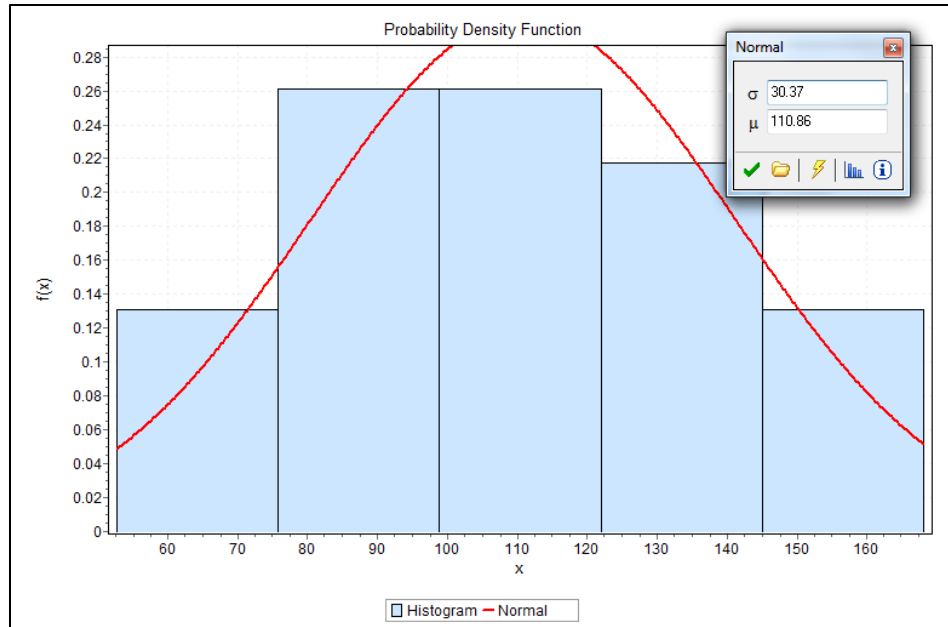
Figure A- 11: QC doubly cycle productivity
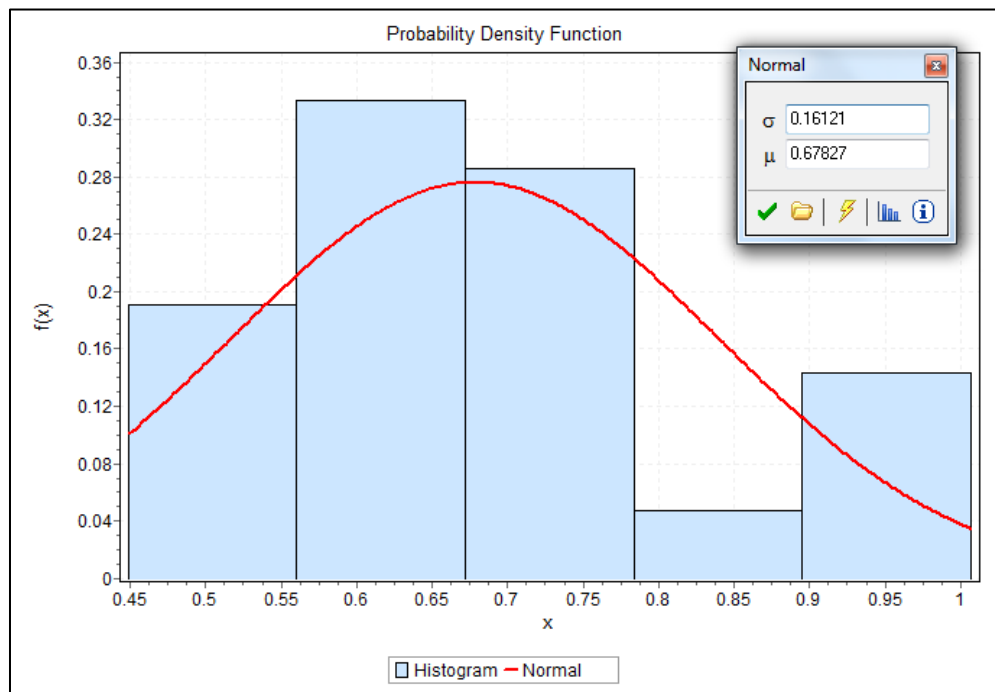
Figure A- 12: YC loading empty forward move
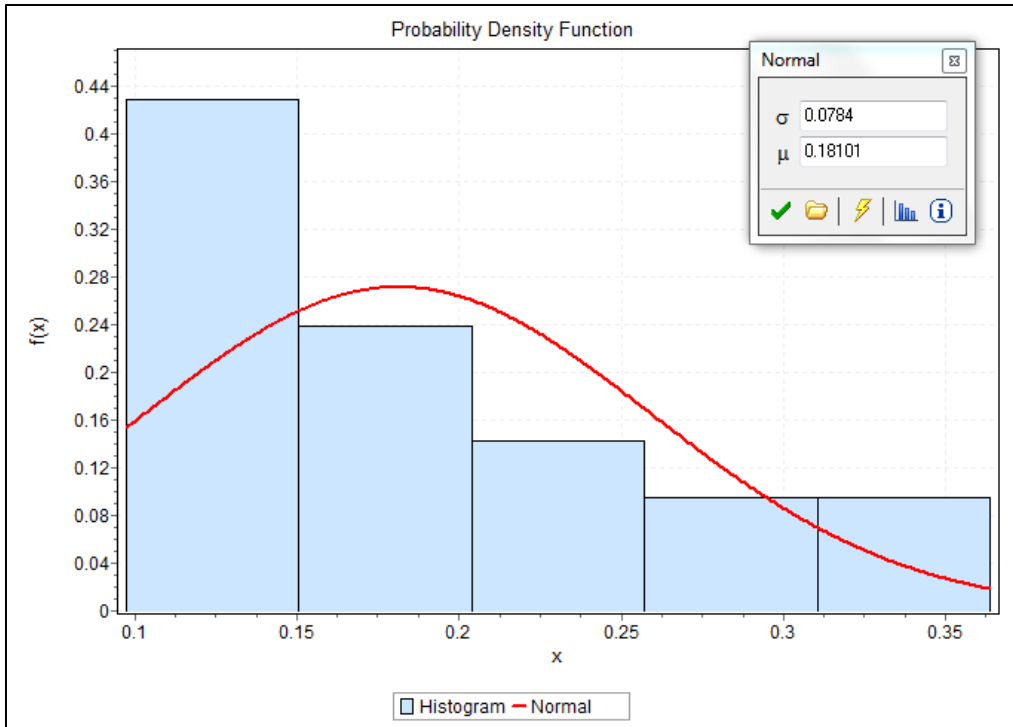
Figure A- 13: YC loading lift container from SY
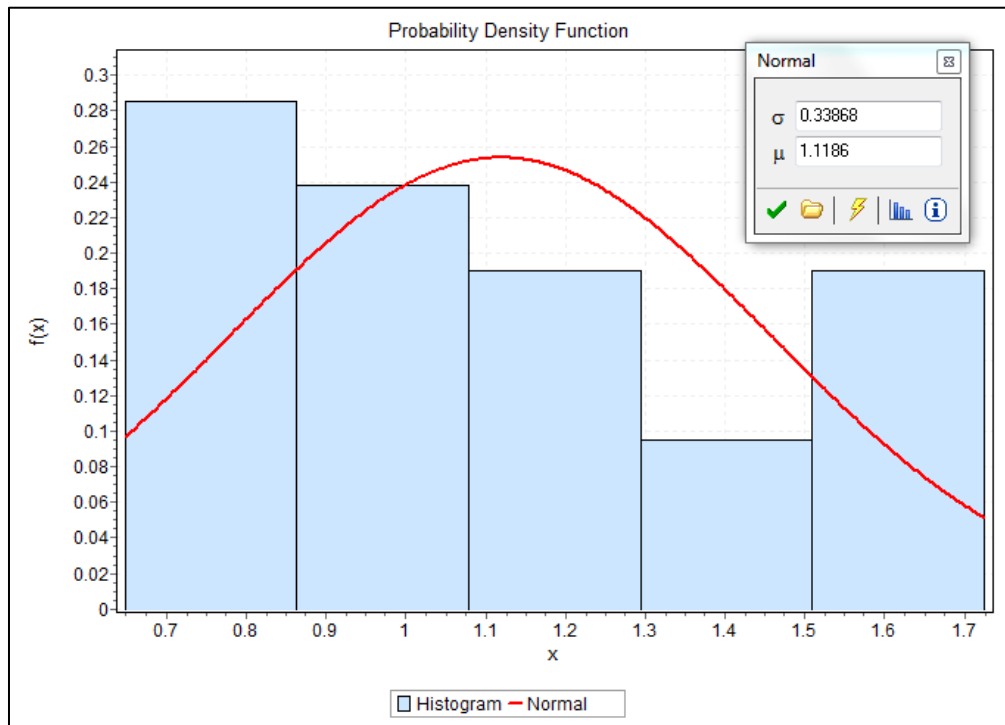
Figure A- 14: YC loading Loaded back ward move
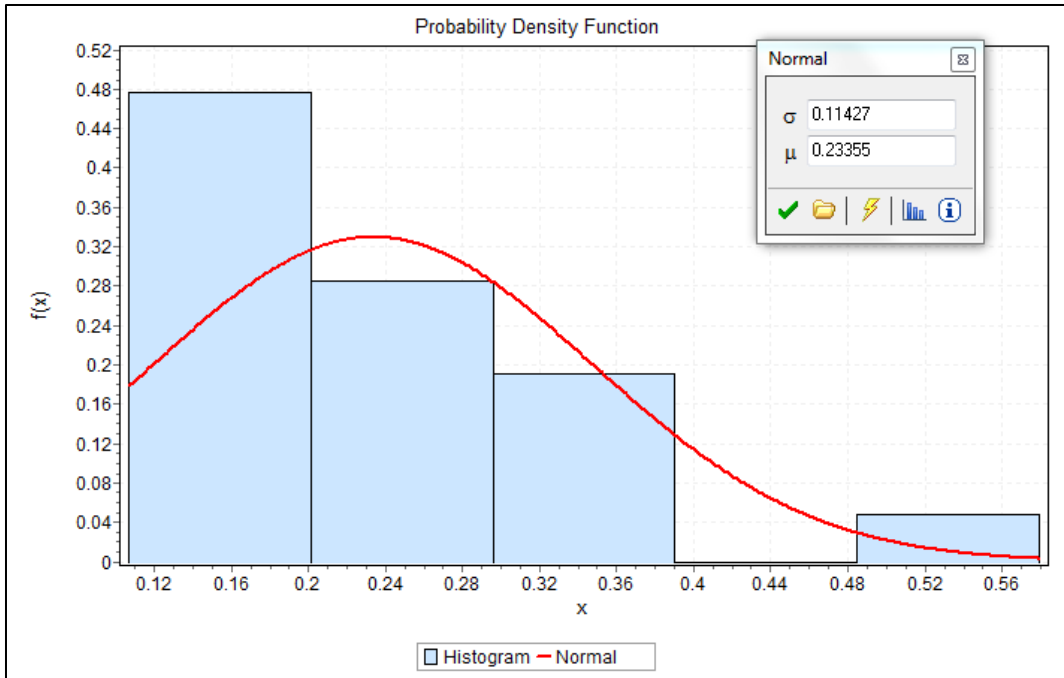
