Optimization of port processes

Simulation of a container terminal
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Abstract

Container terminals are rapidly congested due to globalization and international trade. More than 80 per cent of the amount of products is shipped by sea in standardized containers. In order to reduce the traffic in CT they have to increase their operational efficiency. The Berth Allocation Problem (BAP) and its most complex version Berth Allocation and Quay Crane Assignment Problem (BAQCAP) are key issues for the efficient operation of a CT. This thesis focuses on how BAQCAP and factors such as priority between ships, time between arrivals and handling time of quay cranes affect the process of loading and unloading. For the purpose of our research we simulate three different scenarios with the help of ARENA 14.7 simulation software. The results have slightly differences although we concluded that the berth dedicated to a company was the worst scenario.

Keywords: Containers, Containerships, Container Terminal, Port operations,Berth Allocation Problem, Berth Allocation and Quay Crane Assignment Problem, port of Thessaloniki, Simulation, Arena simulation program.
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Acronyms

AGC: Automated Gantry Crane
AGV: Automatic Guided Vehicles
ALV: Automated Lifting Vehicles
CT: Container Terminal
DGPS: Differential Global Positioning System
BAP: Berth Allocation Problem
BAQCAP: Berth Allocation and Quay Crane Assignment Problem
FCFS: First Come - First Served
GPS: Global Positioning System
ISO: International Organization for Standardization
MIP: Mixed Integer Programming
OBC: Overhead Bridge Cranes
QC: Quay Crane
RMG: Rail Mounted Gantry cranes
RTG: Rubber Tired Gantries
SC: Straddle Carriers
TEU: Twenty-foot Equivalent Unit
1. **Introduction**

A container terminal (CT) is part of a port within which containerized cargo is transported from land to sea and from sea to land. When containers arrive from the ocean, they are fairly often transported to a different kind of transport, like a lorry or, increasingly, a train. Depending on the size of the port and its throughput, the port could have one or more container terminals. The Port of Rotterdam, one amongst the busiest ports in the world has nine container terminals, while the Port of Rijeka, Croatia, has only one. Certain container terminals target particular kinds of trade, like maritime transshipment. This is where a container is being moved from one vessel to a different one as a part of its journey. This is able to happen when there is no direct link between port facilities of arrival and departure. For some major ports, such as Mumbai, transshipment will represent an oversized amount of its throughput (Schwerdtfeger, 2019). The overall amount of containerized trade in 2016 surpassed 140 million TEUs (twenty-foot equivalent units), and more than 30 million TEUs were handled by the most important ports, such as Shanghai and Singapore. Overall, the growth in the volume of containerized trade was more than 40% in the 2007-2016 decade (UNCTAD, 2017).

Container terminals are strategically placed as critical points of a fancy logistic network. Maritime terminals host the transfer of containers from ocean vessels to road and rail vehicles and canal barges, and vice-versa. They are often a part of a bigger port, the biggest of which is found around major ports. When the transshipment is between rail and road, the facility is named as an inland container terminal. These are placed in or nearby major cities and are well-connected to maritime containers by rail.

Connections to maritime terminals within the hinterland are vital to the provision chain. Consider the numerous landlocked countries in Europe that are unable to trade with non-neighboring countries due to a lack of connectivity. The European Sea Ports Organization, which represents all ports within the European Union, has stated that “it is essential to build a sustainable pan-European transport network connecting all relevant ports with main inland nodes.” As many European countries have not any seaports, their economic proper functioning relies heavily on having land connections to seaports in other countries.

Considering the USA as well as the vast area of land cargo has to be distributed throughout. The estimated volume of international freight traffic for 2020 is anticipated
to be 4 million tons per day. That is lots of freight and an enormous demand for efficient inland operations.(Conatiner-xchange, 2020)

For proper operation a container terminal should be able to provide the below:

1. Access from the sea
2. Berth places and quay cranes for loading and unloading ships
3. Anchorage for ships waiting to enter a berth place
4. Cargo management areas, such as:
   • Storage area of full containers
   • Storage space of empty containers
   • Container filling and emptying shed when these procedures are required.
5. Auxiliary spaces, such as:
   • Trailer parking spaces
   • Storage areas of the machines
   • Equipment maintenance areas
   • Vehicle parking spaces
   • Areas for internal highways
   • Areas for connecting train rails.
6. Connection to land transport
7. Cargo management systems inside the station
8. Other places, such as:
   • Administration offices
   • Customs
   • Housing and other services.

Figure 1.1 shows the structure of a terminal. Container terminal can be described as an open material flow system with two workstations. These are the quay, which is the land part next to the berthing sites where the ships are loaded and unloaded and the areas in the hinterland where the containers are delivered and picked up by / from trucks and trains. Containers are stored in layers depending on their destination. (Gargalis & Leivadaras, 2013)
Depending on their ownership between ports, operators, shipping lines and carriers, the container terminals around the world are classified into five main types: Public Terminals, Carrier-leased Terminals, joint venture of the Carriers and Terminal operators, Terminals those are Operator built and operated terminals and finally Carrier built and operated terminals. The following is a brief overview of the five types of terminals:

1. **Public or states run terminals**

   Since they operate on a first come first serve basis, all the facilities of the public terminals such as tariff rates, loading and unloading processes, berths in and out, etc. are shared equally among all the shipping lines. The handling of the containers and other related charges are mostly calculated at regular tariff rates or discounted upon agreed rates.

2. **Carrier-Lease dedicated terminals**
With such terminals in operation, major carriers have cooperated with the port authorities and signed long term lease contracts for the use of terminals. The carriers are liable to pay facility charges, contract kickbacks, berth rents, etc. Maersk group being one of the largest carriers in the world has contracted a large number of terminals for their long-term usage. There are also a few partnerships between shipping lines that have long-term multi-user contracts to share terminal usages.

3. Joint venturing of the carriers and terminal operators

In this type of contract, an agreement is concluded between the shipping lines and the terminal operators, thereby establishing a company. Direct investments are made and terminals are jointly operated for safe, prioritized and efficient handling of containers.

4. Terminals built and operated terminals

Terminal operators invest directly in the construction, operation, handling facilities of a terminal. Operators shall enter into lease agreements with the port authorities by depositing a sum in respect of the total handling charges for the container operation.

5. Carrier – built and operated terminals

The methodology is similar to the one for terminal built and operated terminals. In this type of licensing, the carrier or several carriers lease CTs together by making deposits to the port authorities or by investing directly in their construction, operation and handling services. (Signh, 2019)

Liner ships have a key role in global trade network, transferring almost 60% of the value of the products that they are transferred by sea. They are offering fast, often and reliable transfer for almost all products to any destination and they are giving the opportunity to anyone that uses them to know transportation cost and the time. Therefore, for the traders it is possible to adjust better their prices and their orders, reducing simultaneously the cost variation. This stability of the liner ships is very crucial both for the global market and the maritime.

Liner ships are a relatively new addition in maritime. They started at 1870’s when the scheduled trips could be possible with the help of steamships. At the beginning these trips were very short, but after the construction of Suez Canal and the big prospects of profitability from the East, the trips were rapidly expanded and reached the today’s standards according to which the transportation of every product is possible in every place of the world. (Gargalis & Leivadaras, 2013)
Interestingly, even then the fast growth of transportation technology did not bring about a drastic improvement in the way cargo was delivered. Infrequently, goods were consolidated into larger units mounted by longshoremen or cranes on railroad flatcars, barges, trucks, and ships. But quite often, freight of various shapes and sizes was regularly held in a ship's hold or in boxcars; upon arrival at its destination, the freight was again transferred, piece by piece, by longshoremen. The use of break-bulk cargo persisted well during the 1900's, almost 100 years after the invention of the steamship.

During the Second World War, sea freight transportation increased even more drastically. Whereas the growth resulted in higher storage space, merchant shipping tended to use the conventional break-bulk system for storing cargo. One effect of the increased storage capacity was the delay that ships faced when waiting in port for their cargo to be moved. After the war, intermodal transportation started to experience major changes.

In the mid-1950, Malcolm McLean, the founder of McLean Trucking Company, developed a new approach to cargo shipping. Recognizing that freight forwarders could make considerable savings if the loading and unloading requirements for freight were streamlined, McLean suggested that all forms of cargo should be put in a container suitable for rail, land or sea transport (the cargo would not be restowed in other containers). In addition, in its system containers, gantry cranes would be transported to and from the ship, and railroad cars would then be used to transport the chassis a container in piggyback mode to the next destination. In April 1956, the 55 Maxton, using these methods, successfully transported 66 containers from New York to Houston. The idea of containerization caught on rapidly, and by 1965, McLean had set up a new container shipping firm, Sea-Land Service, Inc., which maintained frequent routes along the U.S. east coast. Motivated by McLean's intermodal example, the freight industry experienced a container revolution from about 1965 to 1972. The revolution was supported and strengthened by the particular benefits of containerization: since a ship whose cargo was in containers could be loaded and unloaded by modern wharf cranes, the amount of time a ship was in port was greatly reduced.

The customers become more and more attracted by the use of containers due to this reduction in transfer delays. At the same time the size of containerships increased dramatically to 3,000 TEU’s (twenty-foot equivalent unit). These changes at containerships were made not only for the transportation of more containers, but also for accelerating the loading and unloading procedures. In the hold and on the deck of a ship were placed container guides and permanent castings. With this change general cargo
vessels transformed into cellularized ships, making the stacking and the securing of containers much easier. (Kiesling & Walton, 1995)

Another crucial factor of the change of shipping was CTs. In the past, ports had miles’ long berths and near them were several warehouses. The ships were docked in the berths for weeks loading and unloading their cargo. The first CTs were completely different; they had two or three berths which were served by cranes. The cranes were storing the containers in open spaces. As mentioned before Sea-Land Service, Inc. was using railroad cars in order to speed up the procedure of loading and unloading a vessel, other companies were stacking the containers, up to three or four, and then they loaded again depending on their destination. Nowadays, these procedures have been automated with the use of special lifting vehicles and other automatic systems. These changes have been proved very beneficial, due to the reduction of loading and unloading time. Furthermore, there has been a dramatic improvement in efficiency, giving the opportunity to container terminals to handle more containers.

The next five years after the adoption of containers, there was an increase in trade by 320% between twenty-two industrialized countries, while for the next 20 years this increase was almost 790%. In contrary, the significant reduction of restrictions in bilateral agreements in world trade, which initially promoted as an idea by the foundation of European Union and afterward by the GATT (General Agreement on Tariffs and Trade) organization, it is response for the 285% growth of world freight.

The above are conclusions from a study conducted by Bernhofen, El-Sahli Kneller and examined the impact of the container on economic figures, considering the container one of the most important things for the evolution of the world economy during the 20th century. (Gargalis & Leivadaras, 2013)

1.1 Aim of the thesis

The aim of the thesis is to highlight the contribution that can be made by the use of simulation models in the description and confrontation of the extensive interdependencies presented by the functions of a CT, with the ultimate goal of using these tools to optimize the latter.

1.2 Outline of the thesis

In the first chapter of the paper, we are discussing the basic concepts such as what
a CT is, what containers are and how they established in maritime trade, what types of cargo ships exist and what equipment a CT uses.

In the second chapter we examine the different ways of loading and unloading process in a CT and the procedures that are followed. In the continuation of the chapter, we present the important decisions that must be taken for a CT, in our research we focus on those that must be taken during loading and unloading process and specifically in the berth allocation problem (BAP) and the berth allocation and quay crane assignment problem (BAQCAP). This chapter also refers to the importance of simulation and the simulation program we use (Arena 14.7).

In the third chapter the literature review is presented, and we focus mainly on the operational issues of the seaside in a CT. Next, we focus on the berth allocation problem and its more complex form which is the berth allocation and quay crane assignment problem. Finally, we refer to the research that has been done for the contribution of simulation to the operation of a CT.

The fourth chapter describes the simulation model and its design. Then we refer to the parameters and objectives of the model, which is to highlight the way in which different variables influence the operation of a CT. At the end of the chapter are presented in detail the three scenarios that will be examined.

The fifth chapter is dedicated to the results of the research. Initially the results are presented per simulation scenario and at the end the comparison is made for all three scenarios.

The sixth chapter provides an overview of what has been written so far and presents the conclusions of our research. Also, at the end of the chapter, suggestions are made for future research related to the subject of our dissertation.

1.3 The Container

Containers are generally made of aluminum or steel with each container size and type built in accordance with the same International Organization for Standardization (ISO) specifications, no matter where the container is manufactured. There are containers of varying standard sizes – 20 foot (6.09 m), 40 foot (12.18 m), 45 foot (13.7 m), 48 foot (14.6 m) and 53 foot (16.15 m) – for loading, transporting and unloading goods. As a result, containers are often seamlessly moved between ships, trucks and trains. The two most significant and most frequently used sizes today are the 20-foot and 40-foot lengths.
The 20-foot container, stated as the Twenty-foot Equivalent Unit (TEU), is now the industry standard reference, so now cargo volume and vessel capacity are commonly measured in TEU. The 40-foot container-literally 2 TEU - became referred to as the Forty-foot Equivalent Unit (FEU) and is today the most commonly used container.

Container sizes must be standardized in order that the containers can be stacked most efficiently-literally, one on top of the other-so that ships, trains, trucks and cranes at ports will be specially fitted or built to a specific size. This standardization now applies to the entire world industry, due to the work of the ISO that set standard sizes for all containers in 1961.

