Università degli Studi di Padova

Dipartimento di Tecnica e Gestione dei Sistemi Industriali

Corso di Laurea Magistrale in Ingegneria Gestionale

Comparison and Improvement of Integrated Berth Allocation and Quay Crane Assignment Models

Relatore: Ch.ma Prof.ssa Daria Battini

Correlatore: Cagatay Iris

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Master’s Thesis carried out at Università degli Studi di Padova
and Technical University of Denmark

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Ai miei genitori

Anna e Bruno

Sommario

Secondo il World Shipping Council, oggi giorno circa il 75-85% delle merci prodotte a livello mondiale viene trasportato via container (worldshipping.org).

Il settore del trasporto marittimo containerizzato ha conosciuto una crescita maggiore rispetto ad altri settori come per esempio il trasporto con navi cisterna o portarinfuse. Nel dettaglio, uno studio condotto dalla società Rickmers Maritime mostra come il commercio di container sia cresciuto del 10% dal 1999 al 2008. A causa della crisi economica, il 2009 è stato segnato da una contrazione del 10% per un totale di 124 milioni di TEU movimentati nell'anno. Già a partire dal 2010, tuttavia, il settore è stato caratterizzato da una forte ripresa: nel 2012 in particolare, la domanda di navi portacontainer è cresciuta del 5%; le statistiche per il 2015 parlano invece di una crescita del 5,8% per il numero di container movimentati e del 6% per la domanda di navi portacontainer (rickmers-maritime.com).

La crescente containerizzazione ha indubbiamente delle implicazioni a livello economico e logistico. Nel corso degli anni il numero di terminal portuali è diventato significativo; di recente inoltre, si sta assistendo ad una forte competizione tra compagnie di navigazione per quanto riguarda la costruzione di navi di dimensioni e capacità sempre maggiori. Ad oggi, la nave portacontainer più grande al mondo è MSC Oscar con una capacità di più di 19200 container (lloydslist.com). L'aumento della dimensione delle navi consente di realizzare economie di scala e di ridurre dunque il prezzo unitario per container trasportato. Tuttavia, per ospitare navi così grandi sono necessari moli e gru per la movimentazione dei container di dimensioni appropriate; anche l'area di stoccaggio deve essere sufficientemente grande per poter contenere un numero di container significativo. Oltre a questo, le crescenti dimensioni del settore rendono più complessi i processi logistici che caratterizzano un terminal container: sarebbe impensabile gestire tali complessità senza il supporto dell'Information Technology e di metodi di ottimizzazione adeguati.

Il focus di questa Tesi è il problema di Berth Allocation e Quay Crane Assignment, uno dei principali problemi logistici che i terminal container devono gestire. L'obiettivo è determinare il punto e l'istante ottimale di attracco per le navi in arrivo al porto e contemporaneamente assegnare ad ogni nave il numero ottimale di gru che andranno

a scaricare e caricare i container. Sino ad ora è stata data maggiore attenzione allo studio dei problemi di Berth Allocation e Quay Crane Assignment in modo separato. Questa tesi contribuisce invece all'analisi del problema integrato, attraverso lo sviluppo e il confronto di nuovi modelli matematici che descrivono il problema e che vanno ad integrare le soluzioni proposte nella Letteratura.

Abstract

According to the World Shipping Council, nowadays 75-85% of the world's manufactured goods are transported in containers (worldshipping.org). The container shipping industry connects countries, markets, companies and people: it is the industry that shapes the global economy.

Growth in the container shipping market has been relatively rapid in comparison to other major shipping sectors such as tankers and bulk carriers. Demand for shipping was strong in the last few years, with world container trade grew at an annual rate of 10% from 1999 to 2008. In 2009, due to weak global economic conditions, world container trade contracted by about 10% to 124 million TEU - the first yearly decline on record. By 2010, the container shipping industry rebounded, fuelled by a recovery in global trade and in 2012, containership demand grew by about 5%. For 2015, the outlook shows sign of gradual recovery for the global shipping industry. Containership demand growth is forecasted at around 6.0% while capacity is projected to grow at an estimated 5.8% (rickmers-maritime.com). The world container trade expressed in million TEUs and the annual growth can be visualised in the following figure.