Figure A- 15: YC loading load the container on the YT
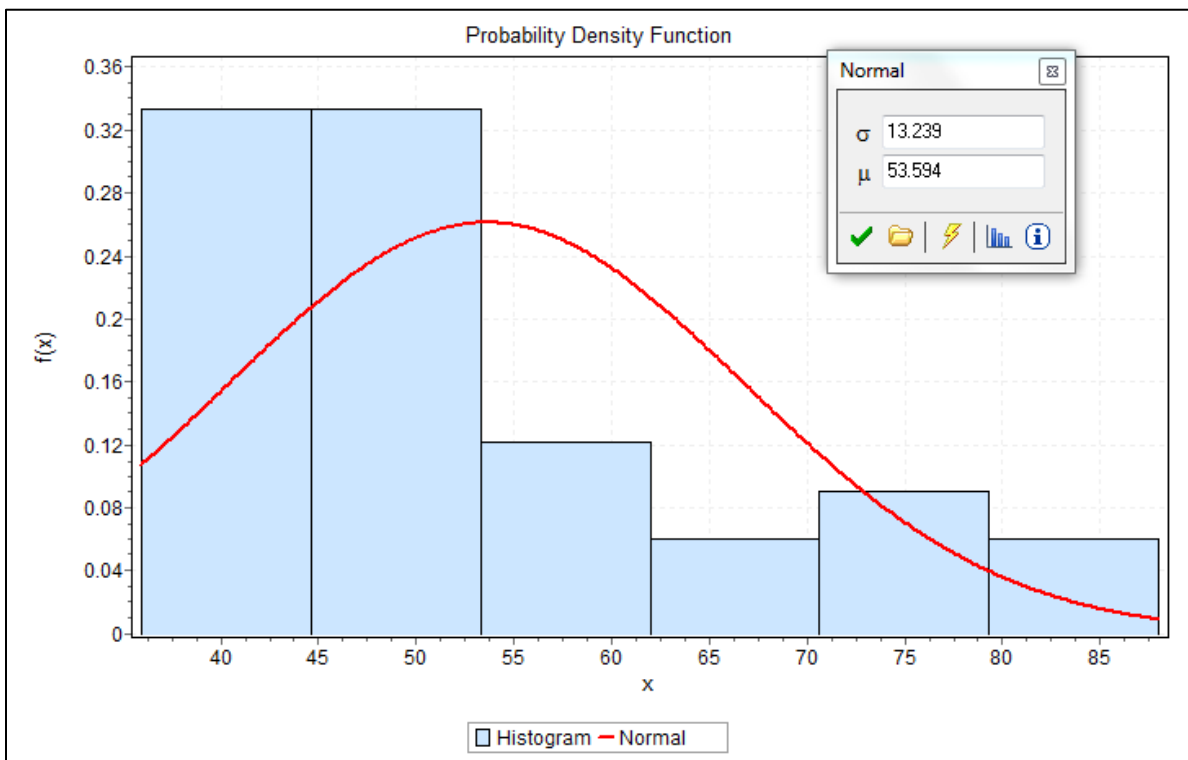
Figure A- 16: YC loading productivity
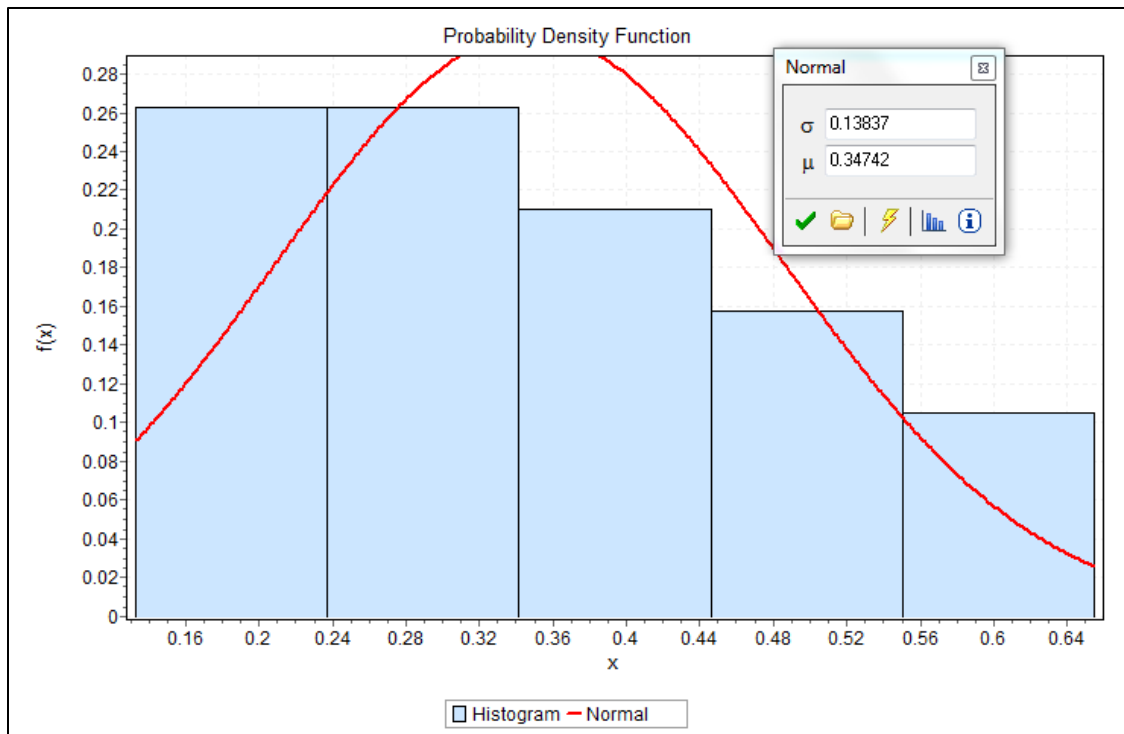
Figure A- 17: YC discharging, lift container from YT
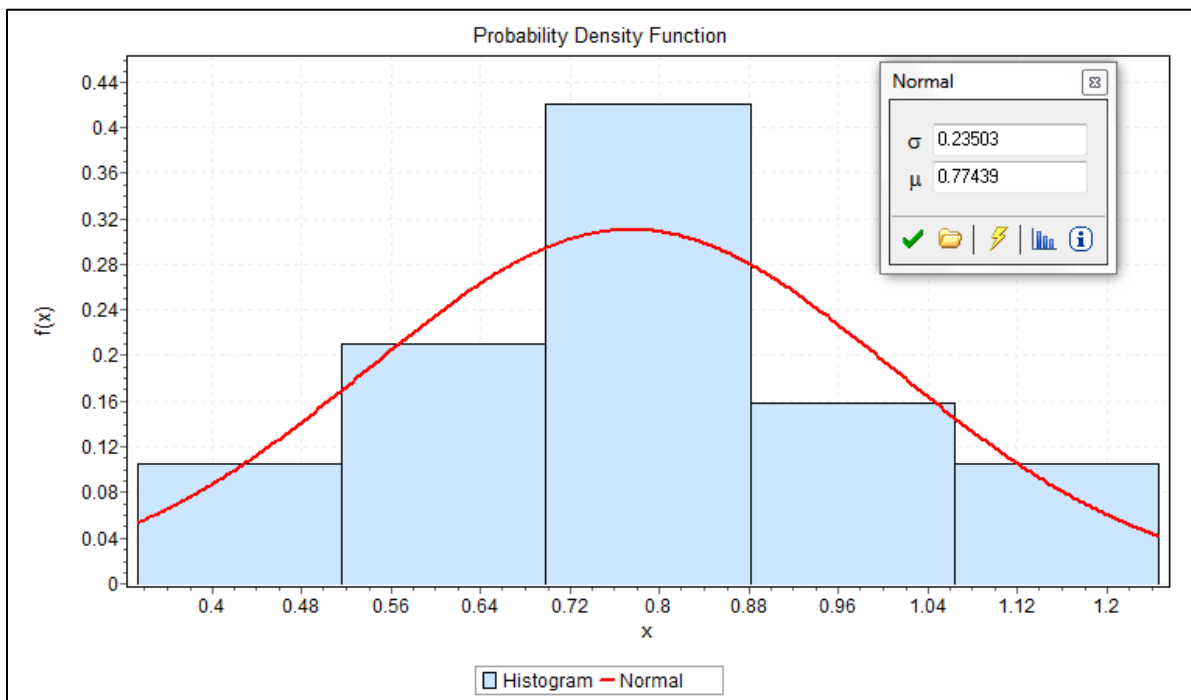
Figure A- 18: YC discharging, loaded forward move
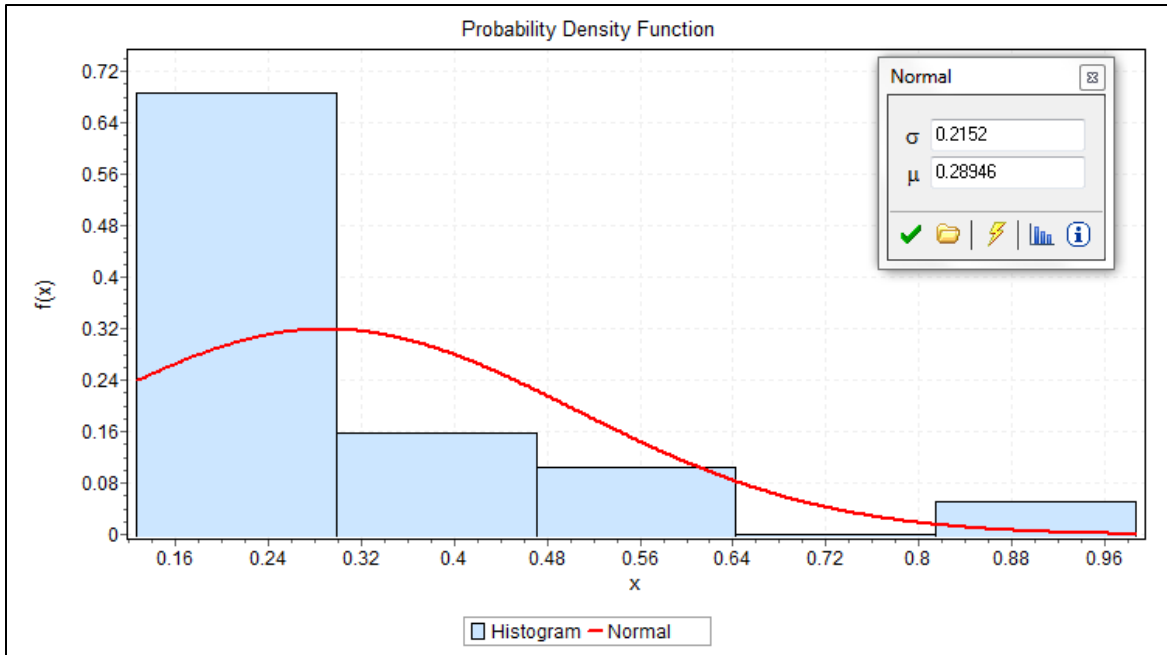