Shipping containers are available in a range of styles additionally to the standard dry cargo container often mentioned as "special" equipment. These special containers include the open end, the open side, the open top, the half-height, the flat rack, the refrigerated (known as the "reefer"), the liquid bulk (tank) and modular all built to same exterior lengths and widths as the standard dry cargo containers. Containers within the global container fleet equate to over 34 million TEU.

Open tops containers provide the ability to remove the top of the container, so that materials of any height can be easily transported such as logs. Flat racks have collapsible sides; they are similar to simple storage shipping containers with foldable sides and can be used to create a flat rack for shipping a wide range of products. Flat racks are often used for ships, vehicles, machinery or industrial equipment. Open-sided containers are equipped with doors that can be turned into fully open sides, providing a much wider space for material loading such as vegetables. A platform container has no sides, ends, and a roof. It is used for freight that is too big to carry on (Figure 1.2).

Each container has its own unique unit number, often called a box number that may be utilized by ship captains, crews, coast guards, dock supervisors, customs officers and warehouse managers to find out who owns the container, who uses the container to ship goods, and even to track the container's location anywhere in the world. (World Shipping Council, 2020)
Even if containerization offers various benefits to the delivery of freight, it does not come without difficulties (Figure 1.3). The key benefits of containerization are as follows:

1. **Standardization.** The container is a standard transport item (ISO standard) that can be handled anywhere around the world by means of specialized modes (ships, trucks, barges, and wagons) and equipment. Each container has its own unique identification number and a size code type.

2. **Flexibility.** It can be used to carry a wide range of goods such as commodities (coal, wheat), refrigerated (perishable) goods, manufactured goods, and cars. Adapted containers are available for dry cargo, liquids (oil and chemical products), and refrigerated cargo. Abandoned containers may be recycled and reused for other purposes.

3. **Costs.** Lower transport costs due to the benefits of standardization. Moving the same quantity of break-bulk freight in a container is about 20 times cheaper than
traditional means. Containers empower economies of scale in modes and terminals that have not been possible due to standard break-bulk handling.

4. **Velocity.** Transshipment activities are minimal and rapid, and port turnaround times have been decreased from 3 weeks to approximately 24 hours. Owning to this transshipment advantage, the transport chains of the containers involved are longer. Containerships are faster than standard freighter ships.

5. **Warehousing.** The container itself is a warehouse, which protects the cargo it carries. This means cheaper and simpler packaging for containerized cargoes, in particular consumer goods. The stacking capacity on ships, on the ground (container yards) and trains (double stacking) is a net benefit of containerization. With the proper equipment, a container may maximize its stacking density.

6. **Security and safety.** The container contents are unknown to the carrier, since they could only be opened at the origin (seller/shipper), customs and destination (buyer). This means reduced spoilage and losses (theft).

The main **drawbacks** of containerization are:

1. **Site constraints.** Containers are a major user of terminal space (mainly for storage), which means that many intermodal terminals have been moved to the urban outskirts. Draft issues are emerging at the port with the arrival of larger containerships, especially those of the post-Panamax class. A draft of at least 13 meters is needed for a large post-Panamax container.

2. **Capital intensiveness.** Container handling infrastructures and equipment (giant cranes, warehouses, inland roads, rail access) are significant capital investments that involve large amounts of available capital. In addition, the push towards automation is growing the capital intensity of intermodal terminals.

3. **Stacking.** The problem regarding to the layout of containers, both on the ground and in modes (containerships and double-stack trains), requires systematic restacking, which incurs extra costs and time for terminal operators. The larger the loading unit or the yard, the more challenging its operational management.

4. **Repositioning.** Due to trade imbalances, several containers are moving empty (20% of all flows). Nevertheless, either full or empty, the container takes up the same amount of space. The observed disparity between production and consumption at the global scale calls for the reconfiguration of containerized assets over long distances (transoceanic).

5. **Theft and losses.** High-value products and a load unit that can be opened by force or carried away (on a truck) indicate a level of cargo vulnerability between the
terminal and the destination. Approximately 1,500 containers are lost at sea per year (fall overboard), mostly due to bad weather.

6. **Illicit trade.** The container is an instrument used in for the illegal trade in good goods, drugs, and weapons, but also for illegal immigration (rare).(Rodrigue, 2020)

![Figure 1.3: Containerization advantages and drawbacks](www.transportgeography.com)

1.4 **The Containerships**

As the name implies, a vessel structured specifically designed to accommodate massive volumes of cargo compacted in various types of containers is referred to as a container vessel (ship). Container ships are the cargo ships that hold the most maritime non-bulk cargoes. Nowadays, container vessels hold nearly 90% of the world's non-bulk cargoes. One of the main means of shipping finished products worldwide is by container vessels. These containers are of a standardized size so that they can be conveniently transported to different modes of transport. Anything could be carried on a containership.

The introduction of the container shipping is one of the most remarkable innovations in the maritime freight industry. Container ships, a type of cargo ship, have completely changed the way in which cargo supplies are delivered and shipped around the world, by ensuring the safety and protection of the cargo supplies being transported.
Some of the largest shipping companies today associate mainly with the containerized type of freight.

The first container ships were launched in the early 1950s and were primarily designed to transport freight cars from goods trains. Using crane systems and ramp systems, these freight cars may be loaded and unloaded from the vessels. Over the years technical advancements have made comparatively much more practical methodologies possible, while cranes still play a significant role in the loading and unloading operations of the containers from and to the holds of vessels. Specialized lashing and cargo handling systems are used to protect the containers at their locations. Container vessels are representative of the fact that they are designed to accommodate large potential cargo loads. The load holding capacity of container vessels is measured in terms of Twenty-foot Equivalent Units or TEUs, with the largest container ships carrying as much as over 15,000 -16,000 TEUs. Due to such large capacities, some of the largest ships in the world are container ships.

Containers vessels have been through different phases. These phases were labeled as generations.

- **First Generation** – 1956 to 1970
- **Second Generation** – 1970 to 1980
- **Third Generation** – 1980 to 1988
- **Fourth Generation** – 1988 to 2000
- **Fifth Generation** – 2000 to 2005
- **Sixth Generation** – 2006 – until now

Container vessels can be categorized with respect to three different attributes, namely handling mode, size and service range:

1. **Handling Modes**

   **LoLo Container Ships**

   Lift-on/Load-off vessels are the Geared container vessel capable of loading and unloading the cargoes on its own by means the ship’s own crane. They have the ability to work without port cranes and can do unaided cargo operations.

   **ROCON Container Ships**

   ROCONs are Ro-Ro (Roll on/Roll off) vessels that also hold containers. The structures are such that the containers can be loaded onto the deck or there is a different hold exclusively for the loading of the containers.
2. Ship Sizes

Some of the main types of container ships, based on their size (Figure 1.4), are:

**Panamax**

Panamax size vessels were first launched in 1980. These vessels were roughly 4000-5000 TEUs. They had such a dimension that they could pass the Panama Canal. Moreover, they were limited to a maximum length of 294.1m, width of 32.3m and a maximum draught of 12m, which was equal to the size of the canal.

**Post-Panamax**

APL (American President Lines Ltd.) has launched a new transport network without the use of the Panama Canal. The ‘Post-Panamax’ type was developed. Introduction of Regina Maersk provided a new trend in the market for container ships with an official size of 6400 TEU's in 1996. Post-Panamax’s development was climactic. They occupy almost 30% of the world's fleet in the world today. These sizes of vessels have become subversive to the implementation of new concepts and approaches in the container shipping industry. Furthermore, the concept of cellular container vessels has been implemented. Where the cell guides ran from the bottom of the hold to a number tier above the deck. This decreased the operating costs of the ship owners, as no lashing materials were used to protect the containers but also increased the speed of loading and unloading and reduced transfer of the container.

**Suezmax**

Suezmax max size vessels have been developed in relation to the Suez Canal. These vessels are almost the same size as the Suez Canal. Suezmax vessels have a carrying capacity of approximately 12000 TEUs, with width of approximately 50-57m and draught in between 14.4m-16.4m.

**Post-Suezmax**

These are extremely large container vessels with a carrying capacity of 18000 TEUs with a width of 60m and 21m max draught. These vessels are known as Post Suezmax because their dimensions are too wide for the vessel to move throughout the Suez Canal.

**Post-Malacamax**

This size emulates the maximum permitted of 21m draught of the Malacca Strait. In order for the vessel to reach the ports, the port authorities would have to be ready. Actually, only two ports in the world are prepared to accept this size of vessels i.e., Singapore & Rotterdam (Jha, 2021).
Gülsün

This is a new class container ship with a carrying capacity of 23000+ TEUs. They are almost 400m long and 61.5m wide, with 16.5m draught (Figure 1.5). Also, they are environmentally friendly with the lowest carbon footprint per container carried. (MSC, 2019)

---

**Figure 1.4:** Evolution of containerships (www.transportgeography.com)
3. Service Range

**Feeder Ship**

These ships are used for short routes. Basically, the journeys are not longer than 500nm and they trade only in coastal areas. The capability of such vessels does not exceed 1500 TEUs.

**Mother Ship**

These are the vessels which are involved in international trade. The size of these vessels is much bigger than feeders.(Jha, 2021)
1.5 Equipment of container terminal

Usually, container terminals are generally defined quite precisely with regard to their equipment and stacking facilities. From a logistics point of view, however, terminals consist of only two components:

- Stocks
- Transport vehicles.

The yard stacks, trains, ships and trucks belong to the “stock” group. Stocks are statically defined by their ability to store containers whereas from a dynamic point of view a stowage (or loading) instruction requires specifying the rules about how and where containers are to be stored. There is no significant difference, but just a difference in capacity and handling difficulty between these various types of stocks. The routing and scheduling of ships, trains and trucks are not part of the container terminal operation. They can therefore be regarded statically as storage units, while in any case a stowage instruction exists also for trucks where at least the location of the containers to be loaded has to be specified. Ships and trains need directions to determine the location for each container of a specific stowage.

Transport refers to two-dimensional or three-dimensional transport containers. Cranes and horizontal transport vehicles fall under this group. Their logistical specifics are that transport jobs have to be allocated to the means of transport and sequences of jobs have to be performed. The sequence calculation is common for the means of transport and describes the key difference compared to the stocks mentioned above. Not searching for these identities but being fixed on the details of each part and system used in container terminals results in a number of operational analysis approaches and solutions.

Regarding cranes, various types are used at CTs. The quay (or gantry) cranes (Fig. 1.6a) for loading and unloading ships play a major role. Two types of quay cranes can be distinguished: single-trolley cranes and dual-trolley cranes. The trolleys ride along the crane arm and are equipped with spreaders, which are special devices to pick up containers. Modern spreaders allow two 20’ containers to be moved simultaneously (twin-lift mode). Conventionally single-trolley cranes are engaged at container terminals. They move the containers from the ship to the sea, either on the quay or on a truck, positioning them (and vice versa for the loading cycle). Single-trolley cranes are operated by humans. A recent concept only applied at very few terminals is the dual-trolley
cranes. The main trolley carries the container from the ship to the platform while the second trolley picks the container from the platform and moves it to the shore. The main trolley is man-driven while the second trolley is automatic. At modern cranes, the crane driver is assisted by a semi-automatic steering system; this is the case with both one and two-wheel cranes.

The optimum performance of the quay cranes depends on the type of the crane. The technical performance of the cranes is in the range of 50–60 boxes/h, although the performance in service is in the range of 22–30 boxes/h.

The second type of cranes is used for stacks. There are three types of cranes, either rail mounted gantry cranes (RMG) or rubber-tired gantries (RTG) and overhead bridge cranes (OBC). RTGs are more versatile in service, however RMG are more rigid and overhead bridge cranes are installed on concrete or steel columns. Generally, gantry cranes span up 8–12 rows and allow 4-10 rows of high containers to be stacked. In order to avoid disruption of operations in the event of technical failures and to improve efficiency and reliability, two RMGs are often used in one stack area (block). Containers which have to be transported from one side of the block to the other then have to be buffered in a transition area of the block. Double-RMG systems represent a new development. They comprise of two RMGs of different height and width capable of passing each other, thus preventing a handshake area (Fig. 1.6b). This results in a slightly higher productivity of the system. Although most of the gantry cranes are man-driven, the tendency is for automatic driverless gantry cranes which are in use at some terminals (e.g. Thamesport, Rotterdam, Hamburg). An Automated Gantry Crane (AGC) also moves over rails in a specific block. It does not have the ability to move between blocks but is fully automated in all of its operations and works without the assistance of a driver. The technical efficiency of gantry cranes is approximately 20 moves/h.

Related cranes are used for loading and discharging of trains. They span several rail tracks (about six). Containers to be transferred from/to trains are pre-stowed in a buffer area alongside the tracks.

Forklifts and reachstackers are used to move and stack light containers – especially empty ones.
A variety of vehicles is employed for the horizontal transport both for the ship-to-shore transportation and the landside operation. The transport vehicles can be separated into two different types.

The first type of vehicles is “passive” vehicles in a sense that they cannot lift containers on their own. Loading and unloading of such vehicles shall be carried out by cranes, either quay cranes or gantry cranes. Trucks with trailers, multi-trailers and automatic guided vehicles (AGV, Fig. 1.7a) belong to this class. AGVs are robots capable of driving on a road network consisting of electrical wires or transponders in the ground to control the location of the AGVs. AGVs may either load one 40'/45’ container or two 20’ containers – multiple load operation is possible in the latter case. Although AGV systems require high investment, they are only operated where labor costs are high; they are now in service at ECT/Rotterdam and at the HHLA/Hamburg – in combination with automated gantry cranes.