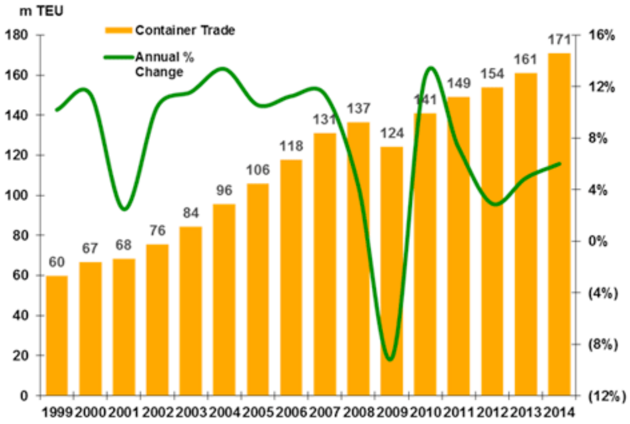

Figure i: world container trade and annual growth
Source: Clarkson Research Services Limited

Referring specifically to seaborne trade, Figure ii shows the volumes carried by container ships from 1980 to 2013 globally. Seaborne containerized cargo amounted to around 1,5 billion tons loaded in 2013 (statista.com).

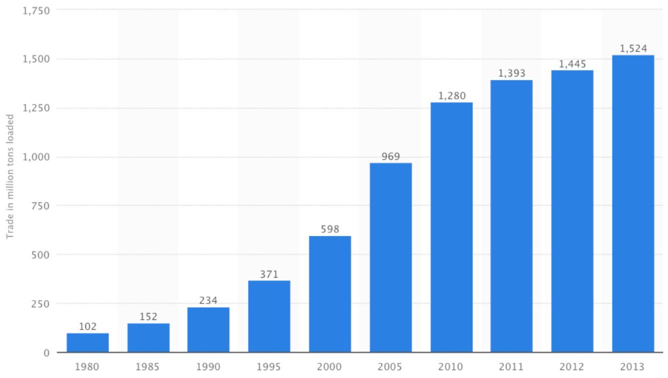

Figure ii: international seaborne trade carried by container ships from 1980 to 2013 (in million tons loaded)
Source: statista.com

With ever increasing containerization, the number of terminals has become significant; furthermore a fierce competition exists amongst shipping lines, as concerns the dimensions and capacity of container vessels. At present, the world's largest container vessel is MSC Oscar, which can carry more than 19.200 containers (lloydslist.com); shipping experts believe though, that vessels capable of holding more than 20.000 containers will be built soon. Indeed, bigger ships means lower shipping prices per container: less fuel per container and basically the same amount of sailors regardless the size of the vessel. However, in order to accommodate big ships, wharfs and quay cranes need to be appropriate along with yards which have to be vast enough to store a remarkable number of containers. In addition to this, the growing dimensions of the industry make logistic processes at container terminals much more complex. It would be unthinkable to deal with these complexities without the support of information technology and effective optimisation methods.

The focus of this Thesis is one of the main logistic problems that container terminal managers have to deal with: the Berth Allocation with Quay Crane Assignment Problem (BACAP). The problem's goal is to find an optimal berthing position and time for incoming container vessels, as well as an optimal number of quay cranes, which will unload the import containers and load the export ones. Being the integration of two sub problems, the BACAP has received less attention in the Literature compared to the separate problems, Berth Allocation Problem and Quay Crane Assignment Problem. This work contributes to the analysis of the BACAP, through the development of new mathematical models compared to the ones proposed so far.

This Thesis can be divided in two parts: the first part, with Chapters 1 and 2, is Logistics oriented; the second one, with Chapters 3 and 4, is Operations Research oriented. Integrating the two disciplines is fundamental in this context since many operations occurring at container terminals are optimised with Operations Research techniques.

Chapter 1 introduces the dynamics of container shipping: the most efficient mode of transportation of goods (worldshipping.org). The industry was born around the fifties with a great potential for expansion; over the years many routes were containerized, new container types were developed and bigger container vessels were built. The last part of the chapter focuses on container shipping costs, describing the different components of freight rates.