Figure A- 19: YC discharging, load the container on SY
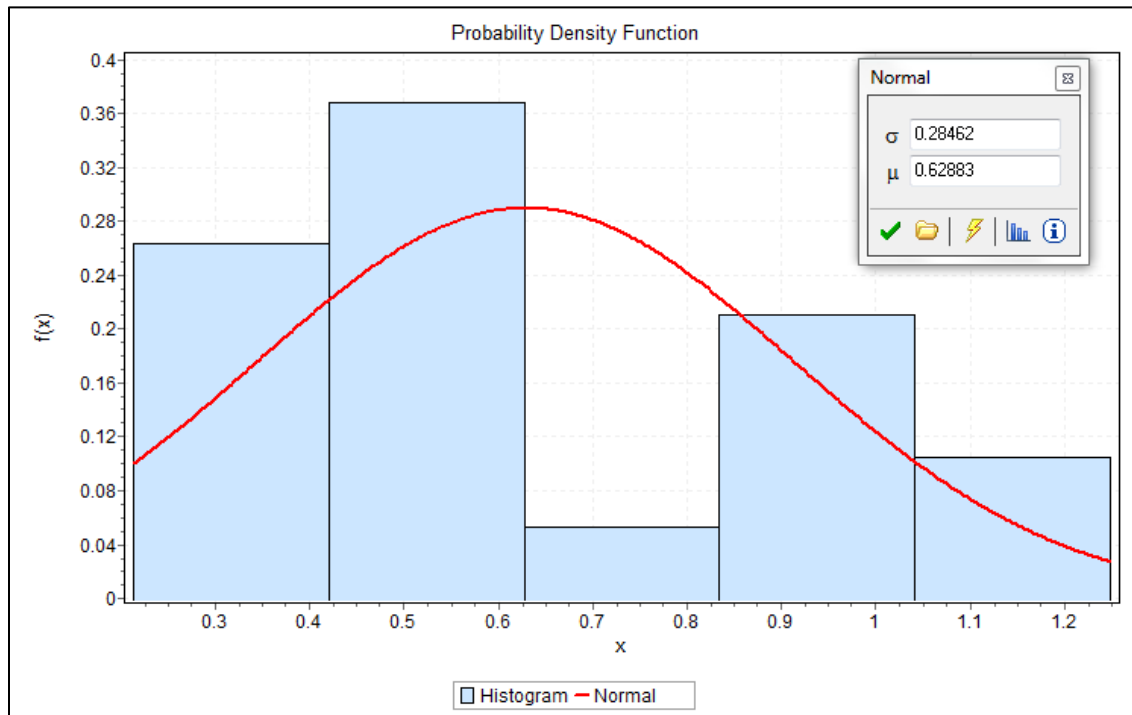
Figure A- 20: YC discharging, empty back ward
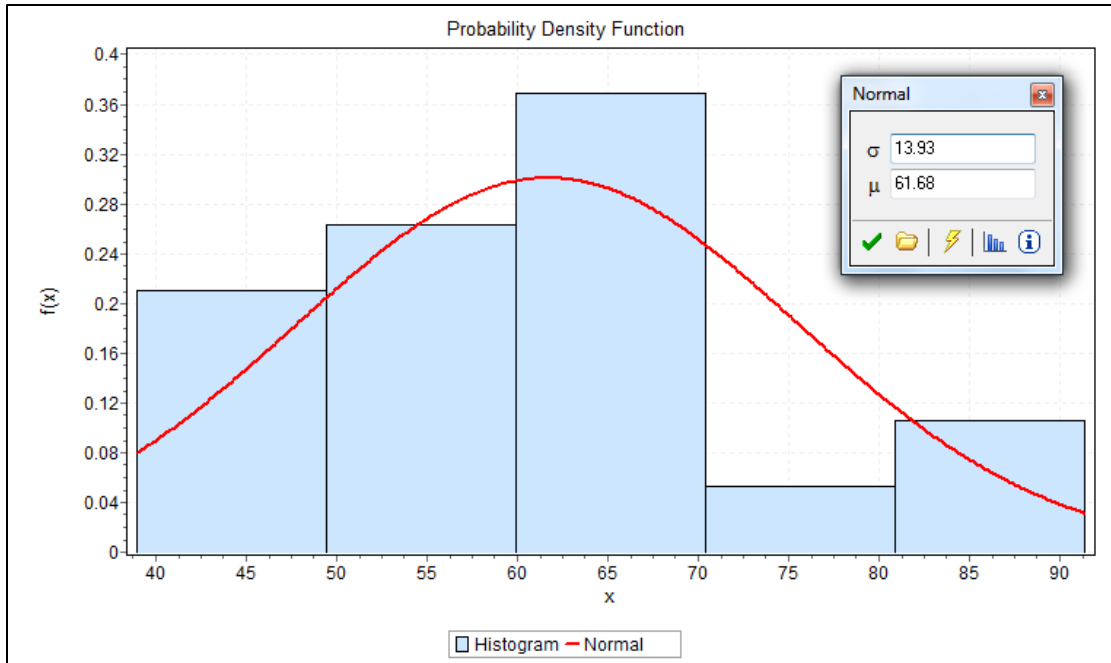
Figure A- 21: YC unloading productivity
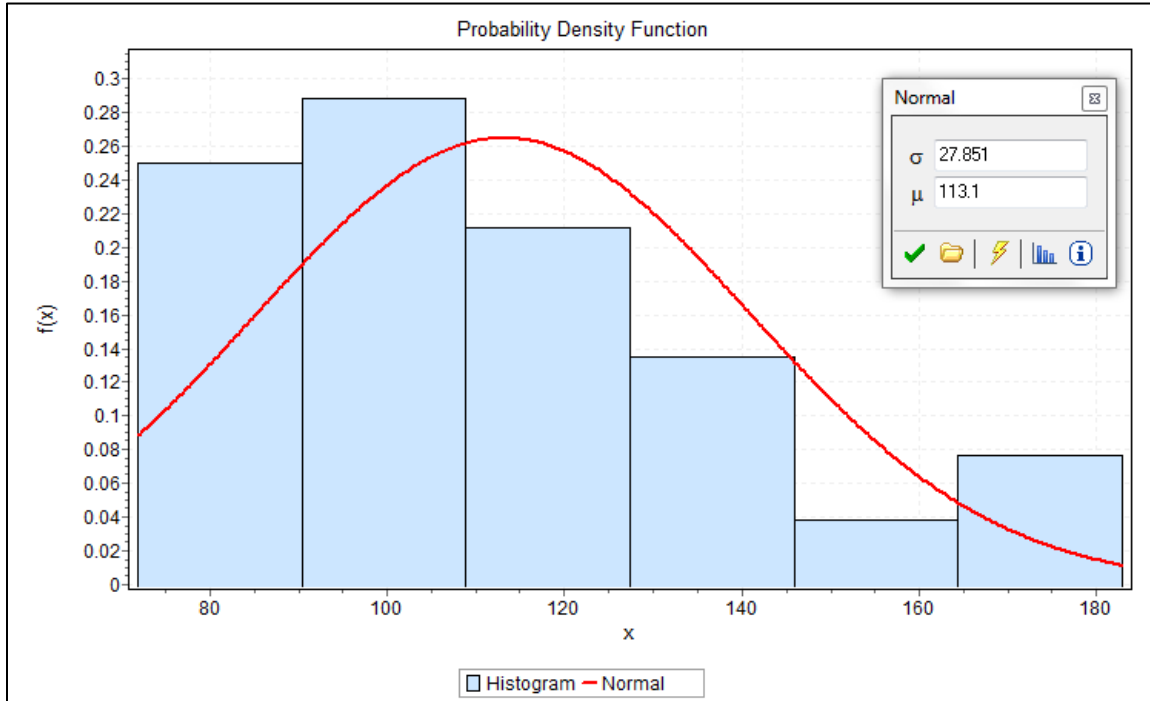
Figure A- 22: YC double cycle productivity
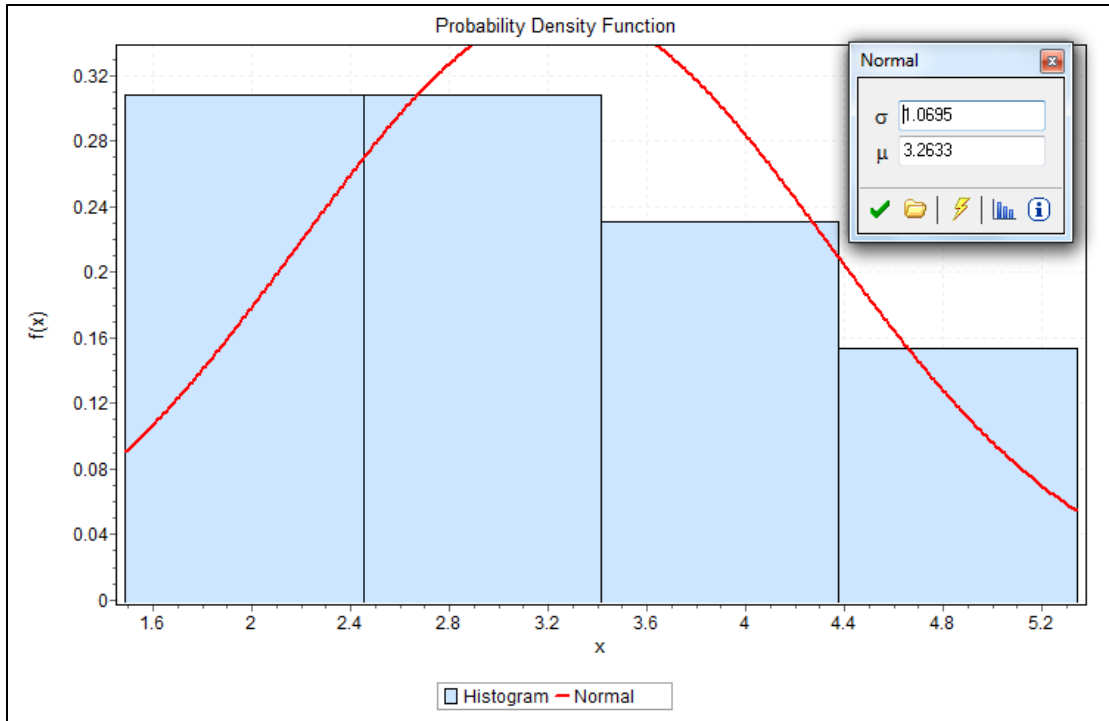
Figure A- 23: YT unloading, empty move from SY to QC