The second type of transport vehicles can lift containers by their own. Straddle carriers (Fig. 1.7b), forklifts, and reachstackers belong to this class. Straddle carriers (SC) are the most significant of them. Straddle carriers are not only capable of carrying containers but are also capable of stacking containers in the yard. They can therefore, be considered as “cranes” which are not locally attached, with free access to containers regardless of their location in the yard. The straddle carrier spreader allows either 20’ or 40’ containers to be transported; SCs permitting two 20’ containers to be transported/stack at the same time are becoming available. SC systems are very versatile and dynamic due to their properties. SCs exist in numerous variants. Generally, SCs are man-driven and capable of stacking 3 or 4 containers high, i.e., they can transfer one container over 2 or 3 other containers, respectively.

Over the past few decades, progress was made to develop automatic SC. At early 2000s’, an automatic straddle carrier system has gone into production at Patrick Terminal/Brisbane, Australia. The SCs are 4m high, the integrated GPS (Global
Positioning System) differential and dead-reckoning system is used for precise positioning and routing. In addition to this form of normal height, automatic straddle carriers of less height (one or two heights) are under progress. Due to the limited height, they are not intended for stacking but for transportation purposes only. Their ability to lift containers enables the workflow of transport and cranes to be decoupled by using buffers at the respective interfaces. Due to the ability to lift containers, automated straddle carriers are also referred to as Automated Lifting Vehicles (ALV).

In parallel to cranes and transport equipment, “assisting” systems play a key role for the organization and optimization of the workflow at CTs. This refers in particular to contact and positioning systems.

Container terminal operators promote very intensive coordination with external parties such as shipping lines, brokers, forwarders, trucks and rail companies, government agencies such as customs, waterway police and others. The electronic communication is based on international standards (EDIFACT; Electronic Data Interchange for Administration, Commerce and Transport). Any adjustment in the status of the container shall be communicated between the involved parties. From the perspective of the terminal operator the most critical factors are: the container loading and unloading lists which specify every container to be loaded or unloaded to/from a ship with relevant data; the “bayplan” which includes all containers of a ship with their accurate data and location within the ship (it is communicated prior arrival in the port); the “instruction” which defines the positions in which the export containers must be placed in a ship and which form the basis for the terminal stowage plan; container pre-advises for shipment by train and truck, and the schedule and loading instruction for trains - only to name a few. While only some of these communications, in particular the
stowage instructions for ships and trains, specifically meddle with the functionality of the terminal, they are very important because they help to the completeness and accuracy of the container data required to optimize the workflow.

In addition to communicating with external partners, internal communication systems play a key role in maximizing terminal activity. The radio data communication, which has been launched at container terminals since the middle of the 1980s, plays a vital role because it is the main means for transmitting job data from the computer to cranes and transport vehicles. The radio data exchange was the technical basis for the application of operational analysis methods for maximizing work sequences.

Global Positioning System (GPS) has been used in CTs since the middle of the 1990s. Initially, it was used to automatically mark the location of the containers in the yard ensuring that the position of the container yard in the terminal computer system was correct. Due to the size of the containers and the yard design, differential GPS (DGPS) is required. The DGPS components are not mounted on containers but on top of the transport and stacking equipment. The location shall be determined, converted into yard coordinates and transmitted to the computer whenever a container is lifted or lowered. Alternatives to DGPS are optical based systems, more specifically Laser Radar. Both systems are often combined to ensure higher reliability. Container positioning systems such as DGPS, dead-reckoning systems or Laser Radar are the technological basis for improved yard and stacking logistics.

Transponder and electrical circuits are used to route gantry cranes and automatic vehicles like AGVs whereas DGPS is used for the steering of automatic straddle carriers and other equipment. (Voss & Stahlbock, 2004)
2. **Container terminal operations**

In a marine container terminal, the containers are arriving by ocean vessels and transferred to inland carriers such as trucks, trains or canal barges and vice versa. Each marine container terminal performs four basic functions: receiving, storage, staging and loading for both import (entering the terminal by sea and usually leaving by land mode) and export (usually entering the terminal by land and leaving by sea mode) containers.

Generally, CTs can also be described as open systems of material flow with two external interfaces. These interfaces include the quayside with the loading and unloading of ships, and the landside where the containers are handled on/off trucks and trains. Containers are stored in stacks, so that facilitating the decoupling of quayside and landside operations.

After arrival at the port, begins the **discharging operation**. When the vessels arrive at the port, they are docked at the quayside where the import and transshipment containers are unloaded from the vessel by quay cranes and loaded into internal trucks or automatic driven vehicles. Internal trucks are manned-vehicles, while AGVs are autonomous, powered by power lines and sensors on a road network. Although AGVs are useful and valuable also require high capital costs and are only used in modern terminals such as Rotterdam and Hamburg. Afterwards, the import and transshipment containers are transported and stored in the appropriate yard areas on the terms of the port storage policy. Yard cranes are machines mounted at the yard side to remove the containers from the truck and to stuck them as planned. Import containers for local use are retrieved by employees and transported via terminal gates. Transshipment containers shall be stored in the yard for a certain period of time until they are loaded into the specified loading vessel.(Nang Laik, 2008)

Also, there are special stack areas reserved for reefer containers, which need electrical supply for cooling, or for hazardous goods storage. Stacks are often divided into different sections for export, import, special and empty containers. Containers arriving at the terminal by road or rail are usually handled within the truck and train operating areas. They are picked up by the internal equipment and distributed to the respective stocks in the yard (Fig. 2.1).

In addition, some terminals also differ in their operating units in these general functions. For example, if the railway stations do not exist within the terminal, the containers must be transported by trucks or by other means of land transport between the
external station and the terminal. This results in additional logistics operations. Other differences occur if sheds exist within the terminal area. In sheds containers are stuffed and stripped, and goods are stored. Additional movements must be made by connecting the yard stacks to the sheds. (Solomenikovs, 2006)

The **loading operation** is the reverse of the discharge process (Fig. 2.2). After arrival at the terminal by truck or train, the container is identified and registered with its major data (e.g., content, destination, outbound vessel, and shipping line), collected by internal vehicles or cranes and distributed to one of the storage blocks in the yard. The respective storage location is given by row, bay, and tier within the block and is assigned in real time upon arrival of the container in the terminal. Specific cranes or lifting vehicles are used to store a container in a yard block. Eventually, after the arrival of the designated vessel, the container is unloaded from the yard block and transferred to the berth where the quay cranes (QC) are loading the container onto the vessel at a pre-defined stacking position. The operations necessary to handle an import container shall be carried out in the reverse order. Scheduling a large number of concurrent operations with all the variety of transportation and handling equipment involved is an extremely complicated problem. (Nang Laik, 2008)
CTs are key nodes in the transportation network interface and it is their role to perform transfer activities in the most efficient way. Even with the exceptional success in implementing technological innovations to improve operating performance at container terminals, uncertainties and variations in daily demand patterns continue to be a challenge for port managers and prevent the successful use of new innovations to their full potential.

To conclude, the number of operations and their complexity are so enormous that, in modern times, an integrated mathematical programming solution has become difficult. Therefore, they are generally grouped together by the above-mentioned areas (landside, yard and seaside operations) and discussed separately. Stahlbock and Voß (2008), Rashidi and Tsang (2013), and Li, Wu, and Goh (2015) addressed general literature reviews of container terminal operations.

2.1 Planning and logistics control issues of container terminals

2.1.1 Task based division of issues

A CT seems to be a complex system with highly dynamic interactions between the different handling, transport and storage units and lack of knowledge for future events. There are many decision-making issues related to logistics planning and control of maritime CTs. As shown in Figure 2.3, these problems can be assigned to three different levels: terminal design, operative planning and real-time control. A brief overview of these planning and control levels and their relationship to the various types
of terminal equipment is provided in the following subsections. (Gunther & Kim, 2006)

2.1.1.1 Terminal design issues

The design problems of the terminal must be resolved by the facility planners in the early design phase of the terminal. These issues need to be analyzed from an economic as well as from a technical feasibility and performance perspective. Specifically, the construction of a completely new CT and the use of automated equipment require considerable investment. From the numerous design problems, only the most significant issues are highlighted. For a more detailed overview, see Steenken et al. (2004)

– **Multi-modal interfaces**: Unlike their Asian counterparts, most European CTs are designed as multimodal facilities, i.e. they are directly linked to rail, truck and inland navigation systems. The integration of these different transport modes has a massive impact on the design of the terminal as a whole.

– **Terminal layout**: The main entities of each CT are the storage yards, transport guides paths and quays. Their capacity and spatial layout significantly determine the performance of the terminal configuration. Terminal layout involves the reservation of certain areas, as well, for reefer or hazardous goods containers, empty containers or non-standard sized containers.
– **Equipment selection**: Various types of equipment may be used for handling and transport inside the terminal. They differ primarily in their degree of automation and in their performance figures. There is presently an ongoing trend to make increased use of automated storage cranes and unmanned vehicles, even though these types of equipment generate complex logistics control problems.

– **Berthing capacity**: The seaside dispatch capacity is the worldwide performance factor for a CT. The berthing capacity not only determines the amount and size of the vessels that can be loaded or unloaded, but also the space requirements for the storage yard and the size of the fleet of vehicles, etc.

– **IT systems and control software**: Eventually, logistics control in big-sized CTs is a highly complex task, requiring real-time decisions on matching the handling tasks with the corresponding equipment units and providing detailed information on each container. Issues of considerable importance include different modes of software and IT support, along with the use of sophisticated optimization tools.(Gunther & Kim, 2006)

### 2.1.1.2 Operative planning issues

The level of operative planning includes guidelines and basic planning processes for the implementation of different logistic procedures at the terminal(Steenken et. al., 2004). As decentralized planning is the only realistic way to control the logistics of automated container terminals, the entire logistics control system is subdivided into different modules for various types or groups of resources. As a result, specific problems occur in the planning and scheduling of the use of key resources for a short-term planning horizon of several days or weeks.

– **Berth allocation**: Before the vessel arrives, the required berthing space must be allocated, taking into account the prospective time the vessel spends at the terminal. Supplementary limitations emerge from the availability of cranes and the berthing and crane requirements of other vessels that have already been moored or are expected to arrive soon.

– **Crane assignment and split**: Several QCs are used to serve a large container vessel. Initially, it must be decided which specific cranes are to be assigned to the various vessels, taking into account the accessibility of cranes at the berth and the inability of exchanging cranes between different berths at the terminal. Furthermore, the cranes operating on one ship must be assigned to different sections or hatches of the vessel.
– **Stowage planning and sequencing**: Shipping lines must decide which positions in a vessel are appointed to specific categories of containers taking into account container attributes such as destination, weight or type of container. On the basis of that assignment, the terminal operator shall decide which container has to be stored in a specific slot within the vessel. This final slot assignment has a major impact on the loading and unloading sequence of containers. On the basis of the stowage plan, the planners in the CTs shall determine the sequence of unloading inbound containers and loading outbound containers. In addition to the loading sequence for individual containers, the slot in the vessel into which each outbound container has to be stacked must be determined at the same time with the outbound containers. The unloading and loading sequences are the main input for determining the schedules of the yard cranes and the vehicles.

– **Storage and stacking policies**: Big European CTs store a total of several 10,000 containers with a typical dwell time of 3–5 days and a daily turnover of 10–20,000 containers. The storage area is divided into blocks, which are organized into bays, rows and tiers. Policies for the assignment of individual storage locations and the stacking of containers shall be governed by the objective of expediting the necessary storage and retrieval operations as much as possible and of avoiding the reshuffling of containers within the block. Particular problems include the reservation of specialized storage areas for import and export containers and the planning of re-engineering operations for stacked containers.

– **Workforce scheduling**: Another significant resource for CTs is workforce. Rosters and schedules for workers to operate equipment shall be generated beforehand.

Container terminals are highly dynamic and highly stochastic logistics systems that do not allow detailed transport and handling activities to be pre-planned for more than 5–10 min. Real-time monitoring of logistics activities is therefore of an utmost importance. **Real-time control** (or real-time planning) is typically caused by certain events or conditions and requires that the underlying decision problem can be resolved within a very short period of time, in practice usually in less than a second. Real-time decisions contain the assignment of transportation orders to vehicles, the routing and scheduling of vehicle trips for land-side transportation along with the transportation between the berth and the storage yard, the assignment of storage slots to individual containers, and the determination of detailed timetables and operation sequences for quay and stacking cranes. (Gunther & Kim, 2006)
2.1.2 Time based division of issues

Another way to categorize the decision-making process in a CT is presented in Table 2.1. Here the process is classified into strategic, tactical and operational levels according to the timescale when the decisions are made. Strategic level decisions are long-term decisions referring to a time frame of 5-10 years; they include setting the company goals, directions, outline of organizational structures and making policies and strategies. The decisions made at this level are less structured and more creative. The impact of mistakes during strategic decision making is not easily corrected and may affect the company future, so decisions of this nature are of most importance. Tactical level decision making refers to the medium-term and the timeline is between weeks to months. The tactical decision-making focuses on the means to support the strategic decisions and conveys the feedback from operational level. Operational decision-making concerns making decisions on a real time basis for efficient daily operations. They pay more attention to the details, and the data is of higher quality. The consequences of operational level decisions are immediate, short-term and usually less costly.