The structure of a container terminal, the handling equipment used and the main logistic processes are described in Chapter 2. Managing a container terminal means creating a lean flow of goods across the different areas the terminal is divided into: quayside, yard and landside. Furthermore, efficient operations increase customer satisfaction and allow terminals to save on costs. Container Terminal Management Systems are also introduced as the technology that supports terminal managers in the optimization of processes and resources. These information systems are discussed in this Thesis because they are founded on mathematical models, which describe the various planning problems occurring at container terminals.

Chapter 3 provides an outline of these problems: Berth Allocation, Quay Crane Assignment, Stowage Planning, Storage and Stacking, just to quote the major ones. Objectives, constraints, input data and output of the problems are presented in detail.

Finally, the integration of Berth Allocation and Quay Crane Assignment is presented in Chapter 4, core part of this Thesis. In the first place, a Literature review has been performed with the aim to study the problem and the models proposed by the different authors. In the second place, six mathematical formulations have been developed for a deeper analysis. Some decision variables and assumptions change, however all the models aim at minimizing the total costs considered for this problem (costs for berthing later than expected and far from the desired position along with costs for using the quay cranes) respecting common logistic constraints. As a third step, the models have been translated into the Optimization Programming Language, in order to optimally solve the BACAP with the software IBM® ILOG® CPLEX® Optimization Studio. Subsequently, the different formulations have been tested with a set of realistic instances of increasing complexity. Berth plans and quay crane-to-vessel assignments can be visualised in time-space diagrams, with the aim to understand the differences between the models and the cost implications of the assumptions made.

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CHAPTER 1
Introduction to the Container Shipping Industry

1.1 Characteristics of the industry

Every day thousands of containers arrive at ports from all around the world. They are carried by ships, which sail on fixed routes to transport products from two points of a given supply chain. In particular, the container shipping industry is part of liner shipping, the most efficient mode of transportation of goods according to the World Shipping Council. Liner vessels, primarily in the form of container ships and roll-on/roll-off ships (RoRo ships), carry about 60% of the goods by value moved internationally by sea each year. Cargo transported by the liner shipping industry represents about two-thirds of the value of total global trade, equating each year to more than US$ 4 trillion worth of goods (worldshipping.org).

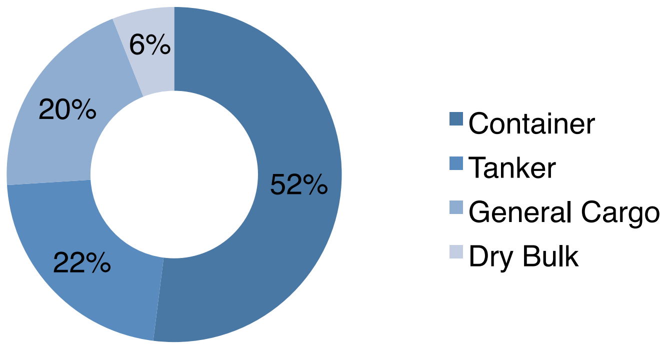


Figure 1: value of world seaborne trade in US$ (2015)
Source: Lloyd's Maritime Intelligence Unit

In details: tankers transport liquids or gases in bulk; general cargo vessels carry a broad mix of cargoes such as vehicles, machinery, forest products, steel, food products and also containers; dry bulk carriers are designed to transport for instance grain, sugars, coal, iron.

The liner container shipping business is schedule based: the route that a specific vessel has to follow, is usually published 3 – 6 months before its departure. In addition to this, container ships typically operate rotations, passing by two or more harbours in their cycles. The industry includes both short-see shipping, which encompasses the movement of ships along coastlines without crossing an ocean and deep-sea shipping, also known as ocean shipping. Products transported in containers might vary from shoes to computers, DVDs, machineries, toys, meat.