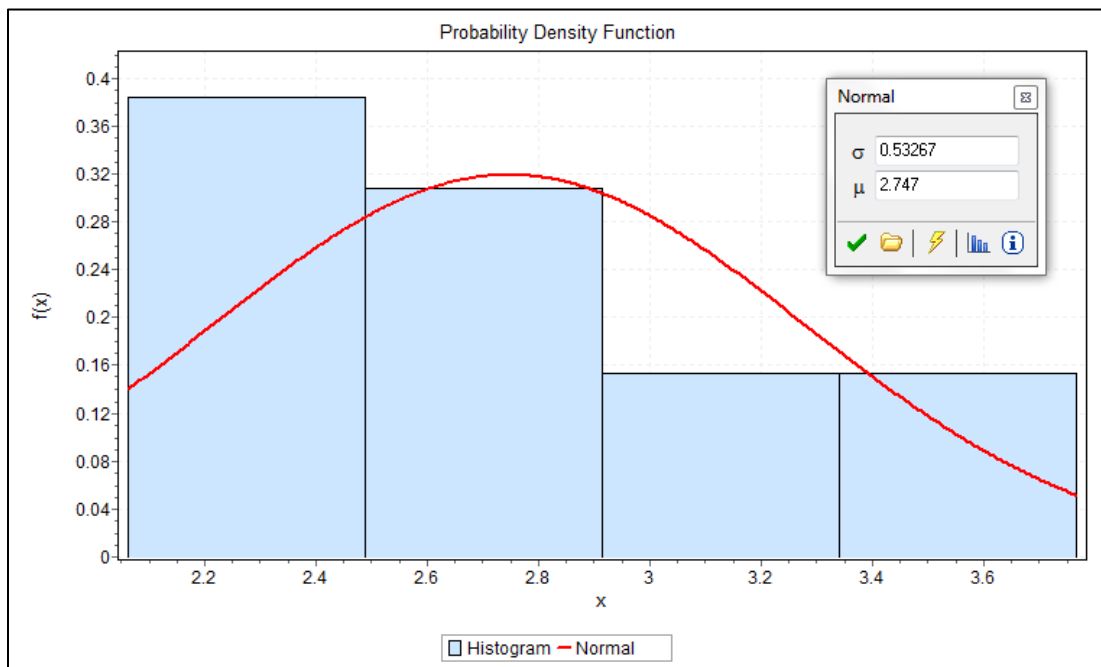
Figure A- 24: YT single cycle unloading, loaded move from QC to SY
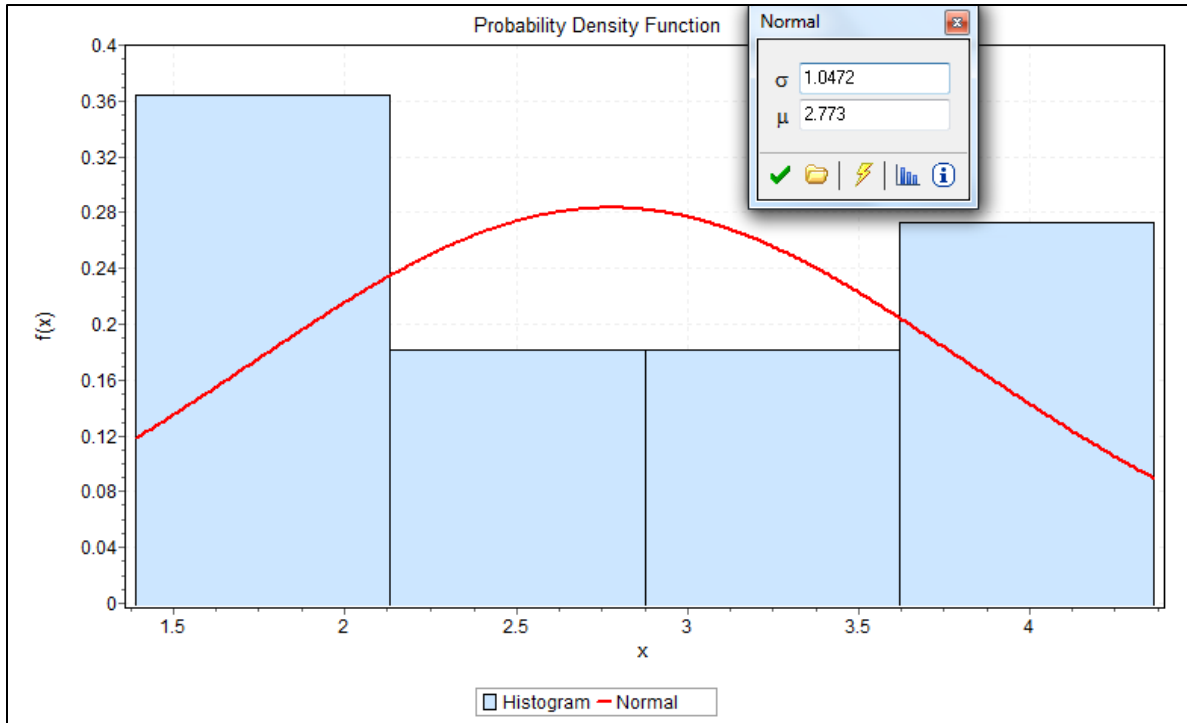
Figure A- 25: YT loading, loaded move from SY to QC
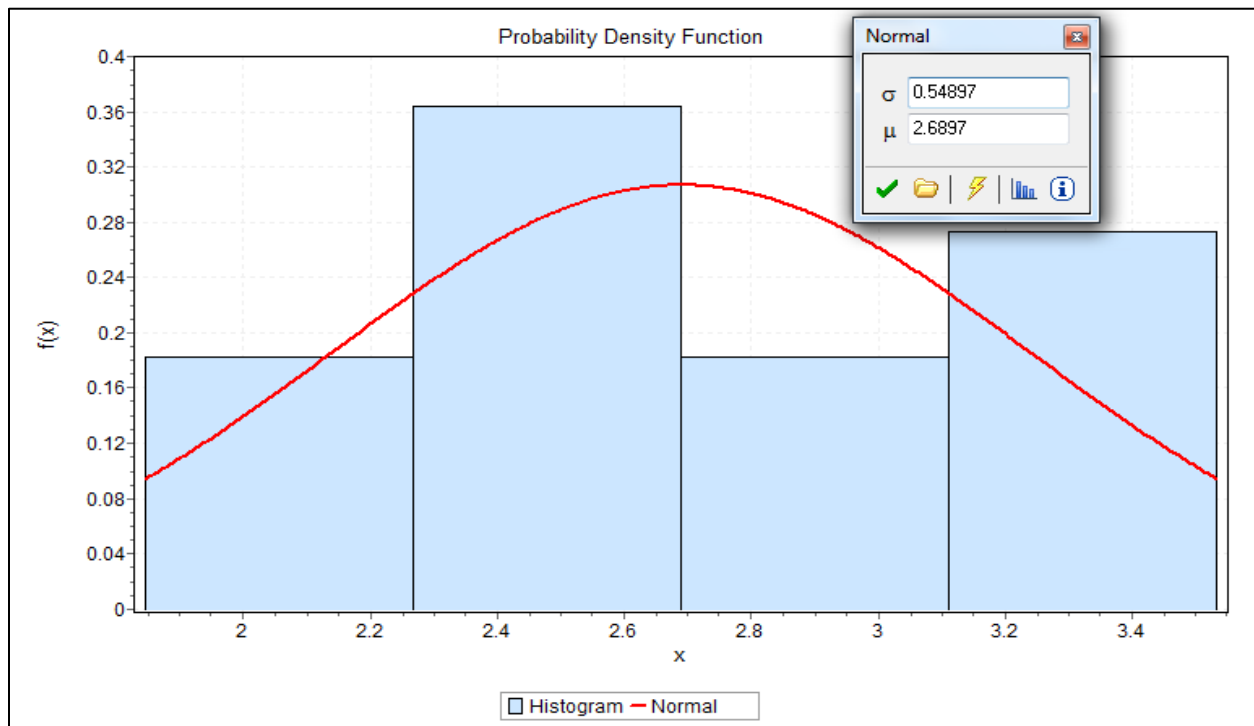
Figure A- 26: YT loading, empty move from QC to SY
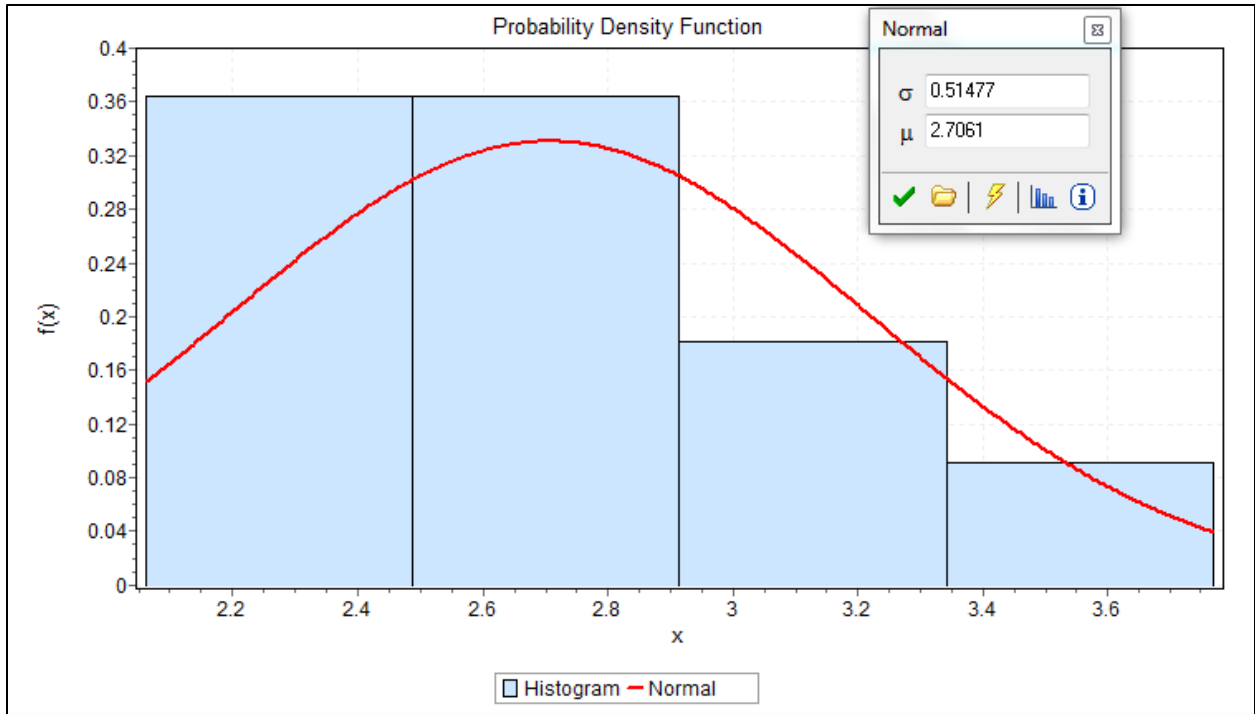
Figure A- 27: YT double cycle, loaded move from QC to SY