<table>
<thead>
<tr>
<th>Decision making level</th>
<th>Time frame</th>
<th>Purpose</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic</td>
<td>Long-term</td>
<td>Define goals, objectives, direction</td>
<td>Hard to correct, high capital required</td>
</tr>
<tr>
<td></td>
<td>(years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tactical</td>
<td>Medium-term</td>
<td>Focus on means to support strategic decisions</td>
<td>Easier to correct than strategic level</td>
</tr>
<tr>
<td></td>
<td>(months– weeks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational</td>
<td>Short-term</td>
<td>Control, detailed decisions, monitor and execute</td>
<td>Immediate and usually less costly</td>
</tr>
<tr>
<td></td>
<td>(days – hours)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.7**: Decision making level in a container terminal (*Nang Laik, 2008, p. 39*)
In Table 2.2 the decision-making problems in a CT are presented accordingly to the strategic, tactical and operational levels

<table>
<thead>
<tr>
<th>Strategic</th>
<th>Tactical</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal-wide planning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Terminal location</td>
<td>• Terminal performance</td>
<td>• Performance indicators</td>
</tr>
<tr>
<td>• Yard layout</td>
<td>• DSS</td>
<td></td>
</tr>
<tr>
<td>• Capacity planning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Demand forecasting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Terminal operations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quayside: Berth Planning</td>
<td></td>
<td>• Berth allocation</td>
</tr>
<tr>
<td>• Number of berths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quayside: Loading/ Unloading of the ships</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Type of handling</td>
<td>• No. &amp; allocation of QCs</td>
<td>• Container-QC assignment</td>
</tr>
<tr>
<td>equipment</td>
<td>• QC scheduling &amp;</td>
<td>• QC sequencing</td>
</tr>
<tr>
<td></td>
<td>interference</td>
<td>• Container sequencing</td>
</tr>
<tr>
<td>Quayside: Risk management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; exception (real-time</td>
<td>• Strategy to handle</td>
<td>• Berth reassignment</td>
</tr>
<tr>
<td>operations</td>
<td>exceptions</td>
<td>• QC reassignment</td>
</tr>
<tr>
<td></td>
<td>• New berth for demand</td>
<td>• Container location</td>
</tr>
<tr>
<td></td>
<td>surges</td>
<td>re-assignment</td>
</tr>
<tr>
<td>Yardside: Container</td>
<td></td>
<td></td>
</tr>
<tr>
<td>storage &amp; stacking</td>
<td>• Storage space for</td>
<td>• IM/ EX/TS or</td>
</tr>
<tr>
<td></td>
<td>discharged containers</td>
<td>empty containers</td>
</tr>
<tr>
<td></td>
<td>• Storage space for</td>
<td>• No. of rehandles for</td>
</tr>
<tr>
<td></td>
<td>general containers</td>
<td>IM containers</td>
</tr>
<tr>
<td></td>
<td>• Space requirement for</td>
<td>• Relocation of EX</td>
</tr>
<tr>
<td></td>
<td>empty containers</td>
<td>containers</td>
</tr>
<tr>
<td></td>
<td>• Yard cluster assignment</td>
<td>• Retrieval of loading</td>
</tr>
<tr>
<td></td>
<td>• Stacking level</td>
<td>containers</td>
</tr>
<tr>
<td></td>
<td>• Retrieval time for IM</td>
<td>• Container scheduling</td>
</tr>
<tr>
<td></td>
<td>containers</td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Strategic</th>
<th>Tactical</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yardside: Transportation of containers from ship to yard and vice versa</td>
<td>• Vehicle type (manned or AGV)</td>
<td>• No. of transport vehicles</td>
</tr>
<tr>
<td></td>
<td>• YC type</td>
<td>• Workload in a shift</td>
</tr>
<tr>
<td></td>
<td>• Vehicle dispatching strategy</td>
<td>• No. of YCs</td>
</tr>
<tr>
<td></td>
<td>• YC- vehicle transfer strategy of containers</td>
<td>• Manpower requirement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• QC- vehicle allocation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vehicle dispatching</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vehicle scheduling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vehicle routing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• YC deployment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• YC scheduling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• YC routing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Manpower assignment</td>
</tr>
<tr>
<td>Yardside: Intermodal transport in container terminal</td>
<td>• Type of intermodal transport</td>
<td>• Truck/ train/ manpower scheduling</td>
</tr>
<tr>
<td></td>
<td>• Type of handling equipment</td>
<td>• Truck/ train routing</td>
</tr>
<tr>
<td>Yardside: Risk management &amp; exception</td>
<td>• Strategy to handle exceptions</td>
<td>• Vehicles re-assignment (congestion)</td>
</tr>
<tr>
<td></td>
<td>• Additional equipment required to handle exceptions</td>
<td>• YC re-assignment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Container location re-assignment</td>
</tr>
<tr>
<td>Landside: Gate operations</td>
<td>• No. of lanes at the gate</td>
<td>• Workload via the gate</td>
</tr>
<tr>
<td></td>
<td>• Strategy to handle EX containers</td>
<td>• EX container assignment</td>
</tr>
</tbody>
</table>

Table 8.2: Strategic, tactical and operational decision-making at the complete container terminal (Nang Laik, 2008, pp. 40-41)

So far, all the logistics and planning issues of a CT have been mentioned, although in this dissertation we will concentrate more at the operational – tactical planning issues. In the subsector 2.3 we will discuss about one of the most important problems of this class, the Berth Allocation and Quay Crane assignment problem (BAQCAP).
2.2 Berth Allocation and Quay Crane Assignment problem (BACQAP)

In the seaside area, the most important operational problem is the Berth Allocation Problem (BAP), also known as the berth scheduling problem. It is a NP-problem in the field of operational research, concerning the allocation of berth space for vessels in CTs. This problem has become a crucial research subject during the last years. Among the models reported in the literature, four cases are the most commonly observed:

1. Discrete vs. Continuous berthing space
2. Static vs. Dynamic vessel handling times
3. Static vs. Dynamic vessel arrivals
4. Variable vessel arrivals.

In the discrete problem, the quay is seen as a limited set of berths in contrast with the continuous problem, vessels can dock anywhere along the quay and most of the study deals with the former case. In the case of static arrival, all vessels are already at the port, while only a portion of the vessels to be scheduled are present in the dynamic. The purpose of the berth allocation issue is to schedule and allocate ships to berthing areas along a quay to achieve the best possible usage. The objective is to minimize the total service time for all ships which is defined as the time elapsed between the arrival in the harbor and completion of handling (Cordeau, 2005). When assigning ships to berths, there are certain limitations and problems. The constraints and issues include the length of ship, depth of berth, time frame, priorities assigned to the ship, and shippers’ favorite berthing areas (Imai et. al., 2007);(Lee & Chen, 2009);(Legato & Mazza, 2001);(Vacca et. al., 2007). Under this context, vessel handling times are normally believed to be set and understood in advance. QCs are also a finite resource in addition to quay capacity. A Quay Crane Assignment Problem (QCAP) occurs if multiple vessels dock on the quay simultaneously. The number of QCs operating on a vessel at the same time is always limited to a minimum and a maximum for operational and contractual purposes.

Since the number of QCs allocated to a vessel dictates its handling period, there is a growing tendency to consider these two problems together. A number of cranes are also allocated to each vessel in the joint BAQCAP, as well as the time and berthing location.

In the literature, two versions of BAQCAP have been discussed. The number of cranes allocated to each vessel in the time-invariant version remains constant during its handling, while this number can be modified in the time-invariant version in each cycle.
The variable-in-time version allows cranes to be used more effectively, as those originally allocated to a vessel can be reallocated to a newly arrived vessel. For instance, this is helpful when the processing of a large vessel is almost finished and only a few cranes are necessary to complete it. Other vessels can be reassigned to the outer cranes, thus speeding up their handling. Only when feasible, terminal operating systems aim to accomplish this variable-in-time assignment; however, this advantage will become a major issue when adapting the strategy to actual scenarios. The solutions may require more complicated crane-to-vessel tasks and thus become more difficult to manage for human operators. In addition, they may also contribute to a larger number of crane movements, requiring more reliable and effective control of dock operations, including the coordination of staff and equipment. As a result, variable-in-time schedules are more vulnerable to contingencies and components that are not normally taken into account during planning, meaning that the actual implementation will easily deviate from the theoretical timeline. In this sense, a highly important case is the general belief that the time taken by the cranes when transferring from one vessel to another is negligible. A huge number of movements greatly increase the time spent in set-up operations and make the optimum variable-in-time timetable less and less practical as it is introduced. For this reason, and in order to eliminate other arbitrary timetables, the amount of crane movements in these models must be reduced, taking them into account in the objective function. In comparison, time-invariant models, taking into account the different numbers of cranes and their associated assembly times, can accept many projections of the handling time for each vessel. In addition, since the allocation of each particular crane needs to be done for each vessel and not for each time period, they correspond to solutions with less crane movements, meaning that the resulting schedules will usually remain closer to their actual implementation and thereby becoming more trustworthy. For the same purpose, time-invariant models need fewer variables that make these models simpler to manage computationally, and hence the size of the instances that they can solve for optimality is typically greater than in the case of variable-in-time models. The key drawback of time-invariant models from a theoretical point of view is that they almost always drain crane capacity; in fact, however, this limitation turns out to be an interesting alternative to having conservative schedules useful for guiding actual operations. (Correcher et. al., 2019)
2.2.1 A small example

An example, from (Hafez et. al., 2013), for the graphical representation of a berth plan with five vessels is shown in Figure 2.4a. Ship 1 spent around 3 hours at berth. Ship 2 spent 9 hours, while ship 3 spent 3 hours. From the figure, it is clear that the quay can accommodate 3 ships at the same time given that maximum ship's length is 200 meters. Berth planning has been shown to be a nondeterministic polynomial time (NP)-hard problem.

![Figure 2.4: a) Berth Allocation Problem b) Quay Crane Assignment Problem (Bierwirth and Meisel 2010)](image)

A feasible berth plan and a set of equivalent QCs accessible for operation are given in the QCAP. The amount of containers to be filled and/or unloaded and the maximum number of cranes allowed to operate at the same time are known for all vessels involved in the berth plan. It is supposed that the cranes are lined up alongside the quay. They can be passed to one of the ships, but they cannot pass into each other. The issue is that cranes should be allocated to vessels so that all required container transshipments can be fulfilled. The QCs numbers 2, 3 and 4 are allocated to vessel 3 in Figure 2.4b. Two cranes are relocated from vessel 3 during time 5 to begin servicing vessel 2. Basically, the QCAP and BAP are interrelated, since solving the QCAP will have a strong effect on the handling times of the vessels. Assignment of cranes to vessels is not required in the case of a discrete berth configuration, where each berth holds a number of dedicated cranes. (Hafez et. al., 2013)
2.3 Simulation in container terminals

2.3.1 The importance of Simulation

The simulation method is one of the stochastic modeling methods of Operational Research. According to Tsitsamis(2009) simulation is defined as the method by which the system, with the help of another system, is studied and familiarized with its characteristics. In order to find the rules that control the operation of the system, simulation models that reflect its internal operation are developed. Each of these models is characterized by its inputs and outputs.

Simulation models generate numbers, which can be analyzed and interpreted to gain a better understanding of the system under study and to implement modifications that enhance its operation. Figure 2.5 demonstrates the philosophy of the methodology that simulation follows.

![Figure 2.5: Schematic representation of the simulation methodology (Tsitsamis D. S., 2009)](image)

Furthermore, the different elements of the system and their interactions can be analyzed in depth with simulation models. In this way the study and the experimentation of a complicated system is more feasible. As a first step of creating a simulation model, the following have to be defined:

- The components of the system
- The role of each element and the interaction between them
✓ The input parameters of the system
✓ The output parameters of the system

The simulation models generate numerical data, the analysis and the interpretation of which leads to a better understanding of the system under study and to the realization of changes that will improve its operation.

The rapid development and evolution of computers has made simulation a practical analysis tool. Computer simulation refers to the methods used to study a variety of real-system models using quantitative estimations, exploiting software designed to mimic the characteristics and processes of systems. From a practical point of view, simulation is the process of designing and creating a model, which is a realistic representation of the actual system, with the ultimate goal of conducting numerical experiments that will give a more complete picture of its behavior for a set of specific conditions.

Moreover, there is a plethora of ways to classify simulation models. The main categorization is the followed:

✓ Static/ Dynamic: The difference between them is the time effect. Time is non-existent in static models. Models in operational research (and thus simulation) are typically dynamic.

✓ Continuous/Discrete: The state of the system may constantly change over time in a continuous time model. In contrast to discrete-time models, state changes occur only at certain points of time. The great majority of operational research systems are represented as discrete time models.