1.1.1 The shipment of a container: main steps

In order to understand how container shipping works, we here revisit an example proposed in the web site worldshipping.org: sport T-shirts produced in Korea and shipped via container to a megastore in the US. For the summer season, the store places an order of 700 T-shirts: the Korean manufacturer arranges the transport from its production site with a freight forwarder. Acting as an expert in the logistic network, the freight forwarder organises and coordinates the shipment from the producer to the final point of distribution, contracting with a carrier to move the goods. A truck arrives at the Korean factory and T-shirts are loaded in the container, perhaps along with orders from other companies. Once closed and sealed, unless customs authorities need to inspect it, the container will not be opened anymore until it arrives in the US at the distribution center the megastore refers to. The freight forwarder decides to truck the container to the Port of Busan, in South Korea, from here the T-shirts will be shipped to the Port of Los Angeles in the US. The freight forwarder has contracted with a container shipping line, which has to submit all the documentation about the shipment to government authorities in both the exporting and importing country. The documentation is extremely important and includes data about the type of goods transported, information about the exporter and importer company and last but not the least about the shipping line itself. The container of T-shirts is now ready to be loaded in the vessel and transported at destination. A couple of days before the ship is due to berth at the US port, the captain of the vessel provides a report to the government of the destination country with information about the ship, crew and cargo. After the mooring operations, quay cranes are scheduled to unload the containers from the ship: some containers might be selected for further inspection by customs officials. Subsequently, dockworkers load the T-shirt container on a new truck directed to the distribution center. Sometimes containers can be loaded on trains if their destination is far from the harbour. Finally, when the truck arrives at the distribution center, the container is opened and the 700 T-shirts ordered by the megastore are separated from the other orders and prepared to be shipped to the store's warehouse.

1.2 History of containerization

Before the first container was conceived in the 1950s, people had shipped goods across lands and oceans in many other different ways: barrels, sacks, wooden crates etc. Break-bulk shipping was the only ship transportation process known at the time: after arriving at ports with land means of transportation, goods were loaded in vessels and then unloaded again upon arrival. Indeed, due to the lack of any technology, the process was highly labour-intensive, risky and slow: ships could even spend more time at the harbour than at sea.

Figure 2: break bulk shipping
Source: Wikipedia

Figure 3: before containerization, loading cargo in the Port of Seattle in the 1930's
Source: University of Washington Ron Magden Archive ILWU 23 Collection

Boxes similar to modern containers had been used for combined rail and horse-drawn transport in England as early as 1792. Years later, the US government used small standard-sized containers during the Second World War, which proved a means of quickly and efficiently unloading and distributing supplies (worldshipping.org).

In 1955, Malcom McLean, an American trucking entrepreneur, sold his trucking company and purchased Pan Atlantic Tanker Company, which he then re-named Sea-Land Shipping. McLean's first idea was to transport the entire trucks with their cargo in the vessels. He then realised it would have been much easier to have just one container which could have been transferred from a vehicle onto a ship, without first unloading its content. His ideas were based on the theory that efficiency could be vastly improved through a system of "intermodalism", in which the same container, with the same cargo, can be transported with minimum interruption via different transport modes during its journey. Containers could be moved seamlessly between ships, trucks and trains (worldshipping.org).

In 1956, Malcolm McLean converted a Second World War tanker vessel, the Ideal X, into a ship which would have hosted 58 metal container boxes in the form of wheel-less truck carts: the first intermodal containers were born. McLean's company later changed its name into Sea-Land Services whose core business was carrying cargo-laden truck trailers via ships, between ports in North and South America. In the following years, many other companies adopted McLean's successful approach.