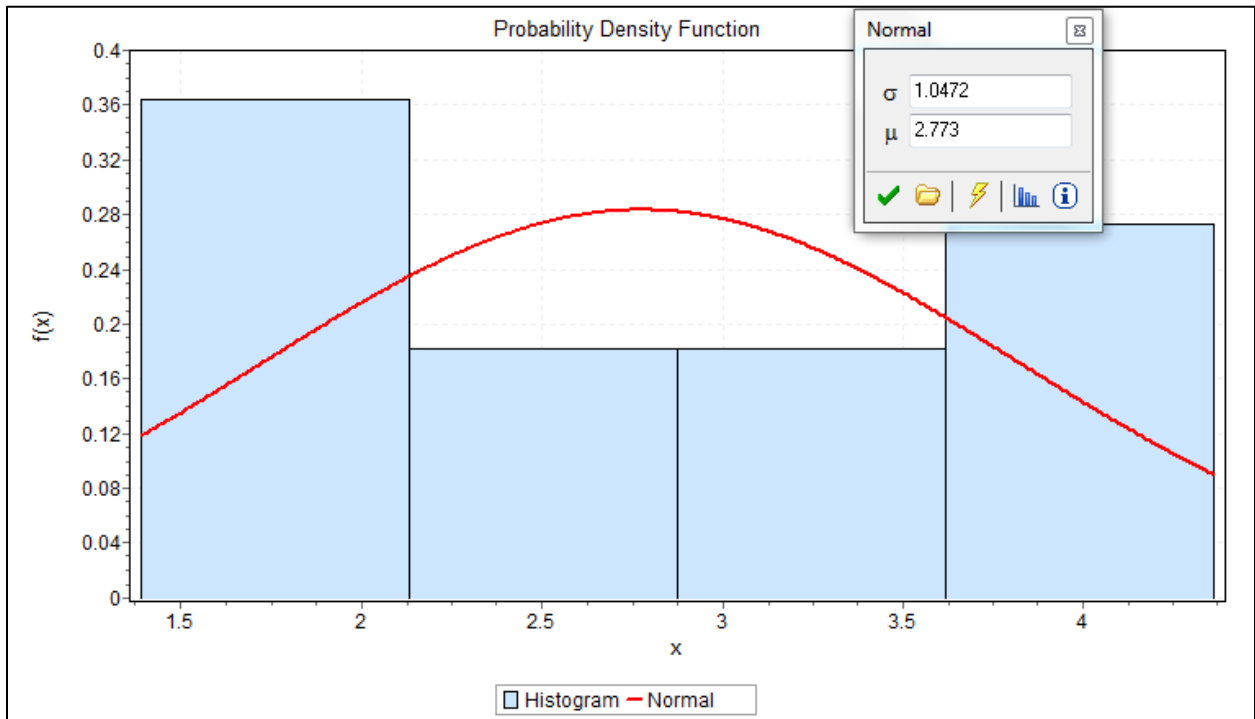
Figure A- 28: YT double cycle, loaded move from SY to QC
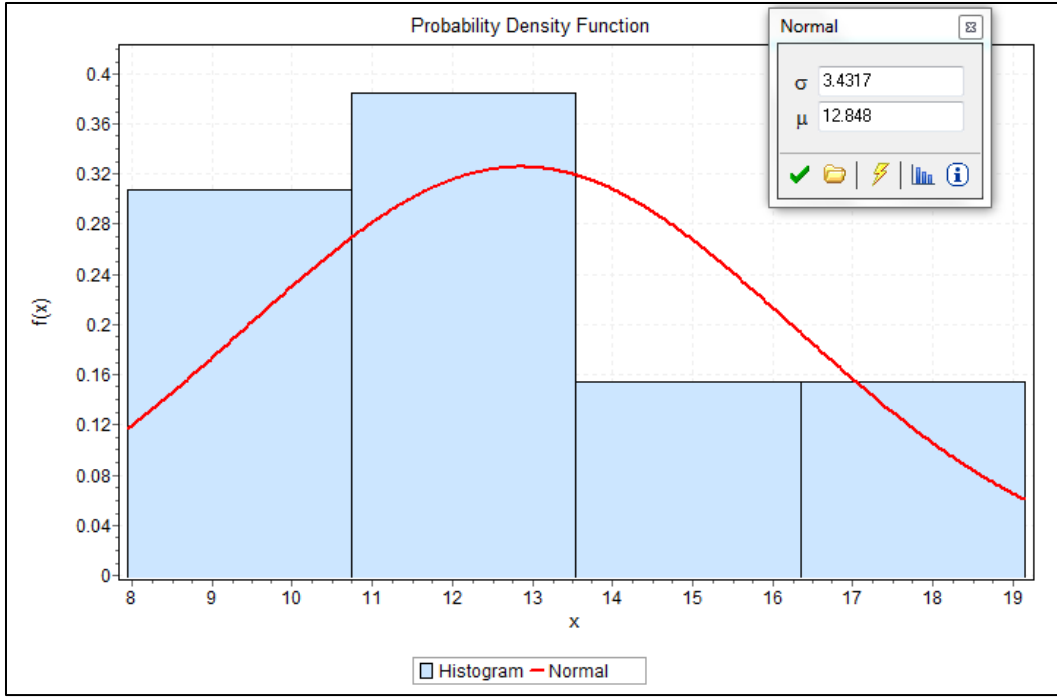
Figure A- 29: YT single cycle, unloading productivity
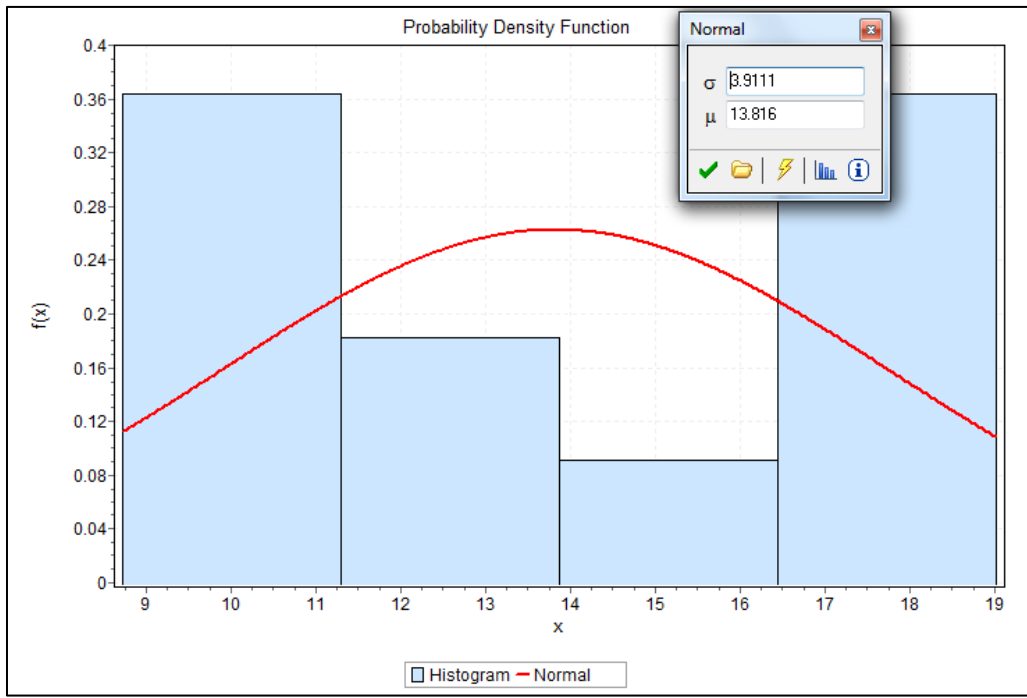
Figure A- 30: YT single cycle, loading productivity
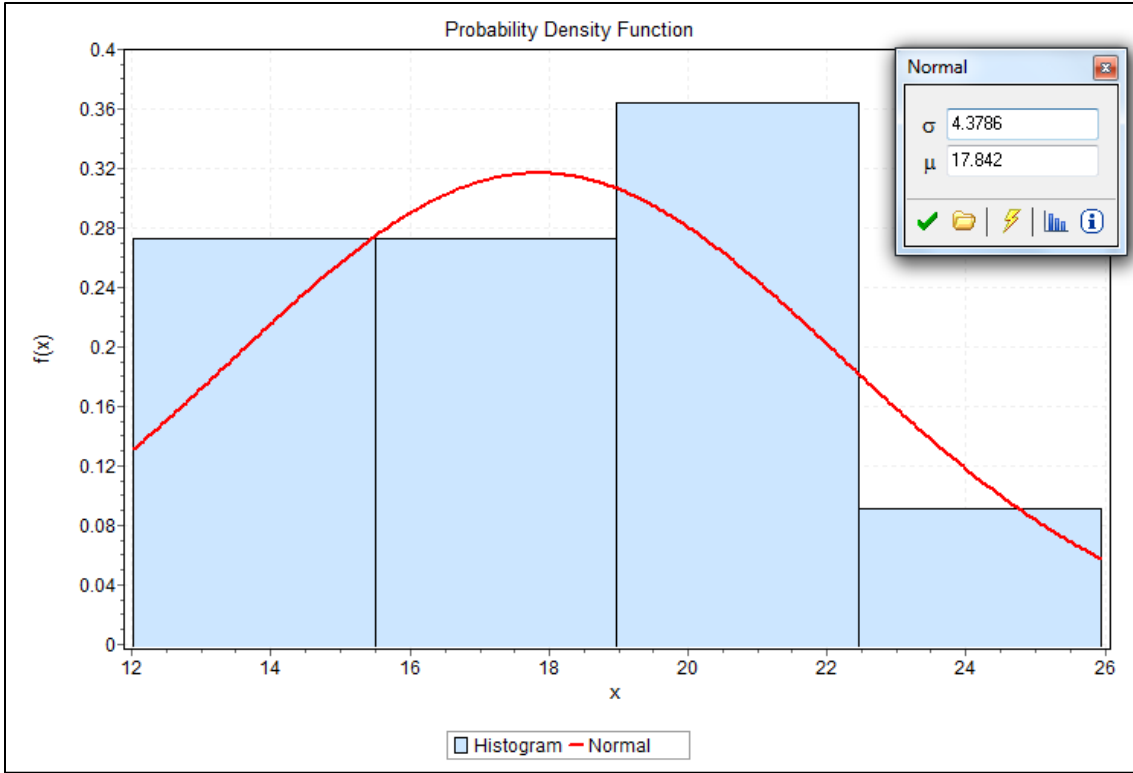
Figure A-31: YT double cycle productivity