✓ Deterministic/Stochastic: Models without randomness in their data are deterministic, whereas when their data follow a distribution, they are stochastic. (Theofanis S., 2009)

2.3.2 Arena simulation software

The tool used in this thesis for the optimization of port processes is Arena 14.7 (Rockwell Software). More specifically the Student Edition. Arena is a comprehensive simulation and visual representation software for a simulated system. It is based on the simulation language SIMAN (Simulation Modeling and Analysis), it preserves its basic structure, but adds a completely graphical interface. SIMAN consists of two categories of objects, the “blocks” and the “elements”. For example, “seize block” represents the
commitment of one service or resource by one entity, while “release block” releases it, in order to be used later from another entity. The “elements” are objects that represent services such as resources and queues or other “elements” such as «dstat» and «tallies», which are used to collect statistics during the simulation. Modules are the main structural elements of an Arena simulation model that have been created from the basic objects of the Arena, the «blocks» or the «elements». For instance, the process module consists of the below blocks: queue, seize, delay and release.
3. Previous research

After 1990, research focused on mathematical programming and simulation because a queuing theory model was unable to explain certain aspects of the problem, such as the available berthing area in a container area. Published work on this subject is limited and includes the research of Legato and Mazza (2001), Dragovic et al. (2006), and Bassan (2007). For the first time, Legato and Mazza (2001) developed a system based on the queuing theory, which describes the procedures for the arrivals of vessels in the CT, berthing and their departure. However, the unstable service stations, the different service cycles due to the priorities and the complicated policies followed by the CT with regard to the allocation of resources, prevent the use of analytical methods to solve the model. As part of the methodology introduced in the original model, a simulation-based model was developed using Visual SLAM programming language for discrete-event simulation. The results of the steady-state simulation showed that the “what if” approach could be used to predict the impact of congestion on the berthing planning problem.

Dragovic et al. (2006) used the queuing theory and a simulation-based model to evaluate the effectiveness of models used for Pusan East Container Terminal. The parameters used to test port operations and procedures were the berth utilization, the average service time of a vessel, the average number of vessels in queue, the average time that a vessel spends in queue, the average total time that a vessel spends in CT, the average QC productivity and the average number of QCs per vessel. In order to validate and verify the simulation model, the results of the simulation were compared with the real data and achieved complete agreement. The simulation model was then matched with the analytical model in order to verify its validity as well. Correlation of outcomes has now been accomplished, enabling the use of specific models to optimize vessel service operations.

Finally, Bassan (2007) attempted to rethink the use of the queuing theory for the design of the port. It proposes four efficiency measures to develop a framework that can calculate the quality of port operations and serve as a tool for decision-makers to validate the investment required.
3.1 The Berth Allocation Problem

The problem of berth allocation can be modeled either as a discrete or a continuous problem. Cordeau et al. (2005) developed two versions of the berth allocation problem in their studies: the discrete case and the continuous case. The discrete scenario operated with a finite set of berthing locations and, in the continuous case vessels berthed anywhere along the quay. Two formulations and a tabu search heuristic were introduced and checked for realistic traffic and berth allocation data collected from the port of Gioia Tauro, Italy.

Imai et al. (2005) provided a continuous model of the problem of berth allocation to reduce the total service time of vessels. The authors proposed a heuristic algorithm that solves the problem in two stages, by modifying the approach for the discrete case. Lee and Chen (2009) introduced an optimization-based method for the berth scheduling problem. The key aim of the research was to evaluate the berthing time and space for arriving vessels. The neighborhood-search based heuristic considers the quay as a continuous space. Besides to the original physical criteria, the proposed model takes into account multiple factors that are relevant in practice, including the first-come-first-served (FCFS) rule, the distance clearance between ships, and the probability of vessel shifting in order to make space for another ship.

Imai et al. (2007) addressed efficient berth and crane allocation scheduling at a multi-user container terminal. This paper suggested a genetic algorithm-based heuristic that iterates the process for berth and crane scheduling determination at the same time. Legato and Mazza (2001) introduced a network queuing model for logistics operations associated to the arrival, berthing and departure process of vessels at CTs. Wang and Lim (2007) suggested a stochastic beam search scheme to resolve the BAP. The applied algorithm is examined on real-life data from the Singapore Port Terminal.

Budipriyanto et. al. (2017) examined how cooperation between berth terminals could affect port efficiency when dealing with uncertainty. They used Jakarta as an example, where two terminals might actually collaborate. Due to the complexity of the problem they used discrete event simulation to model the system. There are two scenarios were evaluated, the non-collaborative-response and the collaborative-response. According to the findings, the collaboration between the two terminal operators supports the entire operation by reducing ship turnaround time, waiting time, and handling time, as well as increasing throughput. Kallel et. al. (2019) They explored the ships to BAP in
A mathematical model is constructed with the goal of reducing the time ships remain in port as well as lowering the waiting time of all ships in port, while matching ship characteristics with those of berths such as depth, length, and so on. This model is demonstrated by a case study in the Tunisian port of Rades and solved by the commercial solver CPLEX. Their method has demonstrated a substantial improvement over the port's current ships to berths assignment solution.

### 3.2 The Berth Allocation and Quay Crane Assignment Problem (BAQCAP)

Since the assignment of the QC has a strong effect on vessel handling time and further impacts the allocation of berths, more and more researchers have shown their strong interest in studying the BAQCAP.

The integration of berth allocation and quay cranes was investigated by Meisel and Bierwirth (2006), concentrating on the elimination of idle time of QCs, which has a major effect on terminal labor costs. A heuristic scheduling algorithm based on resource-constrained project scheduling priority-rules methods is proposed and evaluated on six instances, based on actual data, which considered up to 18 vessels to be served within two days. Preliminary findings were promising relative to the manually generated schedules that have been used in practice. The convergence of the problems of berth and QCs was analyzed by Giallombardo et al. (2008). For the integrated problem, they proposed two formulations: a mixed integer quadratic program and a linearization that decreases to a mixed linear integer program. On the one hand, the objective function aims to optimize the overall value of selected QC profiles and, on the other hand, to minimize the cost of housekeeping produced by ship-to-ship transshipment flows. An economic review of the importance of QC assignment profiles and yard-related costs in the sense of transshipment is given.

The combination of BAP and QCAP with an emphasis on QC efficiency was analyzed by Meisel and Bierwirth (2009). In order to solve the problem, an integer linear model was presented and construction heuristics, local refinement procedures and two meta-heuristics were created. In the same set of cases, writers equate their approach to the one suggested by Park and Kim (2003) and still have better solutions. Using objective programming for berth allocation and quay crane allocations based on a rolling-horizon approach, Chang et al. (2010) developed a dynamic allocation model. A hybrid parallel genetic algorithm (HPGA) was then used to solve the proposed model, which merged the
parallel genetic algorithm (PGA) and the heuristic algorithm. In addition, to test the HPGA and to implement effective gene repair strategies, a simulation was carried out. The computational experiments on a particular container terminal were ultimately extended to demonstrate the models and algorithms proposed.

Also, Krimi et al. (2020) they are focused on the multi-quays berth allocation and crane assignment issue under availability constraints such as weather conditions or cranes should undergo to planned maintenance in order to remain in good performance. This problem was based on a real case involving a bulk port in Morocco. A mixed integer programming (MIP) model is used to solve the problem. Therefore, it is shown that the proposed MIP model is insufficient for solving large-scale instances. As a result, they created a set of heuristics based on General Variable Neighborhood Search (GVNS). The computational results reveal that their GNVS variable neighborhood can be consider as reliable.

In the scientific literature, the simultaneous allocation of berths and allocation of quay cranes gained less publicity mainly due to the difficulty of the issue. A few studies have been published on this particular subject, however.

In the continuous case with the QCAP, Park and Kim (2003) studied the simultaneous BAP, even considering the scheduling of QCs. The optimal start times of the ship operation and corresponding mooring positions were calculated and the optimal allocation of the quay cranes to those ships was determined at the same time. The handling time of a single ship in their analysis is a function of the amount of quay cranes allocated to the ship; moreover, the handling time is independent of the ship's mooring position. Their approach consisted of two stages: one for allocation of berths and the other for allocation of cranes. In a way, they solved the problem of berth-crate allocation easily by separately addressing the berth allocation and crane allocation.

Imai et al. (2008) tackled the issue of simultaneous allocation and scheduling of berth-crate, taking into account the physical limitations of quay cranes that can not move easily between berths because they are all installed on the same route and therefore can not bypass each other. In order to find an approximate solution, a MIP formulation that minimizes the total service time is suggested and a genetic algorithm-based heuristic is developed. Recently, Vacca et al. (2011) investigated the simultaneous optimization in seaport container terminals of berth allocation and quay crane assignment. They suggested a model that is solved by column generation based on an exponential number of variables. To generate optimal integer solutions to the problem, an exact branch-and-price algorithm is used.
Correcher et. al. (2019) they focused on two seaside operational problems: the BAQCAP, which are examined simultaneously. They suggested a new mixed integer linear model for the continuous BAQCAP problem with time-invariant crane assignment, in which the boats can be moored at any position on the quay without requiring any quay discretization. The resulting model outperforms other recently submitted suggestions and can solve cases with up to 50 vessels.

BAP and QCAP interact intensely, according to Meisel and Bierwirth (2006). QCAP specifies the time of the ship in port and is an input for BAP at the same time. In addition, the BAP specifies the ship's time at berth, and is an input for the QCAP again. Therefore, this analysis would present the resolution of both issues.

3.3 Container terminals simulation with Arena

Numerous published papers, doctoral studies and dissertations have used the simulation method using the Arena software for studying CT operation. The following is a summary of those.

Arango et. al. (2011) studied the problems associated with the BAP in port of Seville by using Arena software. The simulation model aimed to evaluate the total service time for each ship, considering that the strategy of BAP obeys the FCFS rule.

Assuma and Vivetta (2006) introduced a stochastic discrete simulation model to simulate loading and unloading operations using rail system at a Ro-Ro container terminal. Using the Arena software, they developed a model such that they can control crucial situations, such as the probability of problems that could arise and affect daily operations. By simulating the system, they collected information about the efficiency of the system.

Park et. al. (2009) using data and information from the container terminal of Bussan in south Korea, considered a system consisting of yard trucks and QCs. A comparison was made between the strategy of dedicated assignment, which the port uses, and the strategy of dynamic resources assignment. Using the simulation method with Arena software, they concluded that the strategy of dynamic resources assignment of yard trucks leads to a 25% increase in efficiency.

Shahpanah et. al. (2014) focused on the waiting time of a vessel at the berthing area of a container terminal in Malaysia. They attempted to solve the queuing problem during the tugging operation of the vessel in order to reduce the average waiting time. The problem was modeled with Arena simulation software and the data was real. In
respect to the tugging operation many scenarios were tested, such as the fluctuations in ship arrivals and tug/pilot numbers. The results indicate that, after the implementation of these scenarios, the average waiting time of vessels at the berthing area significantly reduced from 180 hours to 140 hours per vessel.

Shammoon(2009) in his dissertation studies the port in Maldives. The country imports almost all the goods it consumes and the congestion is heavy. Various scenarios for the port were tested with the help of Arena software. The models were used to evaluate the completion time of the procedures on the vessels, berth capacity, yard capacity, container waiting time in port and the utilization of QCs and other container handling equipment. The findings revealed that the decreased capacity of berths was the key cause for the queues and delays of the vessels.

Sheikholeslai et. al.(2013) studied the BAP using simulation. They formulated the problem in the Arena simulation software and tested different strategies in the port of Rajaee in Iran. The results show that different port expansion options have different port efficiency consequences.

Solomenikovs(2006) in his doctoral dissertation uses the Arena software to model the operation of the port of Riga in Latvia. The paper introduces an original approach, based on parametric and non-parametric statistical methods, to create a model for simulating port terminal containers at a required level of realism.

Tahar and Hussain(2000) developed a simulation model using Arena software to assist in the operation and maintenance of the Kelang terminal in Malaysia. The model simulates all the processes necessary for effective port operation and provides detailed data on port traffic levels and utilization rates with a high degree of accuracy. The allocation of QCs and system resources and the scheduling of various processes are modeled to maximize port efficiency.

Tsitsamis and Vlachos(2010) developed a simulation-based approach using Arena software to evaluate decision-making on the loading and unloading of trucks incorporating economic and environmental parameters into the CT. The implementation of the suggested methodology took place at the container terminal of Thessaloniki.
4. The Simulation model

4.1 Problem description

The daily loading and unloading capacity of the CT depends on a number of variables, such as the available equipment, the way of stacking, the operating hours, the human resources and the arrival rate of trucks and vessels. Improving this operation means minimizing waiting times and overall service time, as well as increasing the usage of available resources. In the issue we are going to look at, we concentrated on the seaside part of the container terminal.

In order to configure the system parameters; the following steps have been implemented:

- Collection of real data from previous research on container terminals.
- Data analysis.
- Modeling.

By using the simulation model we created, we want to assess the efficiency of a CT under different scenarios and operating conditions. For this reason, the simulation model we use in our dissertation is a container terminal with three berths and four QCs. Each berth is composed of two sections. The positions of the cranes on the piers are as follows:

- QC 1 is always on berth 1.
- QCs 2 and 3 are located on berth 2 and can be moved to all three berths.
- QC 4 is always on berth 3.

The vessels that arrive at the port are divided into three groups according to their length. Vessels’ length specifies the space they occupy at the berths and the maximum number of cranes that can be used for the loading and unloading processes. The three groups shall be as follows:

- Small vessels – occupy two sections of the berth and require only one QC.
- Medium vessels – occupy three sections of the berths and require up to two QCs.
- Large vessels – occupy four sections of the berths and require up to three QCs.