Figure 4: Malcolm McLean
Source: containerstuffers.com

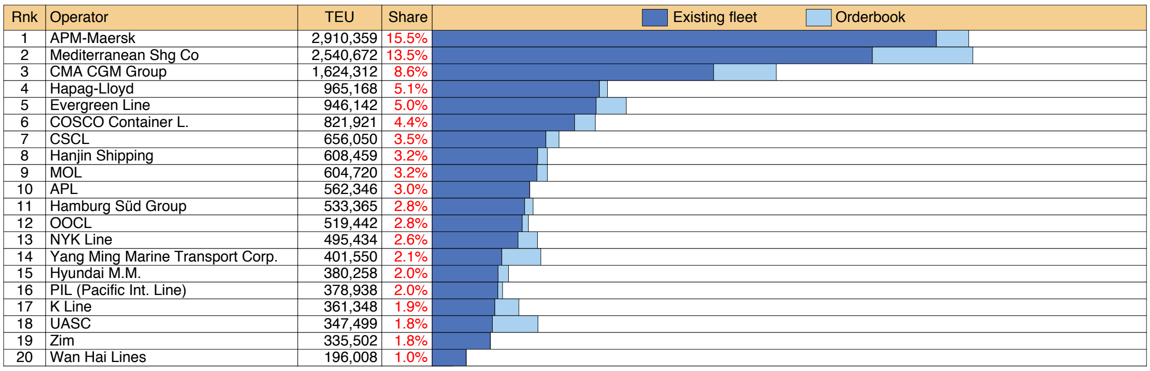
Given the continuous growth of the container shipping industry and acknowledged its importance and potential, the need of having standardized containers' sizes arose. The standardization would have come along with many advantages: higher efficiency in the stacking operations, easier and faster handling, possibility of building ships, trucks, trains and quay cranes following one containers' size specification. In 1961, the International Organization for Standardization (ISO) set standard sizes. The two most important, and most commonly used sizes even today, are the 20-foot and 40-foot lengths (worldshipping.org), whose features will be detailed in Section 1.5.

For the first time in 1966 a container ship made an international voyage from Port Elizabeth in the US to Rotterdam in the Netherlands with 236 containers. From that moment on, container shipping started its international expansion and growth, becoming the backbone of global trade, title which the industry is still awarded with.

1968 and 1969 were the Baby Boomer years for container shipping. In 1968 alone, 18 container vessels were built, ten of them with a capacity of 1.000 TEU which was large for the time. In 1969, 25 ships were built and the size of the largest ships increased to approaching 2.000 TEU. In 1972, the first container ships, with a capacity of more than 3.000 TEU were completed by the Howaldtwerke Shipyard in Germany (worldshipping.org). In the 1970s and 1980s the industry had an exponential growth: new routes were created to connect the US west coast and Japan, the US east cost and Europe. By the end of the decade, shipping between Europe, Asia, South Africa, Australia, North and South America were all largely containerized.

1.3 Top container shipping lines

The following figure shows the top 20 leading container shipping lines worldwide by total capacity of the container ship fleet (in TEU). The light blue bars represent the current orderbook (firm orders in TEU) while the red percentages show the company's share of the world liner fleet in TEU terms (alphaliner.com as of December 21, 2014).



Rnk	Operator	TEU	Share
1	APM-Maersk	2,910,359	15.5%
2	Mediterranean Shg Co	2,540,672	13.5%
3	CMA CGM Group	1,624,312	8.6%
4	Hapag-Lloyd	965,168	5.1%
5	Evergreen Line	946,142	5.0%
6	COSCO Container L.	821,921	4.4%
7	CSCL	656,050	3.5%
8	Hanjin Shipping	608,459	3.2%
9	MOL	604,720	3.2%
10	APL	562,346	3.0%
11	Hamburg Süd Group	533,365	2.8%
12	OOCL	519,442	2.8%
13	NYK Line	495,434	2.6%
14	Yang Ming Marine Transport Corp.	401,550	2.1%
15	Hyundai M.M.	380,258	2.0%
16	PIL (Pacific Int. Line)	378,938	2.0%
17	K Line	361,348	1.9%
18	UASC	347,499	1.8%
19	Zim	335,502	1.8%
20	Wan Hai Lines	196,008	1.0%

Figure 5: top 20 container shipping lines by total capacity of the container fleet (2014)
Source: alphaliner.com

The next figure shows a list of the top 20 container shipping companies in the world based on the number of owned and chartered ships (statista.com as of December 3, 2014). The latters are vessels which are hired by one or more merchants for a particular voyage between a load and a discharge port (charter voyage) or for a certain period of time (time charter).