Appendix B

VBA Excel coding

```vba
1.  Sub FindSolution()
2.  ' This code aims to solve a Non-Linear programming problem.
3.
4.  ' Definte variables. Lastrow: stores the value of the last row, b: binary value used to
    determine for loop direction and step
5.  ' l,m,n,o: Variables used in Looping between values
6.  Dim Lastrow, b, i, l, m, n, o As Integer
7.
8.  ' Define Variables. Obj: Stores the temporary objective function values. Sol: Stores th
    e current optimal solution
9.  ' u,j,k,s,g,f: Store problem parameters, Min/Max: Store the lowest and highest bounds o
    f each variable
10. Dim Obj(23), Sol(23), u(3), j(3), k(3), s(3), g(3), f(3) As Double
11. Dim Min(), max() As Variant
12.
13. ' Turn off automatic formulat recalculation in the spreadsheet (To improve processing s
    peed)
14. Application.Calculation = xlCalculationManual
15.
16. ' Turn off screen updating (To improve processing speed)
17. Application.ScreenUpdating = False
18.
19. ' Clear all cells below row (11) to make room for new answer
20. With Rows(11 & ":" & Rows.Count).Delete
21. End With
22.
23. ' Identify last row with data in the spreadsheet
24. Lastrow = ActiveSheet.Range("B" & Rows.Count).End(xlUp).Row + 1
25.
26. ' Store all minimum variable values (constraints) into array
27. Min = Range("B10:X10")
28. ' Store all maximum variable values (constraints) into array
29. max = Range("B9:X9")
30.
31. ' Store initial temporary objective function value (Using minimum variable values)
32. For l = 1 To 23
33. Obj(l) = Cells(10, l + 1)
34. Next l
35.
36. ' Store optimal objective function value (Using minimum variable values)
37. For l = 1 To 23
38. Sol(l) = Cells(10, l + 1)
39. Next l
40.
41. ' Store values for u,k,j,s,g,f
42.
43. For l = 1 To 3
```

```vba
44.  u(l) = Cells(1, l * 5)
45.  k(l) = Cells(2, l * 5)
46.  j(l) = Cells(3, l * 5)
47.  s(l) = Cells(4, l * 5)
48.  g(l) = Cells(5, l * 5)
49.  f(l) = Cells(6, l * 5)
50.  Next l
51.
52.
53.  ' Generate random answer
54.  For i = 1 To 1024
55.
56.  ' Generate a random answer for x1,y1,z1 (B is a binary variable that determines the dir
     ection of the loop
57.  ' (From lower to upper bound or vice versa)
58.
59.  b = Int(2 * Rnd + 1) - 1
60.  For m = max(1, 1) - b * (max(1, 1) - Min(1, 1)) To Min(1, 1) + b * (max(1, 1) -
      Min(1, 1)) Step -1 + 2 * b
61.  b = Int(2 * Rnd + 1) - 1
62.  For n = max(1, 2) - b * (max(1, 2) - Min(1, 2)) To Min(1, 2) + b * (max(1, 2) -
      Min(1, 2)) Step -1 + 2 * b
63.  b = Int(2 * Rnd + 1) - 1
64.  For o = max(1, 3) - b * (max(1, 3) - Min(1, 3)) To Min(1, 3) + b * (max(1, 3) -
      Min(1, 3)) Step -1 + 2 * b
65.
66.  ' Set temorary objective function values based on randomly generated answer
67.
68.  Obj(1) = m
69.  Obj(2) = n
70.  Obj(3) = o
71.
72.  ' Calculate A1 and B1
73.  Obj(10) = WorksheetFunction.Min(u(1) * Obj(1), k(1) * Obj(3), j(1) * Obj(2))
74.  Obj(11) = (1.25 * (s(1) * Obj(1) + f(1) * Obj(2) + g(1) * Obj(3))) / Obj(10)
75.
76.  ' Calculate T1 (Contribution to Time Objective Function) and C1 (Contribution to Cost O
     bjective Function)
77.  Obj(16) = 5400 / Obj(10)
78.  Obj(19) = Obj(16) + Sol(17) + Sol(18)
79.
80.  ' Calculate T and C
81.  Obj(20) = 5400 * Obj(11)
82.  Obj(23) = Obj(20) + Sol(21) + Sol(22)
83.
84.  ' Check if temporary T*C is smaller than current optimal T*C
85.  If Obj(19) * Obj(23) < Sol(19) * Sol(23) Then
86.
87.  ' If Yes, set current best to temporary values
88.  Sol(1) = Obj(1)
89.  Sol(2) = Obj(2)
90.  Sol(3) = Obj(3)
91.  Sol(10) = Obj(10)
```

```
92. Sol(11) = Obj(11)
93. Sol(16) = Obj(16)
94. Sol(19) = Sol(16) + Sol(17) + Sol(18)
95. Sol(20) = Obj(20)
96. Sol(23) = Sol(20) + Sol(21) + Sol(22)
97.
98. ' Add new solution to spreadsheet
99. For l = 1 To 23
100.Cells(Lastrow, l + 1) = Sol(l)
101.Next l
102.Lastrow = Lastrow + 1
103.End If
104.
105.' Check another random answer
106.Next o
107.Next n
108.Next m
109.
110.
111.' Generate a random answer for x2,y2,z2 (B is a binary variable that determines the dir
    ection of the loop
112.' (From lower to upper bound or vice versa)
113.b = Int(2 * Rnd + 1) - 1
114.For m = max(1, 4) - b * (max(1, 4) - Min(1, 3)) To Min(1, 4) + b * (max(1, 4) -
    Min(1, 4)) Step -1 + 2 * b
115.b = Int(2 * Rnd + 1) - 1
116.For n = max(1, 5) - b * (max(1, 5) - Min(1, 5)) To Min(1, 5) + b * (max(1, 5) -
    Min(1, 5)) Step -1 + 2 * b
117.b = Int(2 * Rnd + 1) - 1
118.For o = max(1, 6) - b * (max(1, 6) - Min(1, 6)) To Min(1, 6) + b * (max(1, 6) -
    Min(1, 6)) Step -1 + 2 * b
119.
120.' Set temorary objective function values based on randomly generated answer
121.Obj(4) = m
122.Obj(5) = n
123.Obj(6) = o
124.
125.' Calculate A2 and B2
126.Obj(12) = WorksheetFunction.Min(u(2) * Obj(4), k(2) * Obj(6), j(2) * Obj(5))
127.Obj(13) = (1.25 * (s(2) * Obj(4) + f(2) * Obj(5) + g(2) * Obj(6))) / Obj(12)
128.
129.' Calculate T2 (Contribution to Time Objective Function) and C2 (Contribution to Cost O
    bjective Function)
130.Obj(17) = 13200 / Obj(12)
131.Obj(19) = Sol(16) + Obj(17) + Sol(18)
132.
133.' Calculate T and C
134.Obj(21) = 13200 * Obj(13)
135.Obj(23) = Sol(20) + Obj(21) + Sol(22)
136.
137.
138.' Check if temporary T*C is smaller than current optimal T*C
139.If Obj(19) * Obj(23) < Sol(19) * Sol(23) Then
```

```vba
140.
141.' If Yes, set current best to temporary values
142.Sol(4) = Obj(4)
143.Sol(5) = Obj(5)
144.Sol(6) = Obj(6)
145.Sol(12) = Obj(12)
146.Sol(13) = Obj(13)
147.Sol(17) = Obj(17)
148.Sol(19) = Sol(16) + Sol(17) + Sol(18)
149.Sol(21) = Obj(21)
150.Sol(23) = Sol(20) + Sol(21) + Sol(22)
151.
152.' Add new solution to spreadsheet
153.For l = 1 To 23
154.Cells(Lastrow, l + 1) = Sol(l)
155.Next l
156.Lastrow = Lastrow + 1
157.End If
158.
159.' Check another random answer
160.Next o
161.Next n
162.Next m
163.
164.' Generate a random answer for x3,y3,z3 (B is a binary variable that determines the dir
    ection of the loop
165.' (From lower to upper bound or vice versa)
166.b = Int(2 * Rnd + 1) - 1
167.For m = max(1, 7) - b * (max(1, 7) - Min(1, 7)) To Min(1, 7) + b * (max(1, 7) -
    Min(1, 7)) Step -1 + 2 * b
168.b = Int(2 * Rnd + 1) - 1
169.For n = max(1, 8) - b * (max(1, 8) - Min(1, 8)) To Min(1, 8) + b * (max(1, 8) -
    Min(1, 8)) Step -1 + 2 * b
170.b = Int(2 * Rnd + 1) - 1
171.For o = max(1, 9) - b * (max(1, 9) - Min(1, 9)) To Min(1, 9) + b * (max(1, 9) -
    Min(1, 9)) Step -1 + 2 * b
172.
173.' Set temorary objective function values based on randomly generated answer
174.Obj(7) = m
175.Obj(8) = n
176.Obj(9) = o
177.
178.' Calculate A3 and B3
179.Obj(14) = WorksheetFunction.Min(u(3) * Obj(7), k(3) * Obj(9), j(3) * Obj(8))
180.Obj(15) = (1.25 * (s(3) * Obj(7) + f(3) * Obj(8) + g(3) * Obj(9))) / Obj(14)
181.Obj(18) = 2400 / Obj(14)
182.Obj(19) = Sol(16) + Sol(17) + Obj(18)
183.Obj(22) = 2400 * Obj(15)
184.Obj(23) = Sol(20) + Sol(21) + Obj(22)
185.
186.' Check if temporary T*C is smaller than current optimal T*C
187.If Obj(19) * Obj(23) < Sol(19) * Sol(23) Then
188.
```

```vba
189.' If Yes, set current best to temporary values
190.Sol(7) = Obj(7)
191.Sol(8) = Obj(8)
192.Sol(9) = Obj(9)
193.Sol(14) = Obj(14)
194.Sol(15) = Obj(15)
195.Sol(18) = Obj(18)
196.Sol(19) = Sol(16) + Sol(17) + Sol(18)
197.Sol(22) = Obj(22)
198.Sol(23) = Sol(20) + Sol(21) + Sol(22)
199.
200.
201.' Add new solution to spreadsheet
202.For l = 1 To 23
203.Cells(Lastrow, l + 1) = Sol(l)
204.Next l
205.Lastrow = Lastrow + 1
206.End If
207.
208.' Check another random answer
209.Next o
210.Next n
211.Next m
212.
213.' Add most recently reached temporary answer to spreadsheet (For reference purposes)
214.For l = 1 To 23
215.Cells(Lastrow, l + 1) = Obj(l)
216.Next l
217.Lastrow = Lastrow + 1
218.
219.' Generate another complete set of variables
220.Next i
221.
222.' Add all Pareto Chart values to the appropriate sheet
223.Sheets("Pareto Chart").Cells(2, 2) = Sol(1)
224.Sheets("Pareto Chart").Cells(3, 2) = Sol(2)
225.Sheets("Pareto Chart").Cells(4, 2) = Sol(3)
226.Sheets("Pareto Chart").Cells(5, 2) = Sol(4)
227.Sheets("Pareto Chart").Cells(6, 2) = Sol(5)
228.Sheets("Pareto Chart").Cells(7, 2) = Sol(6)
229.Sheets("Pareto Chart").Cells(8, 2) = Sol(7)
230.Sheets("Pareto Chart").Cells(9, 2) = Sol(8)
231.Sheets("Pareto Chart").Cells(10, 2) = Sol(9)
232.Sheets("Pareto Chart").Cells(2, 3) = Sol(16) / 3
233.Sheets("Pareto Chart").Cells(3, 3) = Sol(16) / 3
234.Sheets("Pareto Chart").Cells(4, 3) = Sol(16) / 3
235.Sheets("Pareto Chart").Cells(5, 3) = Sol(17) / 3
236.Sheets("Pareto Chart").Cells(6, 3) = Sol(17) / 3
237.Sheets("Pareto Chart").Cells(7, 3) = Sol(17) / 3
238.Sheets("Pareto Chart").Cells(8, 3) = Sol(18) / 3
239.Sheets("Pareto Chart").Cells(9, 3) = Sol(18) / 3
240.Sheets("Pareto Chart").Cells(10, 3) = Sol(18) / 3
241.Sheets("Pareto Chart").Cells(2, 5) = Sol(20) / 3
```

```
242. Sheets("Pareto Chart").Cells(3, 5) = Sol(20) / 3
243. Sheets("Pareto Chart").Cells(4, 5) = Sol(20) / 3
244. Sheets("Pareto Chart").Cells(5, 5) = Sol(21) / 3
245. Sheets("Pareto Chart").Cells(6, 5) = Sol(21) / 3
246. Sheets("Pareto Chart").Cells(7, 5) = Sol(21) / 3
247. Sheets("Pareto Chart").Cells(8, 5) = Sol(22) / 3
248. Sheets("Pareto Chart").Cells(9, 5) = Sol(22) / 3
249. Sheets("Pareto Chart").Cells(10, 5) = Sol(22) / 3
250.
251. With Sheets("Pareto Chart")
252.
253.     .Range("A2:F10").Sort .Range("B2:B10"), xlDescending
254.
255. End With
256.
257. ' Turn automatic calculation back on
258. Application.Calculation = xlCalculationAutomatic
259.
260. ' Turn screen updating on
261. Application.ScreenUpdating = True
262. End Sub
```