The assumptions we make about this model are as follows:

- All containers are the same size (40ft) and all of them are full. Also, there is no separation by type and content.
• Tugboats that assist in berthing the vessel at the berth are not modeled explicitly in the simulation. Only the time needed for this process shall be taken into account.
• Failures of the mechanical equipment of the port are not taken into consideration.
• We assume that the CT operates 24 hours a day, 365 days per year.
• Unloading and loading takes place at the same area, using the same resources of the terminal.
• The total number of containers that will be unloaded from or loaded onto a vessel depends on vessel’s size.
• Berth 1 is closest to the port’s entrance, while berth 3 is farther away. Therefore, the time it takes to moor a vessel varies from berth to berth, as their distance from the terminal’s entrance is different. For this reason, vessels have precedence over mooring at berth 1.
• The time it takes for a vessel to depart from the berth is not affected by the location of the berth in the port.
• All QCs are identical and thus they have the same lifting capability and capacity.
• The time it takes for a vessel to moor or leave a berth differs with respect to vessel’s type.
• For the most efficient operation of the port, medium-sized vessels use two sections either of berth 1 or berth 3 and one section of berth 2.

4.2 Design of the simulation model

The modeling of the CT procedures using Arena is shown in Figure 4.1. Generally, when the vessel arrives at the CT will wait if there is no available berth. If one berth is available, then the vessel will move on according to its length. If the vessel needs more than one berth, then it will wait once again. When enough berths become available the vessel will be redirected to them and the berthing procedure will start. When the vessel is secured in the berth the unloading/loading procedure will start. This procedure is simplified when the vessel is small, otherwise there are a few extra steps needed. By the completion of the previous procedure the vessel departure from the CT.
For a more detailed presentation, we divide the model in three parts:

- Vessels’ arrivals and redirection according to vessel’s length.
- Unloading and loading procedures.
- Vessels’ departures.

After the arrival of a vessel, we have the following procedures as shown in the Figure 4.2:

1. Vessel arrival at the CT.
2. Attribute assign for the length of the vessel.
3. Hold until a berthing location becomes available.
4. Redirection according to the vessel’s length.
5. Attribute assign for the characteristics of the vessels (e.g. containers’ number, berthing time, etc.).
6. Hold until a berthing location suitable for the vessel’s specifications become available.
7. Berthing of the vessel according to its length.

The deference between procedure 3 and 6 is that in the first one the hold is for all vessels’ categories, but in the second is only for the specific vessel’s category. Both of them are necessary in order to avoid having two vessels simultaneously in the same berthing location or section.
Figure 4.2: Vessels’ arrivals and redirection according to vessel's length

With respect to the unloading and loading process, there is a small differentiation between the small and medium/large vessels, as the latter need more than one berth and one quay crane.

a. Small vessels:
   1. Seize of the berth and QC needed for the unloading and loading. In this category only one berth and one quay crane needed.
   2. Delay equal to the time which is required for the mooring of the vessel.
   3. Delay equal to the time which is required for unloading and loading procedure. This time is a function of the containers that will be unloaded and loaded on the vessel.
   4. Release of the resources that were seized previously.
   5. Record of the container number that were unloaded and loaded.

b. Medium and large vessels:
   1. Seize of the berth needed for the unloading and loading.
   2. Separation of the vessel in parts depending on the maximum number of QCs allowed. Without this separation it wouldn't be possible for a vessel to be served by a number of quay cranes smaller than its maximum needs. For example, a medium vessel could be served only if two QCs were available. With this separation a medium vessel it is now possible to be served by only one QC, but the procedure will last longer.
   3. Hold for empty QC. This module will hold a part of a vessel only if the number of available quay crane is smaller than its maximum needs.
4. Redirection depending on the quay crane that will be used.
5. Quay crane assignment on every part of the vessel.
6. Delay equal to the time which is required for the mooring of the vessel.
7. Delay equal to the time which is required for unloading and loading procedure.
8. Redirection depending on the quay crane that was used before.
9. Release of the QCs.
10. Reunification of the vessel.
12. Record of the container number that were unloaded and loaded.

The aforementioned Arena processes are depicted in Figures 4.3 and 4.4.
Finally, for modeling the departure of the vessel from the CT, we have the following procedures as shown in the Figure 4.5:

1. Time which is required for the departure of the vessel from the berth.
2. Record of the total number of containers that were unloaded and loaded, regardless of the vessel length.
3. Departure of the vessel from the CT.

![Figure 4.5: Vessels’ departures](image)

4.3 Objectives and Parameters of the Simulation model

In this section of the dissertation, with the help of the model we have developed above, we will examine the mode of operation for a CT from the seaside aspect during the loading and unloading process. In addition, we will examine how different factors influence the system. The main issues how the priorities between vessels affecting the CT efficiency. In parallel we examine how various factors contribute to the operation of the loading and unloading procedures. These are the below:

- How does berth allocation and quay assignment affect system performance?
- What is the impact of the vessel arrival rate on the system?
- How does the handling time of a QC affect the operation of the container terminal?
- How the ratio between small, medium and large vessels affects the efficiency of the CT?

For this purpose, we examine three scenarios which differ with respect to the priority given to different vessels. The objective is to study, the effect of changes in vessels’ prioritization on the output parameters and port operation in general.
4.4 Simulation scenarios

First come – First served

In this scenario the vessels are served according to the rule of first come – first served, which means that the first vessel that arrives at the CT will be the first that will be moored at the berth.

Priority for company vessel

Here we examine the situation where a specific company’s vessels have priority over other companies’ vessels, which imply that the company’s vessels will be served first. Nevertheless, the FCFS rule still applies among company’s vessels and separately among the rest of the vessels.

Berth dedicated to a company

In that case the rules of the previous scenario (priority for company vessel) still apply, but the difference here is that now the third berth serves exclusively the vessels of the company. For example, a not prioritized vessel will be served by berth 1 and/or berth 2. If these berths are occupied the vessel will wait, even if the berth 3 is not occupied. In contrast, the company’s vessels can be served by all three berths, but they are heading firstly to berth 3 and if it is occupied, they use the other berths. Between berths 1 and 2, all the vessels heading first to berth 1.

For all three scenarios the length of each replication is 90 days, but we use a 30 day warm up period. Thus, our results are based on a 60 day period, during which the CT is operating at its maximum capacity. In every case, we use a sample of 1000 replications. In order to have reliable data we checked the confidence interval.

In Table 4.1 the input parameters that we used in our scenarios are shown. These are the number of berths and QCs of the CT, the types of vessels according to their length, the berthing time for each type of vessel and the extra berthing time that it is required for berthing in berths 2 and 3. Also we characterize the distributions of the time between arrivals of the vessels and of the berthing/unberthing time. Finally, we cite the warm up period, the length of simulation and the replication number.
INPUT PARAMETERS | VALUES
--- | ---
Number of berths | 3
Number of quay cranes | 4
Types of vessel length | Small, Medium, Large
Berthing time for small vessels (berth 1) | 0.2 hours
Berthing time for medium vessels (berth 1) | 0.3 hours
Berthing time for large vessels (berth 1) | 0.5 hours
Extra time needed for berthing in berth 2 | 20%
Extra time needed for berthing in berth 3 | 50%
Distribution of time between arrivals | Exponential
Distribution of berthing and unberthing time | Exponential
Warm up period | 30 days
Length of simulation | 90 days
Replication number | 1000

Table 4.1: Input parameters

The number of containers of each vessel type follows a uniform distribution. This distribution is classified according to a discrete probability. This information is given in Table 4.2.

<table>
<thead>
<tr>
<th>VESSEL TYPE</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small vessels</td>
<td>0.17, 0.5, 0.33</td>
</tr>
<tr>
<td></td>
<td>100-200, 200-300, 300-400</td>
</tr>
<tr>
<td>Medium vessels</td>
<td>0.43, 0.4, 0.17</td>
</tr>
<tr>
<td></td>
<td>400-500, 500-600, 600-700</td>
</tr>
<tr>
<td>Large vessels</td>
<td>0.23, 0.385, 0.385</td>
</tr>
<tr>
<td></td>
<td>700-800, 800-900, 900-1100</td>
</tr>
</tbody>
</table>

Table 4.2: Container number per vessel type

The variables used in the simulation are presented in the Table 4.3. Their values will be presented analytically in the next chapter in Tables 5.1 and 5.2.

<table>
<thead>
<tr>
<th>VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals</td>
</tr>
<tr>
<td>Handling time of Quay Cranes</td>
</tr>
<tr>
<td>Probability of small vessels</td>
</tr>
<tr>
<td>Probability of medium vessels</td>
</tr>
<tr>
<td>Probability of large vessels</td>
</tr>
<tr>
<td>Percentage of small company vessels</td>
</tr>
<tr>
<td>Percentage of medium company vessels</td>
</tr>
<tr>
<td>Percentage of large company vessels</td>
</tr>
</tbody>
</table>

Table 4.3: Simulation's variables
The time between arrivals is the time that passes between the arrivals of two vessels. In our simulation this time follows an exponential distribution. As handling time of QCs, we considered the period of successful unloading or loading between two containers. The probability of each vessel’s category shows what percentage, compared to the total number of ships, belongs to this category. Finally, the percentage of company vessels indicates how many vessels of each category belong to the company with the priority.
5. Results

In our analysis the minimum value of the confidence interval was 95%. We had this level of uncertainty because of the input parameters that we used. As we mention before, we used data from previous researches in order to have a realistic scenario for our simulation. Nevertheless, our results could be considered as reliable.

5.1 First Come – First Served

As we already mentioned before the main characteristic of this scenario is that the vessel that will arrive first to the CT will be the first that will be moored at the berth. For this scenario we create eight different sub scenarios, as they shown at the Table 5.1, in order to give an answer to our main issues.

<table>
<thead>
<tr>
<th>SUB SCENARIOS</th>
<th>VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time between arrivals (in hours)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.9: The sub scenarios of FCFS

We divided the sub scenarios in two groups depending on their time between arrivals, thus we have one group with 20 hours and another group with 15 hours. Then we split each group in two parts depending on the handling time of the QCs. Finally, each part was divided again in two according to the probability of each vessel category.

From our results we notice that the average total time and the average waiting time follow the same pattern as it is shown in Figures 5.1 and 5.2.
In more details we observe that a decrease in time between arrivals increases the waiting and the total time. In contrast, a decrease in the handling time of QCs reduces these times. As far for the probabilities of each vessel category, we conclude that a change at the small vessel’s percentage brings the opposite change at the waiting and total time. On the other hand, a change at the percentages of medium and large vessels brings the same change at these times. These results can be more comprehensive in the
Tables 5.2 and 5.3, which show the average total time and waiting time respectively, for each value of the variables that we used.

<table>
<thead>
<tr>
<th></th>
<th>Average Total Time for large vessels</th>
<th>Average Total Time for medium vessels</th>
<th>Average Total Time for small vessels</th>
<th>Average Total Time for all vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 20h</td>
<td>74.83</td>
<td>61.22</td>
<td>44.30</td>
<td>58.99</td>
</tr>
<tr>
<td>Time between arrivals= 15h</td>
<td>156.63</td>
<td>144.90</td>
<td>129.47</td>
<td>142.56</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>181.61</td>
<td>168.11</td>
<td>149.20</td>
<td>164.95</td>
</tr>
<tr>
<td>Handling Time of QCs= 100&quot;</td>
<td>49.86</td>
<td>38.01</td>
<td>24.58</td>
<td>36.60</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>154.43</td>
<td>142.73</td>
<td>126.20</td>
<td>141.87</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>77.04</td>
<td>63.40</td>
<td>47.57</td>
<td>59.68</td>
</tr>
</tbody>
</table>

Table 5.10: Average Total time for FCFS scenario

<table>
<thead>
<tr>
<th></th>
<th>Average Waiting Time for large vessels</th>
<th>Average Waiting Time for medium vessels</th>
<th>Average Waiting Time for small vessels</th>
<th>Average Waiting Time for all vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 20h</td>
<td>43.03</td>
<td>42.35</td>
<td>34.60</td>
<td>39.68</td>
</tr>
<tr>
<td>Time between arrivals = 15h</td>
<td>124.85</td>
<td>126.02</td>
<td>119.77</td>
<td>123.24</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>143.67</td>
<td>145.58</td>
<td>137.64</td>
<td>141.91</td>
</tr>
<tr>
<td>Handling Time of QCs= 100&quot;</td>
<td>24.21</td>
<td>22.79</td>
<td>16.73</td>
<td>21.02</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>122.63</td>
<td>123.86</td>
<td>116.50</td>
<td>121.22</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>45.25</td>
<td>44.51</td>
<td>37.87</td>
<td>41.71</td>
</tr>
</tbody>
</table>

Table 5.11: Average Waiting time for FCFS scenario

The utilization of berth 1 and 2 as well the utilization of QC 1, 2 and 3 have the same fluctuation, on the other hand the utilization of berth 3 and QC 4 have different fluctuation, as shown in the Figures 5.3 and 5.4. This difference is a result from the increased use of small vessels in some sub scenarios. As the berth 3 is the berth with the least preference, it has more chances to be used when more small vessels come in the CT.
From our results we comprehend that once again decrease intime between arrivals, increases the utilizations and a decrease in the handling time of QCs reduces the utilizations. The most interesting outcome is when the probabilities of each vessel’s category change. Here we observe that when the percentage of small vessels increases,
which means that the percentages of medium and large vessels decrease, all the utilizations are decreasing except from the berth 3 and QC 4 utilizations, which are increasing too. Also, when the handling time was increased the utilizations of berth 3 and QC 4 were affected by the changes at the vessels' percentages, but when the handling time was decreased there was no affection on these utilizations. In other words when the handling time is 100 seconds the berth 3 and QC 4 reaching their maximum possible utilization in compliance with the time between arrivals, so a change in the vessels’ ratio does not affect them. The Tables 5.4 and 5.5 present numerically the above conclusions.