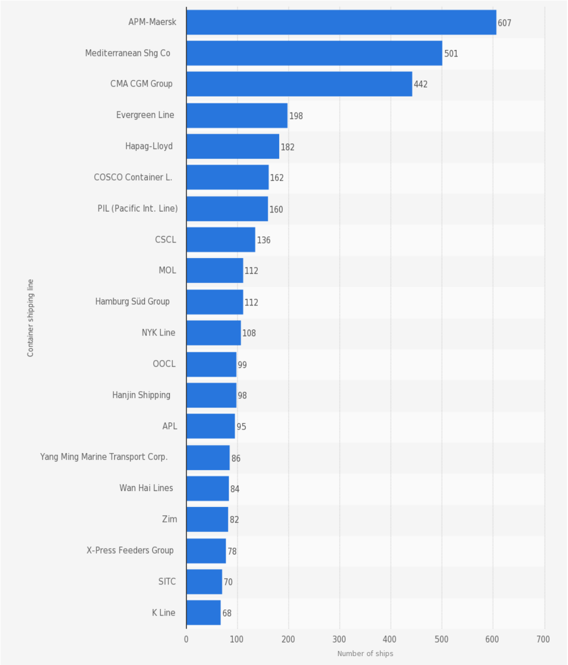


Figure 6: top 20 container shipping lines by number of owned and chartered ships (2014)
Source: alphaliner.com

Another list is then proposed based on the number of own ships (statista.com, as of December 3, 2014).

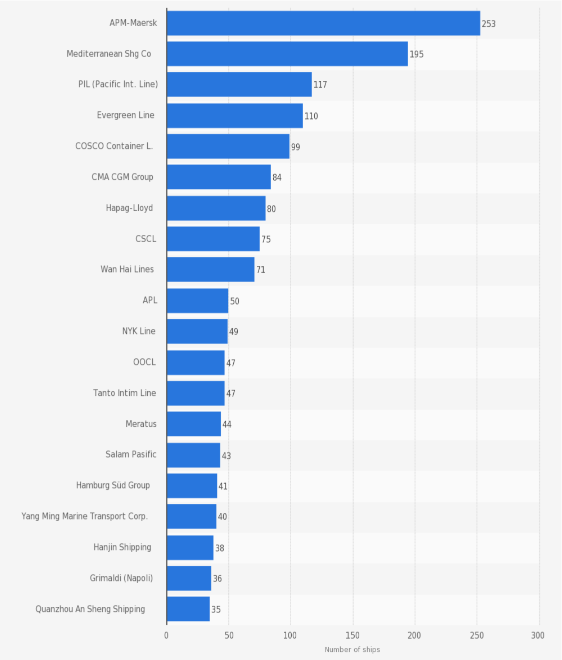


Figure 7: top 20 container shipping lines by number of own ships (2014)
Source: alphaliner.com

As we can notice, the top two companies, which hold the record in all the three classifications are A.P. Møller–Maersk Group and Mediterranean Shipping Company S.A.

1.4 Types of liner vessels

Today, there are 5968 ships active on liner trades, including 5051 fully cellular ships that is to say container ships (alphaliner.com as of March 8, 2015). The overwhelming majority of these ships were built since 1980.

In an average year, a large container ship travels three-quarters of the distance to the moon. That means that in its lifetime it travels to the moon and back nearly ten times (worldshipping.org).

The liner ships category includes not only container ships but also RoRo ships and car carriers. The following pie chart shows the percentages associated to each type.

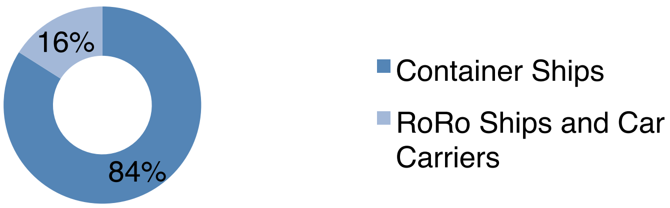


Figure 8: liner ships

1.4.1 Container vessels

Container vessels come in many different sizes; as we can see in figure 9, the trend has been to build larger and larger ships.