Appendix C

Table C- 1: 16000 TEU vessel GA set of twenty best alternatives selected (16000 TEUs vessel)

ID	G0	G1	G2	G3	G4	G5	G6	G7	G8	Pro1 (TEU/hr)	Unit cost 1 ($/TEU)	Pro2 (TEU/hr)	Unit cost 2 ($/TEU)	Pro3 (TEU/hr)	Unit cost 3 ($/TEU)	Total time (hr)	Total Cost ($)	Productivity total (TEU/hr)	Unit cost average ($/TEU)
A	3	30	5	3	30	5	3	30	5	165.990	3.349	332.700	2.581	204.090	2.724	107.974	84789	296.369	2.650
B	3	14	5	3	30	5	3	14	5	165.990	2.536	332.700	2.581	193.424	2.177	108.622	81522	294.600	2.548
C	3	12	4	3	29	5	3	27	4	153.960	2.542	332.700	2.556	204.090	2.538	109.103	81716	293.300	2.554
D	3	22	5	3	20	3	3	13	5	165.990	2.943	332.700	2.175	179.608	2.297	109.576	71748	292.033	2.242
E	3	11	3	3	26	4	3	23	4	141.130	2.624	332.700	2.404	204.090	2.373	110.520	77375	289.539	2.418
F	3	11	4	3	21	4	3	14	4	141.130	2.714	332.700	2.277	193.424	2.111	111.169	73513	287.850	2.297
G	3	20	4	3	23	5	3	11	4	165.990	2.765	332.700	2.404	151.976	2.520	112.006	78068	285.699	2.440
H	3	12	4	3	19	3	3	23	3	153.960	2.542	332.700	2.150	160.770	2.933	112.272	71625	285.022	2.238
I	3	10	5	3	30	5	3	14	5	128.300	3.018	332.700	2.581	193.424	2.177	112.869	82679	283.513	2.584
J	3	24	2	3	24	4	3	26	4	122.760	3.807	332.700	2.353	204.090	2.497	113.065	79132	283.023	2.473
K	3	16	5	3	21	4	3	10	3	165.990	2.638	332.700	2.277	138.160	2.620	113.585	74551	281.727	2.330
L	3	14	3	3	19	3	2	10	3	165.990	2.383	332.700	2.150	136.060	2.073	113.853	69179	281.063	2.162
M	3	9	2	3	26	5	3	19	4	115.470	2.951	332.700	2.480	204.090	2.207	114.299	79834	279.966	2.495
N	3	22	2	3	20	3	3	13	5	122.760	3.670	332.700	2.175	179.608	2.297	114.668	73493	279.066	2.297
O	2	27	5	3	25	3	3	30	4	110.660	4.074	332.700	2.302	204.090	2.662	115.203	78788	277.771	2.462
P	3	25	4	3	20	3	2	9	4	165.990	3.019	332.700	2.175	124.344	2.302	115.515	71944	277.020	2.248
Q	3	25	2	3	21	4	3	24	3	122.760	3.876	332.700	2.277	160.770	2.986	116.234	78402	275.307	2.450
R	3	8	5	3	24	5	3	19	4	102.640	3.608	332.700	2.429	204.090	2.207	116.898	80030	273.744	2.501
S	3	9	3	3	19	3	3	18	3	115.470	3.061	332.700	2.150	160.770	2.671	117.468	72240	272.414	2.258
T	3	10	4	3	23	5	2	19	4	128.300	2.919	332.700	2.404	136.060	2.724	118.101	78928	270.955	2.467

Table C- 2: Set of ranked best 20 alternatives Matrix craiteria

ID	Pro1	Pro2	Pro3	Productivity	C1	C2	C3	Time	Unit cost
A	165.99	332.7	204.09	296.369	3.349	2.581	2.724	107.974	2.650
B	165.99	332.7	193.424	294.600	2.536	2.581	2.177	108.622	2.548
C	153.96	332.7	204.09	293.300	2.542	2.556	2.538	109.103	2.554
D	165.99	332.7	179.608	292.033	2.943	2.175	2.297	109.576	2.242
E	141.13	332.7	204.09	289.539	2.624	2.404	2.373	110.520	2.418
F	141.13	332.7	193.424	287.850	2.714	2.277	2.111	111.169	2.297
G	165.99	332.7	151.976	285.699	2.765	2.404	2.520	112.006	2.440
H	153.96	332.7	160.77	285.022	2.542	2.150	2.933	112.272	2.238
I	128.3	332.7	193.424	283.513	3.018	2.581	2.177	112.869	2.584
J	122.76	332.7	204.09	283.023	3.807	2.353	2.497	113.065	2.473
K	165.99	332.7	138.16	281.727	2.638	2.277	2.620	113.585	2.330
L	165.99	332.7	136.06	281.063	2.383	2.150	2.073	113.853	2.162
M	115.47	332.7	204.09	279.966	2.951	2.480	2.207	114.299	2.495
N	122.76	332.7	179.608	279.066	3.670	2.175	2.297	114.668	2.297
O	110.66	332.7	204.09	277.771	4.074	2.302	2.662	115.203	2.462
P	165.99	332.7	124.344	277.020	3.019	2.175	2.302	115.515	2.248
Q	122.76	332.7	160.77	275.307	3.876	2.277	2.986	116.234	2.450
R	102.64	332.7	204.09	273.744	3.608	2.429	2.207	116.898	2.501
S	115.47	332.7	160.77	272.414	3.061	2.150	2.671	117.468	2.258
T	128.3	332.7	136.06	270.955	2.919	2.404	2.724	118.101	2.467

Table C- 3: Decision matrix normalization

ID	Pro1	Pro2	Pro3	Productivity	C1	C2	C3	Time	Unit cost
A	27552.7	110689.3	41652.7	87834.5	11.2	6.7	7.4	11658.3	7.0
B	27552.7	110689.3	37412.8	86788.9	6.4	6.7	4.7	11798.7	6.5
C	23703.7	110689.3	41652.7	86024.9	6.5	6.5	6.4	11903.5	6.5
D	27552.7	110689.3	32259.0	85283.6	8.7	4.7	5.3	12007.0	5.0
E	19917.7	110689.3	41652.7	83832.9	6.9	5.8	5.6	12214.8	5.8
F	19917.7	110689.3	37412.8	82857.8	7.4	5.2	4.5	12358.5	5.3
G	27552.7	110689.3	23096.7	81623.9	7.6	5.8	6.4	12545.3	6.0
H	23703.7	110689.3	25847.0	81237.7	6.5	4.6	8.6	12605.0	5.0
I	16460.9	110689.3	37412.8	80379.8	9.1	6.7	4.7	12739.5	6.7
J	15070.0	110689.3	41652.7	80101.8	14.5	5.5	6.2	12783.7	6.1
K	27552.7	110689.3	19088.2	79370.0	7.0	5.2	6.9	12901.6	5.4
L	27552.7	110689.3	18512.3	78996.6	5.7	4.6	4.3	12962.6	4.7
M	13333.3	110689.3	41652.7	78381.1	8.7	6.1	4.9	13064.4	6.2
N	15070.0	110689.3	32259.0	77878.0	13.5	4.7	5.3	13148.8	5.3
O	12245.6	110689.3	41652.7	77156.6	16.6	5.3	7.1	13271.7	6.1
P	27552.7	110689.3	15461.4	76739.8	9.1	4.7	5.3	13343.8	5.1
Q	15070.0	110689.3	25847.0	75794.0	15.0	5.2	8.9	13510.3	6.0
R	10535.0	110689.3	41652.7	74935.8	13.0	5.9	4.9	13665.0	6.3
S	13333.3	110689.3	25847.0	74209.6	9.4	4.6	7.1	13798.8	5.1
T	16460.9	110689.3	18512.3	73416.6	8.5	5.8	7.4	13947.8	6.1
SumX^2	407690.6	2213785.8	640537.6	1602843.8	191.2	110.4	121.9	256229.2	116.1
(sumX^2)^0.5	638.5	1487.9	800.3	1266.0	13.8	10.5	11.0	506.2	10.8

Table C- 4: Divide each column by (Sumx^2)^0.5

ID	Pro1	Pro2	Pro3	Productivity	C1	C2	C3	Time	Unit cost
A	0.259966	0.2236068	0.255005412	0.2340922	0.242231	0.245711	0.24671	0.213306	0.245919
B	0.259966	0.2236068	0.241678508	0.2326947	0.183409	0.245711	0.197107	0.214587	0.236445
C	0.241125	0.2236068	0.255005412	0.2316682	0.183868	0.243297	0.229859	0.215538	0.237006
D	0.259966	0.2236068	0.224415758	0.2306678	0.21282	0.20708	0.208015	0.216473	0.208097
E	0.221031	0.2236068	0.255005412	0.2286977	0.189773	0.228809	0.214883	0.218338	0.224416
F	0.221031	0.2236068	0.241678508	0.2273637	0.196259	0.216739	0.191178	0.219619	0.213215
G	0.259966	0.2236068	0.189890257	0.2256644	0.199953	0.228813	0.228234	0.221272	0.226425
H	0.241125	0.2236068	0.200878142	0.2251298	0.183868	0.204666	0.265651	0.221798	0.20774
I	0.200938	0.2236068	0.241678508	0.2239381	0.218263	0.245711	0.197107	0.222978	0.2398
J	0.192261	0.2236068	0.255005412	0.2235504	0.275338	0.223981	0.226115	0.223365	0.229513
K	0.259966	0.2236068	0.172627506	0.222527	0.190762	0.216739	0.237227	0.224392	0.216225
L	0.259966	0.2236068	0.170003608	0.2220029	0.17238	0.204666	0.18774	0.224922	0.200646
M	0.180844	0.2236068	0.255005412	0.2211364	0.213448	0.236055	0.199907	0.225803	0.231549
N	0.192261	0.2236068	0.224415758	0.2204254	0.265396	0.20708	0.208015	0.226531	0.213157
O	0.173311	0.2236068	0.255005412	0.2194022	0.294619	0.21915	0.241091	0.227588	0.228516
P	0.259966	0.2236068	0.155364755	0.2188088	0.218335	0.20708	0.208507	0.228205	0.208665
Q	0.192261	0.2236068	0.200878142	0.2174562	0.280309	0.216739	0.270404	0.229625	0.227394
R	0.16075	0.2236068	0.255005412	0.2162215	0.260938	0.231227	0.199907	0.230936	0.232118
S	0.180844	0.2236068	0.200878142	0.2151713	0.221375	0.204666	0.241887	0.232063	0.209523
T	0.200938	0.2236068	0.170003608	0.2140187	0.211129	0.228813	0.246712	0.233313	0.228921

Table C-5: multiply each column by wj to get A* and A`.