<table>
<thead>
<tr>
<th></th>
<th>Berth 1 Utilization</th>
<th>Berth 2 Utilization</th>
<th>Berth 3 Utilization</th>
<th>Average Berth Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 20h</td>
<td>0.71</td>
<td>0.62</td>
<td>0.22</td>
<td>0.51</td>
</tr>
<tr>
<td>Time between arrivals = 15h</td>
<td>0.85</td>
<td>0.77</td>
<td>0.30</td>
<td>0.64</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>0.87</td>
<td>0.80</td>
<td>0.32</td>
<td>0.66</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>0.68</td>
<td>0.59</td>
<td>0.20</td>
<td>0.49</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>0.84</td>
<td>0.76</td>
<td>0.25</td>
<td>0.61</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>0.72</td>
<td>0.62</td>
<td>0.27</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 5.12: Average Berth Utilization for FCFS scenario

<table>
<thead>
<tr>
<th></th>
<th>QC 1 Utilization</th>
<th>QC 2 Utilization</th>
<th>QC 3 Utilization</th>
<th>QC 4 Utilization</th>
<th>Average QC Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 20h</td>
<td>0.71</td>
<td>0.68</td>
<td>0.56</td>
<td>0.21</td>
<td>0.54</td>
</tr>
<tr>
<td>Time between arrivals = 15h</td>
<td>0.85</td>
<td>0.82</td>
<td>0.70</td>
<td>0.30</td>
<td>0.67</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>0.87</td>
<td>0.85</td>
<td>0.73</td>
<td>0.31</td>
<td>0.69</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>0.68</td>
<td>0.65</td>
<td>0.53</td>
<td>0.20</td>
<td>0.51</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>0.84</td>
<td>0.82</td>
<td>0.70</td>
<td>0.24</td>
<td>0.65</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>0.72</td>
<td>0.68</td>
<td>0.56</td>
<td>0.27</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Table 5.13: Average QC Utilization for FCFS scenario

Finally, the containers’ number is increasing as the time between arrivals is decreasing or the handling time of QCs is decreasing. It is important to mention here that when we have large values at time between arrivals with increased probability for small vessels, the impact of the handling time of QCs is small. Lastly, when the probability of small vessels is increased, the number of containers is decreased, except for sub scenario 5 and 6. These sub scenarios are identical; their only difference is on the probability of vessels’ category. Therefore, it was expected that the number of containers in sub scenario 6 will be lower than sub scenario 5, but due to the long waiting queues the final number of the served vessels in sub scenario 5 is lower and as a result the containers’
number is decreased compare to sub scenario 6. The above conclusions are presented graphically in Figure 5.5. Also, Table 5.6 shows the average number of containers for each value of the variables that we used.

![Graph showing the number of containers for different scenarios.](image)

**Figure 5.5:** Average containers' number for FCFS scenario

<table>
<thead>
<tr>
<th>Time between arrivals = 20h</th>
<th>37998</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 15h</td>
<td>47723</td>
</tr>
<tr>
<td><strong>Handling Time of QCs = 150”</strong></td>
<td>40952</td>
</tr>
<tr>
<td><strong>Handling Time of QCs = 100”</strong></td>
<td>44769</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>44650</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>41071</td>
</tr>
</tbody>
</table>

**Table 5.14:** Average containers' number for FCFS scenario
5.2 Priority for Company

In this case, a company's vessels have priority over those of other companies, meaning that the company's vessels would be served first. However, the First-come First-served rule continues to remain between the company’s vessels and to the rest of the vessels separately. Moreover, we create sixteen sub scenarios (Table 5.7) in order to answer our queries. The sub scenarios were defined in the same way as in FCFS scenario, with the exception that each sub scenario is examined for two different values of the percentage of company’s ships.

<table>
<thead>
<tr>
<th>SUB SCENARIOS</th>
<th>VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time between arrivals (in hours)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
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<td>5</td>
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<td>6</td>
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<td>15</td>
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<tr>
<td>13</td>
<td>15</td>
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<tr>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.7: The sub scenarios of Priority for a company

Afterward, from our results we can easily notice that the Average Total time and the Average Waiting time have the same behavior as shown in the diagrams below. (Figures 5.6 and 5.7)
Figure 5.6: Average Total Time for Priority scenario

Figure 5.7: Average Waiting Time for Priority scenario
We note that decreasing the time between arrivals from 20 to 15 hours results in an increase in waiting time and total time. In terms of handling time of QCs, the change from 150 seconds to 100 seconds reduces these times again. Regarding the probabilities of each vessel categories, we observe that an increase in the percentage of small vessels, and simultaneously a decrease in the percentage of medium and large vessels, brings a decrease in waiting and total time. As for the percentages of company’s vessels we notice that a change from the PC1 (small=55%, medium=85%, large=90%) to PC2 (small=90%, medium=60%, large=85%) has as result an increase in average waiting and total time. Analyzing these times for each vessel category we observe that the average waiting and total time for small vessels are increasing. From the other hand, at the medium vessels’ category, the average waiting and total time are decreasing. Lastly, the average waiting and total time for large vessels are increasing, but more smoothly compared to small vessels. The above observations are shown graphically in Figures 5.8 and 5.9.

**Figure 5.8:** Average Waiting Time per vessel type for Priority scenario
The previous conclusions are shown numerically in the Tables 5.8 and 5.9, which show the average total time and waiting time respectively, for the two levels of the variables examined.

Table 5.8: Average Total time for Priority scenario

<table>
<thead>
<tr>
<th>Time between arrivals = 20h</th>
<th>Average Total Time for large vessels</th>
<th>Average Total Time for medium vessels</th>
<th>Average Total Time for small vessels</th>
<th>Average Total Time for all vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 15h</td>
<td>75.61</td>
<td>58.25</td>
<td>41.88</td>
<td>57.55</td>
</tr>
<tr>
<td>Handling Time of QC's = 150&quot;</td>
<td>143.97</td>
<td>143.95</td>
<td>130.39</td>
<td>138.37</td>
</tr>
<tr>
<td>Handling Time of QC's = 100&quot;</td>
<td>169.89</td>
<td>163.44</td>
<td>146.64</td>
<td>158.79</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>141.96</td>
<td>135.21</td>
<td>120.74</td>
<td>133.23</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>77.61</td>
<td>66.99</td>
<td>51.52</td>
<td>62.69</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>107.95</td>
<td>111.71</td>
<td>64.59</td>
<td>93.74</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>111.63</td>
<td>90.49</td>
<td>107.68</td>
<td>102.17</td>
</tr>
</tbody>
</table>

Table 5.9: Average Waiting time for Priority scenario

<table>
<thead>
<tr>
<th>Time between arrivals = 20h</th>
<th>Average Waiting Time for large vessels</th>
<th>Average Waiting Time for medium vessels</th>
<th>Average Waiting Time for small vessels</th>
<th>Average Waiting Time for all vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 15h</td>
<td>43.81</td>
<td>39.40</td>
<td>32.18</td>
<td>38.25</td>
</tr>
<tr>
<td>Handling Time of QC's = 150&quot;</td>
<td>112.18</td>
<td>125.08</td>
<td>120.69</td>
<td>119.06</td>
</tr>
<tr>
<td>Handling Time of QC's = 100&quot;</td>
<td>131.94</td>
<td>140.94</td>
<td>135.09</td>
<td>135.76</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>24.05</td>
<td>23.54</td>
<td>17.78</td>
<td>21.55</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>110.18</td>
<td>116.36</td>
<td>111.04</td>
<td>112.60</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>45.81</td>
<td>48.12</td>
<td>41.83</td>
<td>44.71</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>76.15</td>
<td>92.85</td>
<td>54.89</td>
<td>74.44</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>79.84</td>
<td>71.63</td>
<td>97.98</td>
<td>82.87</td>
</tr>
</tbody>
</table>
According to Figures 5.10 and 5.11, the utilization of berths 1 and 2 and furthermore the utilization of QCs 1, 2 and 3 follows the same pattern, on the other hand the utilization of berth 3 and QC 4 have once again different fluctuation.

**Figure 5.10:** Berth Utilization for Priority scenario

**Figure 5.11:** Quay Crane utilization Priority scenario
Regarding our findings we are able to perceive that a variant in time between arrivals may affect in opposite way the utilizations. On the contrary, a change in handling time of QCs leads to the same changes in utilizations. As for the probabilities of each vessel’s category, once again we observe that when the percentage of small vessels increases, which mean that the percentages of medium and large vessels decrease, all the utilizations are decreasing. The previous result does not hold for berth 3 and QC4, for which an increase in the number of small vessels results in an increase in utilizations. It is also observed that this change has no effect on utilization when the handling time is 100 seconds. As for the impact of the different percentages of company’s vessels we notice that it is very small, and we considered it as negligible. Tables 5.10 and 5.11 show numerically the above assumptions.

<table>
<thead>
<tr>
<th>Time between arrivals</th>
<th>Berth 1 Utilization</th>
<th>Berth 2 Utilization</th>
<th>Berth 3 Utilization</th>
<th>Average Berth Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>20h</td>
<td>0.71</td>
<td>0.62</td>
<td>0.22</td>
<td>0.52</td>
</tr>
<tr>
<td>15h</td>
<td>0.84</td>
<td>0.77</td>
<td>0.31</td>
<td>0.64</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>0.87</td>
<td>0.80</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>0.68</td>
<td>0.59</td>
<td>0.20</td>
<td>0.49</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>0.83</td>
<td>0.76</td>
<td>0.25</td>
<td>0.62</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>0.72</td>
<td>0.62</td>
<td>0.28</td>
<td>0.54</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>0.78</td>
<td>0.69</td>
<td>0.27</td>
<td>0.58</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>0.78</td>
<td>0.69</td>
<td>0.26</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Table 5.10: Average berth utilization for Priority scenario

<table>
<thead>
<tr>
<th>Time between arrivals</th>
<th>QC 1 Utilization</th>
<th>QC 2 Utilization</th>
<th>QC 3 Utilization</th>
<th>QC 4 Utilization</th>
<th>Average QC Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>20h</td>
<td>0.71</td>
<td>0.68</td>
<td>0.56</td>
<td>0.22</td>
<td>0.54</td>
</tr>
<tr>
<td>15h</td>
<td>0.84</td>
<td>0.82</td>
<td>0.70</td>
<td>0.31</td>
<td>0.67</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>0.87</td>
<td>0.85</td>
<td>0.73</td>
<td>0.33</td>
<td>0.70</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>0.68</td>
<td>0.65</td>
<td>0.53</td>
<td>0.20</td>
<td>0.51</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>0.83</td>
<td>0.82</td>
<td>0.70</td>
<td>0.25</td>
<td>0.65</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>0.72</td>
<td>0.68</td>
<td>0.56</td>
<td>0.28</td>
<td>0.56</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>0.78</td>
<td>0.75</td>
<td>0.63</td>
<td>0.27</td>
<td>0.60</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>0.78</td>
<td>0.75</td>
<td>0.63</td>
<td>0.26</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 5.11: Average QC utilization for Priority scenario

Last but not least, the containers number has a behavior similar to the FCFS scenario. More specifically, as the time between arrivals decreases, the number of containers increases. Also, when the handling time of QCs decreases, we detect a similar
change. Finally, the number of containers decreases as the probability of small vessels increases, with the exception of sub scenarios 9-11 and 10-12. The only difference between these pairs of sub scenarios is the probability of vessels’ category. As a result, it was estimated that the number of containers in sub scenarios 11 and 12 will be smaller than in sub scenarios 9 and 10. But, owing to long waiting lines, the final number of served vessels in sub scenarios 9 and 10 is lower, resulting in fewer containers than in sub scenarios 11 and 12. As for the percentages of company’s vessels, we notice that the differences are very small, and we considered them as negligible. The outcomes are graphically depicted in Figure 5.12 and numerically displayed in Table 5.12.

Figure 5.12: Average containers' number for Priority scenario

<table>
<thead>
<tr>
<th>Time between arrivals</th>
<th>Average containers' number</th>
</tr>
</thead>
<tbody>
<tr>
<td>20h</td>
<td>38063</td>
</tr>
<tr>
<td>15h</td>
<td>47703</td>
</tr>
<tr>
<td>Handling Time of QCs = 150''</td>
<td>40959</td>
</tr>
<tr>
<td>Handling Time of QCs = 100''</td>
<td>44807</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>44618</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>41147</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>42932</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>42833</td>
</tr>
</tbody>
</table>

Table 5.12: Average containers' number for Priority scenario
5.3 Berth Dedicated to a Company

As we stated in section 4.4, the rules from the previous scenario (priority for company vessels) still apply in this scenario, although the difference is that the third berth now serves exclusively the company’s vessels. The sub scenarios that we use are the same sixteen that are shown in Table 5.7.

Our findings regarding the average waiting and total time are similar with the previous scenario. Repeatedly, a decrease in time between arrivals results in an increase in average total (Figure 5.13) and waiting time (Figure 5.14). In contrast a decrease in handling time of QCs is decreasing the average total and waiting time. Concerning the probabilities of each vessel categories, we observe that an increase in the percentage of small vessels, and simultaneously a decrease in the percentage of medium and large vessels, brings a decrease in waiting and total time. As for the impact of the percentages of company’s vessels we notice that a change from the PC1 (small=55%, medium=85%, large=90%) to PC2 (small=90%, medium=60%, large=85%) has as a result an increase in average waiting and total time.

![Average Total Time in hours](image.png)

**Figure 5.13:** Average Total Time for Dedicated scenario
Figure 5.14: Average Waiting Time for Dedicated scenario

These results are shown more clearly in Tables 5.13 and 5.14, which show the average total time and waiting time respectively, for each value of the variables that we used.

<table>
<thead>
<tr>
<th></th>
<th>Average Total Time for large vessels</th>
<th>Average Total Time for medium vessels</th>
<th>Average Total Time for small vessels</th>
<th>Average Total Time for all vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 20h</td>
<td>103.46</td>
<td>81.98</td>
<td>70.57</td>
<td>84.33</td>
</tr>
<tr>
<td>Time between arrivals = 15h</td>
<td>223.35</td>
<td>178.60</td>
<td>169.92</td>
<td>189.28</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>260.51</td>
<td>209.27</td>
<td>198.88</td>
<td>221.32</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>66.31</td>
<td>51.32</td>
<td>41.61</td>
<td>52.29</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>206.39</td>
<td>165.02</td>
<td>155.88</td>
<td>176.76</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>120.43</td>
<td>95.56</td>
<td>84.61</td>
<td>96.85</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>165.73</td>
<td>148.22</td>
<td>90.25</td>
<td>133.17</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>161.08</td>
<td>112.37</td>
<td>150.24</td>
<td>140.44</td>
</tr>
</tbody>
</table>

Table 5.13: Average Total time for Dedicated scenario
Analyzing the average total and waiting time for each vessel category we observe similar changes for the time between arrivals, handling time of QCs and the probabilities of each vessel’s category. But when the percentage of company vessels changes then we see that for small vessels the average total and waiting time increase. From the other hand, at the medium vessels’ category, the average waiting and total time are reduced. Finally, the average waiting and total time for large vessels decrease, but more smoothly compared to medium vessels. The above observations are shown graphically in Figures 5.15 and 5.16.
With respect to the utilizations, we notice that a change to the time between arrivals leading to an opposite change to all the utilizations, as shown in Figures 5.17 and 5.18. With reference to the handling time of QCs, a change to this value brings a similar change to all the utilizations. Relating to the probabilities of each vessel category we observed that when the percentage of small vessels’ increases, the utilizations are decreasing. Some exceptions to this rule are met at berth 1 with QC1 and berth 3 with QC4. At berth 1 and QC1 we perceived that in sub scenarios 11-12 the utilization is bigger compared to sub scenarios 9-10 respectively. This is happening due to the reduced time between arrivals and simultaneously increased handling time of QCs, which lead to long waiting queues in sub scenarios 9 and 10. These queues created by the fact that there is greater participation of medium and large vessels in the specific sub scenarios. As for the berth 3 and QC4, it has been noticed that when the percentage of company’s small vessels is big and the same time, the probability of small vessels’ category is increased, the utilizations remain stable. Finally, regarding the percentages of company’s vessels, a change from the PC1 (small=55%, medium=85%, large=90%) to PC2 (small=90%, medium=60%, large=85%) increases the utilization in berths 2 and 3 as well as in QC3 and QC4, but decreases utilization in berth 1, such as in QC1 and QC2.
Tables 5.15 and 5.16 display the numerical results of the above conclusions, which represent the average berth and QC utilization, respectively, for each value of the variables that we used.
<table>
<thead>
<tr>
<th>Time between arrivals = 20h</th>
<th>Berth 1 Utilization</th>
<th>Berth 2 Utilization</th>
<th>Berth 3 Utilization</th>
<th>Average Berth Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 15h</td>
<td>0.72</td>
<td>0.62</td>
<td>0.17</td>
<td>0.50</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>0.84</td>
<td>0.74</td>
<td>0.23</td>
<td>0.60</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>0.69</td>
<td>0.59</td>
<td>0.17</td>
<td>0.48</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>0.81</td>
<td>0.74</td>
<td>0.21</td>
<td>0.58</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>0.75</td>
<td>0.62</td>
<td>0.19</td>
<td>0.52</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>0.80</td>
<td>0.67</td>
<td>0.18</td>
<td>0.55</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>0.75</td>
<td>0.69</td>
<td>0.22</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 5.15: Average berth utilization for Dedicated scenario

<table>
<thead>
<tr>
<th>Time between arrivals = 20h</th>
<th>QC 1 Utilization</th>
<th>QC 2 Utilization</th>
<th>QC 3 Utilization</th>
<th>QC 4 Utilization</th>
<th>Average QC Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals = 15h</td>
<td>0.72</td>
<td>0.68</td>
<td>0.53</td>
<td>0.17</td>
<td>0.53</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>0.84</td>
<td>0.81</td>
<td>0.64</td>
<td>0.23</td>
<td>0.63</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>0.69</td>
<td>0.66</td>
<td>0.52</td>
<td>0.17</td>
<td>0.51</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>0.81</td>
<td>0.81</td>
<td>0.65</td>
<td>0.21</td>
<td>0.62</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>0.75</td>
<td>0.68</td>
<td>0.53</td>
<td>0.19</td>
<td>0.54</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>0.80</td>
<td>0.77</td>
<td>0.55</td>
<td>0.18</td>
<td>0.58</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>0.75</td>
<td>0.72</td>
<td>0.63</td>
<td>0.22</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Table 5.16: Average QC utilization for Dedicated scenario

Last of all, the containers’ number has a similar behavior with the previous scenarios as it shown in Figure 5.19. Once more we observe that the existence of long waiting queues affecting negatively the final outcome of the container’s number. Again, this phenomenon is detected between the sub scenarios 9-11 and 10-12. The numerical results are presented in Table 5.17.
Figure 5.19: Average containers' number for Dedicated scenario

<table>
<thead>
<tr>
<th>Time between arrivals</th>
<th>Average containers' number</th>
</tr>
</thead>
<tbody>
<tr>
<td>20h</td>
<td>37395</td>
</tr>
<tr>
<td>15h</td>
<td>45474</td>
</tr>
<tr>
<td>Handling Time of QCs = 150&quot;</td>
<td>38397</td>
</tr>
<tr>
<td>Handling Time of QCs = 100&quot;</td>
<td>44472</td>
</tr>
<tr>
<td>P1 (S=0.30/M=0.35/L=0.30)</td>
<td>42863</td>
</tr>
<tr>
<td>P2 (S=0.45/M=0.30/L=0.25)</td>
<td>40006</td>
</tr>
<tr>
<td>PC1 (S=0.55/M=0.85/L=0.90)</td>
<td>41368</td>
</tr>
<tr>
<td>PC2 (S=0.90/M=0.60/L=0.85)</td>
<td>41501</td>
</tr>
</tbody>
</table>

Table 5.17: Average containers' number for Dedicated scenario

5.4 Results comparison for the three main scenarios

In order to understand how the variables affect the efficiency of the CT in the three scenarios examined (First come – First served, Priority for company vessels, Berth dedicated to a company), we compare their results from the previous chapters, for every sub scenario. We notice that as the handling time decreases the differences between the performance values are very low and we consider them as negligible. In contrast, a decrease in time between arrivals has as result more noticeable differences. With regard to the changes of the percentage of vessels length, we notice that the increased number of small vessels in the container terminal have the same result with a decrease of handling
time.

In more details as shown at Table 5.18 the average total times between FCFS and Priority scenario have very small differences, but in Dedicated scenario the differences are more intense.

<table>
<thead>
<tr>
<th></th>
<th>Average Total Time for large vessels</th>
<th>Average Total Time for medium vessels</th>
<th>Average Total Time for small vessels</th>
<th>Average Total Time for all vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average FCFS values</td>
<td>115.73</td>
<td>103.06</td>
<td>86.89</td>
<td>100.77</td>
</tr>
<tr>
<td>Average Priority values</td>
<td>109.79</td>
<td>101.10</td>
<td>86.13</td>
<td>97.96</td>
</tr>
<tr>
<td>Average Dedicated values</td>
<td>163.41</td>
<td>130.29</td>
<td>120.24</td>
<td>136.80</td>
</tr>
</tbody>
</table>

Table 5.18: Average Total time for all the scenarios

We also notice similar results for the average waiting times at Table 5.19. Once again, the Dedicated scenarios have the biggest waiting time.

<table>
<thead>
<tr>
<th></th>
<th>Average Waiting Time for large vessels</th>
<th>Average Waiting Time for medium vessels</th>
<th>Average Waiting Time for small vessels</th>
<th>Average Waiting Time for all vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average FCFS values</td>
<td>83.94</td>
<td>84.18</td>
<td>77.18</td>
<td>81.46</td>
</tr>
<tr>
<td>Average Priority values</td>
<td>78.00</td>
<td>82.24</td>
<td>76.44</td>
<td>78.66</td>
</tr>
<tr>
<td>Average Dedicated values</td>
<td>131.61</td>
<td>111.44</td>
<td>110.59</td>
<td>117.52</td>
</tr>
</tbody>
</table>

Table 5.19: Average Waiting time for all the scenarios

As for the berths and QCs utilizations as shown in Tables 5.20 and 5.21 are the same in all scenarios, except the berth 3 and QC 4 utilizations. These resources in Dedicated scenarios have the lowest values, even if the idea for this scenario was to increase the utilization of the lowest resources.

<table>
<thead>
<tr>
<th></th>
<th>Berth 1 Utilization</th>
<th>Berth 2 Utilization</th>
<th>Berth 3 Utilization</th>
<th>Average Berth Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average FCFS values</td>
<td>0.78</td>
<td>0.69</td>
<td>0.26</td>
<td>0.58</td>
</tr>
<tr>
<td>Average Priority values</td>
<td>0.78</td>
<td>0.69</td>
<td>0.26</td>
<td>0.58</td>
</tr>
<tr>
<td>Average Dedicated values</td>
<td>0.78</td>
<td>0.68</td>
<td>0.20</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 5.20: Average Berth utilization for all the scenarios

<table>
<thead>
<tr>
<th></th>
<th>QC 1 Utilization</th>
<th>QC 2 Utilization</th>
<th>QC 3 Utilization</th>
<th>QC 4 Utilization</th>
<th>Average QC Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average FCFS values</td>
<td>0.78</td>
<td>0.75</td>
<td>0.63</td>
<td>0.25</td>
<td>0.60</td>
</tr>
<tr>
<td>Average Priority values</td>
<td>0.78</td>
<td>0.75</td>
<td>0.63</td>
<td>0.26</td>
<td>0.60</td>
</tr>
<tr>
<td>Average Dedicated values</td>
<td>0.78</td>
<td>0.75</td>
<td>0.59</td>
<td>0.20</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Table 5.21: Average QC utilization for all the scenarios
Finally, with respect to the average number of containers, the difference between FCFS and Priority scenarios are once again insignificant. In Dedicated scenarios we detect again the lowest values as shown in Table 5.22.

<table>
<thead>
<tr>
<th></th>
<th>Average containers' number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average FCFS values</td>
<td>42861</td>
</tr>
<tr>
<td>Average Priority values</td>
<td>42883</td>
</tr>
<tr>
<td>Average Dedicated values</td>
<td>41434</td>
</tr>
</tbody>
</table>

Table 5.22: Average number of containers for all the scenarios

Overall, we conclude that the berth dedicated to a company scenario has the lowest performance value outcome, but the variations between the other two scenarios are very small. Both scenarios have almost similar performance values under these conditions, but if we could pick one, the Priority for company vessels scenario has the better performance values, with minor differences in all sub scenarios.
6. Conclusions and Future Research

In this dissertation, we studied the BACQAP at CT with three berths and four QCs. The data that we used were collected mainly from previous researches. The values of our inputs and variables are relatively similar to the average of the values used in previous researches. Thus, we achieved to have a better representation of a real case. After we created three different simulation models in order to simulate the three different priority policies that we want to examine. For every one of the policies, we created alternative scenarios, so we could investigate the impact that our variables have to the container terminal’s effectiveness. For each one of them we ran the model 1000 times with duration of 90 days and a warm-up period of 30 days, with the help of the Arena simulation software.

The results indicated that the time between the vessels’ arrivals has significant impact to our performance values. As this time is decreasing, the performance values are increasing. Crucial role is also played by the handling time of the QCs. The smaller this time is getting, the faster the vessels will be served. But we should also consider about the waiting queues and time. After a point the long waiting queues cause a negative effect on the container terminal’s operations, because the number of vessels that they have been served is smaller compare to the situations where we have short queues. This phenomenon became obvious when we had less time between vessels’ arrivals and more handling time for QCs. Significant impact on our results has also the percentage of the small vessels in our system. We observed that when we had long waiting queues the increase of the small vessels’ percentage could improve the CT’s operations, but in all the other cases it decreases the effectiveness of the CT.

From our research we conclude that there was not large difference between FCFS and Priority scenarios for any of the sub scenarios that we examined. From the other hand, the berth dedicated scenario had always the worst results, due to the larger waiting times that occurred because of the commitment of berth 3 to a company.

For the implementation of our simulation model, we made some assumptions and we concentrate only on the seaside operations of a CT. In future research the simulation model could be extended in order to include some of the assumptions that have been made and also to investigate an integration of seaside and landside operations of a CT. More specifically, variables may be introduced to investigate how truck or train arrivals influence the loading process, or how stacking policies improve (or do not improve) the container terminal’s effectiveness. Last but not least, the current model could be modified
in such way that the overpasses in the waiting queues are permitted when a vessel from behind can be served, instead of the other vessels ahead waiting for more resources.
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