wj	0.05	0.1	0.05	0.25	0.05	0.1	0.05	0.1	0.25
ID	Pro1	Pro2	Pro3	Productivity	C1	C2	C3	Time	Unit cost
A	0.012998	0.02236068	0.012750271	0.058523	0.012112	0.024571111	0.012335486	0.021331	0.0614798
B	0.012998	0.02236068	0.012083925	0.058174	0.00917	0.024571111	0.009855344	0.021459	0.0591113
C	0.012056	0.02236068	0.012750271	0.057917	0.009193	0.02432971	0.011492949	0.021554	0.0592515
D	0.012998	0.02236068	0.011220788	0.057667	0.010641	0.02070797	0.010400731	0.021647	0.0520242
E	0.011052	0.02236068	0.012750271	0.057174	0.009489	0.022880942	0.01074415	0.021834	0.056104
F	0.011052	0.02236068	0.012083925	0.056841	0.009813	0.021673934	0.009558914	0.021962	0.0533037
G	0.012998	0.02236068	0.009494513	0.056416	0.009998	0.0228813	0.011411714	0.022127	0.0566062
H	0.012056	0.02236068	0.010043907	0.056282	0.009193	0.020466568	0.013282559	0.02218	0.0519349
I	0.010047	0.02236068	0.012083925	0.055985	0.010913	0.024571111	0.009855344	0.022298	0.0599499
J	0.009613	0.02236068	0.012750271	0.055888	0.013767	0.022398139	0.011305749	0.022336	0.0573783
K	0.012998	0.02236068	0.008631375	0.055632	0.009538	0.021673934	0.011861353	0.022439	0.0540563
L	0.012998	0.02236068	0.00850018	0.055501	0.008619	0.020466568	0.009387022	0.022492	0.0501614
M	0.009042	0.02236068	0.012750271	0.055284	0.010672	0.023605505	0.009995352	0.02258	0.0578871
N	0.009613	0.02236068	0.011220788	0.055106	0.01327	0.02070797	0.010400731	0.022653	0.0532892
O	0.008666	0.02236068	0.012750271	0.054851	0.014731	0.021914978	0.012054548	0.022759	0.0571289
P	0.012998	0.02236068	0.007768238	0.054702	0.010917	0.02070797	0.010425347	0.022821	0.0521664
Q	0.009613	0.02236068	0.010043907	0.054364	0.014015	0.021673934	0.0135202	0.022962	0.0568484
R	0.008038	0.02236068	0.012750271	0.054055	0.013047	0.023122701	0.009995352	0.023094	0.0580295
S	0.009042	0.02236068	0.010043907	0.053793	0.011069	0.020466568	0.012094353	0.023206	0.0523808
T	0.010047	0.02236068	0.00850018	0.053505	0.010556	0.0228813	0.012335624	0.023331	0.0572302
A*	0.012998	0.02236068	0.012750271	0.058523	0.008619	0.020466568	0.009387022	0.021331	0.0501614
A`	0.008038	0.02236068	0.007768238	0.053505	0.014731	0.024571111	0.0135202	0.023331	0.0614798

Table C- 6: define the POS separation measures for each alternative , S*

ID	Pro1	Pro2	Pro3	Productivity	C1	C2	C3	Time	Unit cost		S*
A	0	0	0	0	1.21978E-05	1.68473E-05	8.69344E-06	0	0.000128	0.000166	0.012878
B	0	0	4.44016E-07	1.22062E-07	3.04101E-07	1.68473E-05	2.19326E-07	1.64109E-08	8.01E-05	9.81E-05	0.009902
C	8.87443E-07	0	0	3.67242E-07	3.29907E-07	1.49239E-05	4.43493E-06	4.98133E-08	8.26E-05	0.000104	0.01018
D	0	0	2.33932E-06	7.32893E-07	4.08847E-06	5.82748E-08	1.02761E-06	1.00275E-07	3.47E-06	1.18E-05	0.003438
E	3.78976E-06	0	0	1.81882E-06	7.56283E-07	5.8292E-06	1.8418E-06	2.53159E-07	3.53E-05	4.96E-05	0.007043
F	3.78976E-06	0	4.44016E-07	2.8296E-06	1.4255E-06	1.45773E-06	2.95469E-08	3.98482E-07	9.87E-06	2.02E-05	0.0045
G	0	0	1.06E-05	4.43925E-06	1.90063E-06	5.83093E-06	4.09938E-06	6.34613E-07	4.15E-05	6.9E-05	0.008309
H	8.87443E-07	0	7.3244E-06	5.02025E-06	3.29907E-07	0	1.51752E-05	7.21084E-07	3.15E-06	3.26E-05	0.00571
I	8.71087E-06	0	4.44016E-07	6.44419E-06	5.26311E-06	1.68473E-05	2.19326E-07	9.35489E-07	9.58E-05	0.000135	0.011605
J	1.14599E-05	0	0	6.94563E-06	2.65005E-05	3.73097E-06	3.68151E-06	1.01178E-06	5.21E-05	0.000105	0.010267
K	0	0	1.69653E-05	8.35971E-06	8.44726E-07	1.45773E-06	6.12231E-06	1.229E-06	1.52E-05	5.01E-05	0.007082
L	0	0	1.80633E-05	9.13443E-06	0	0	0	1.34924E-06	0	2.85E-05	0.005343
M	1.56508E-05	0	0	1.04909E-05	4.21642E-06	9.85292E-06	3.70065E-07	1.56177E-06	5.97E-05	0.000102	0.010091
N	1.14599E-05	0	2.33932E-06	1.16738E-05	2.16296E-05	5.82748E-08	1.02761E-06	1.7491E-06	9.78E-06	5.97E-05	0.007728
O	1.87729E-05	0	0	1.34873E-05	3.73559E-05	2.09789E-06	7.11569E-06	2.03972E-06	4.85E-05	0.000129	0.011376
P	0	0	2.48207E-05	1.4599E-05	5.27954E-06	5.82748E-08	1.07812E-06	2.21982E-06	4.02E-06	5.21E-05	0.007216
Q	1.14599E-05	0	7.3244E-06	1.72973E-05	2.91213E-05	1.45773E-06	1.70832E-05	2.66294E-06	4.47E-05	0.000131	0.011451
R	2.46095E-05	0	0	1.99601E-05	1.96062E-05	7.05504E-06	3.70065E-07	3.10806E-06	6.19E-05	0.000137	0.011688
S	1.56508E-05	0	7.3244E-06	2.2375E-05	6.0013E-06	0	7.32964E-06	3.5182E-06	4.93E-06	6.71E-05	0.008193
T	8.71087E-06	0	1.80633E-05	2.51842E-05	3.7536E-06	5.83093E-06	8.69426E-06	4.00268E-06	5E-05	0.000124	0.011145

Table C-7: define the NOI separation measures for each alternative, S`

ID	Pro1	Pro2	Pro3	Productivity	C1	C2	C3	Time	Unit cost		S`
A	2.46095E-	0	2.48207E-	2.51842E-	6.86129E-	0	1.40355E-06	4.00268E-	0	8.69E-05	0.009321
B	2.46095E-	0	1.86252E-	2.17997E-	3.09191E-	0	1.34312E-05	3.5065E-06	5.61E-06	0.000119	0.010886
C	1.61504E-	0	2.48207E-	1.94691E-	3.06647E-	5.82748E-	4.10975E-06	3.15944E-	4.97E-06	0.000103	0.010168
D	2.46095E-	0	1.19201E-	1.73247E-	1.67277E-	1.49239E-	9.73108E-06	2.83589E-	8.94E-05	0.000187	0.013692
E	9.08459E-	0	2.48207E-	1.34671E-	2.74817E-	2.85667E-	7.70645E-06	2.24257E-	2.89E-05	0.000117	0.010796
F	9.08459E-	0	1.86252E-	1.11305E-	2.41868E-	8.39364E-	1.56918E-05	1.8753E-06	6.68E-05	0.000156	0.012483
G	2.46095E-	0	2.98003E-	8.47646E-	2.24042E-	2.85546E-	4.44571E-06	1.44972E-	2.38E-05	9.1E-05	0.009538
H	1.61504E-	0	5.17867E-	7.71615E-	3.06647E-	1.68473E-	5.64733E-08	1.32596E-	9.11E-05	0.000169	0.013002
I	4.03759E-	0	1.86252E-	6.14964E-	1.45756E-	0	1.34312E-05	1.06805E-	2.34E-06	6.02E-05	0.007761
J	2.48236E-	0	2.48207E-	5.67837E-	9.29457E-	4.72181E-	4.90379E-06	9.89622E-	1.68E-05	6.13E-05	0.007833
K	2.46095E-	0	7.45006E-	4.52444E-	2.69658E-	8.39364E-	2.75177E-06	7.95786E-	5.51E-05	0.000124	0.011131
L	2.46095E-	0	5.3574E-07	3.98428E-	3.73559E-	1.68473E-	1.70832E-05	7.04091E-	0.000128	0.000229	0.01514
M	1.0094E-06	0	2.48207E-	3.16635E-	1.64719E-	9.32396E-	1.24246E-05	5.63943E-	1.29E-05	7.23E-05	0.008503
N	2.48236E-	0	1.19201E-	2.56542E-	2.13505E-	1.49239E-	9.73108E-06	4.59867E-	6.71E-05	0.000111	0.01055
O	3.94419E-	0	2.48207E-	1.81139E-	0	7.05504E-	2.14814E-06	3.27738E-	1.89E-05	5.55E-05	0.007449
P	2.46095E-	0	0	1.43408E-	1.45483E-	1.49239E-	9.57812E-06	2.60879E-	8.67E-05	0.000152	0.012333
Q	2.48236E-	0	5.17867E-	7.38543E-	5.11989E-	8.39364E-	0	1.36028E-	2.14E-05	3.89E-05	0.006236
R	0	0	2.48207E-	3.03293E-	2.83603E-	2.09789E-	1.24246E-05	5.65017E-	1.19E-05	5.44E-05	0.007379
S	1.0094E-06	0	5.17867E-	8.30385E-	1.34117E-	1.68473E-	2.03304E-06	1.5621E-08	8.28E-05	0.000121	0.011017
T	4.03759E-	0	5.3574E-07	0	1.74267E-	2.85546E-	1.40322E-06	0	1.81E-05	4.43E-05	0.006657

Table C-8: Calculate the relative closeness to the ideal solution Ci* = S'i / (Si* +S'i) and rank the alternatives, the farthest from the NOS is the best

ID	S*	S`	C*=[S`/(S`+S*)]	Distance from best solution	Ranking
A	0.013	0.009	0.420	0.379	15
B	0.010	0.011	0.524	0.276	11
C	0.010	0.010	0.500	0.300	12
D	0.003	0.014	0.799	0.000	1
E	0.007	0.011	0.605	0.194	7
F	0.004	0.012	0.735	0.064	3
G	0.008	0.010	0.534	0.265	10
H	0.006	0.013	0.695	0.104	4
I	0.012	0.008	0.401	0.399	16
J	0.010	0.008	0.433	0.367	14
K	0.007	0.011	0.611	0.188	6
L	0.005	0.015	0.739	0.060	2
M	0.010	0.009	0.457	0.342	13
N	0.008	0.011	0.577	0.222	8
O	0.011	0.007	0.396	0.404	17
P	0.007	0.012	0.631	0.168	5
Q	0.011	0.006	0.353	0.447	20
R	0.012	0.007	0.387	0.412	18
S	0.008	0.011	0.573	0.226	9
T	0.011	0.007	0.374	0.425	19