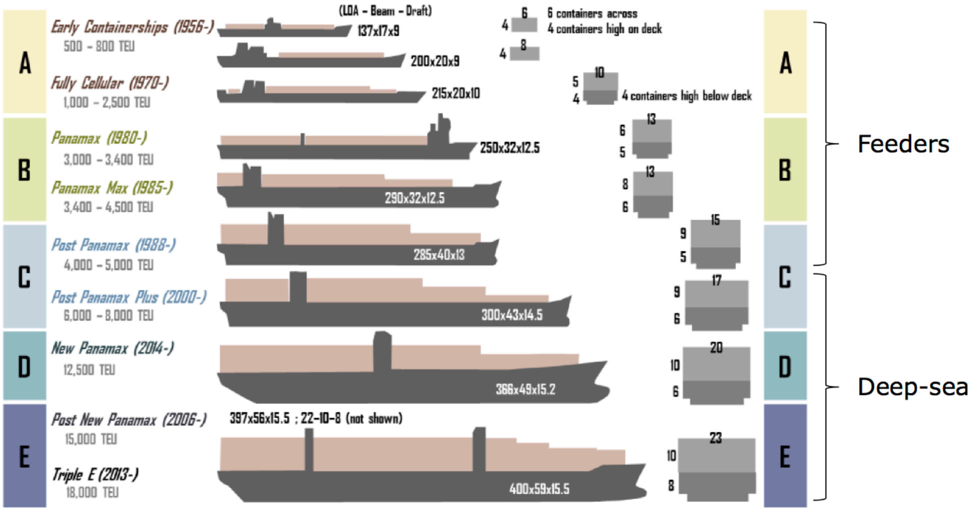


Figure 9: evolution of container vessels
Source: godues.blogspot.com

In the '50s, the first container ships could host only 500-800 TEU, nowadays this number has grown 30 times. This trend can be explained by two facts: in the first place, since much more cargo was converted to containers, vessels had to increase their capacity, therefore size; in the second place, studies showed that bigger ships have a lower fuel consumption, efficiency which in turn reduces operating costs.

Figure 9 shows the most renowned ships built from the 1950s to 2013. As the name suggests, Panamax vessels travel through the Panama Canal opened in 1914. At the beginning, the lock chambers of the Panama canal were 320,04 m in length, 33,53 m in width and 12,56 m in depth. Following the size regulations set by the Panama Canal Authorities, Panamax vessels couldn't be longer than 294,13 m, wider than 32,31 m and their draught couldn't exceed 12,04 m (maritime-connector.com).

In 2009, the expansion plan of the Panama Canal started with the aim to handle larger vessels and double the Canal’s capacity. According to maritime-connector.com, New Panamax ships will be 366 m long, 49 m wide and 15,2 m deep. The project is expected to end in 2015 and several ship manufacturing companies around the world have already started building vessels which match the new regulations. Thanks to the expansion of the Canal, Post Panamax vessels (mainly supertankers, modern containers and passengers ships) can travel through the canal as well.

However, even after the completion of this project, some of the very large ships won’t still be able to sail through the Panama Canal. These vessels are in general called Post New Panamax and include for example VLCC (Very Large Crude Carriers), ULCC (Ultra Large Crude Carriers) or ships in Maersk E and Triple E classes. VLCC and ULCC are the largest operating cargo vessels in the world and are mainly used to carry huge amounts of crude oil usually from the Persian Gulf to European countries, North America and Asia (maritime-connector.com). Examples of VLCC and ULCC are shown in Figure 10 and 11 respectively.

Figure 10: VLCC
Source: maritime-connector.com

Figure 11: ULCC
Source: maritime-connector.com

Maersk E-class ships are a series of 20’ container ships all owned by APM Maersk Group and whose names start with “E”. The first vessel belonging to this category is Emma Maersk built in 2006 with the following dimensions: 397 m long, 56 m wide and 15,5 m deep (ship-technology.com).

In 2013, the largest ship in the world was built with the name of Maersk Mc-Kinney Moeller under the new category Triple-E. With a length of 400 m, a width of 59 m and a depth of 15,5 m, Triple-E ships are an example of environmentally friendly and energy efficient vessels which can create economies of scale: their capacity of more than 18.000 containers, reduces the costs of moving a container by 20-30 per cent compared to other vessels in the Asia-Europe trade lane (maerskline.com).

Figure 12: Triple-E
Source: Wikipedia

The Triple E lost its capacity primatum in November 2014: a new container vessel was built, The Globe, with a capacity of 19.100 TEU. The Globe is the first of a series of four other vessels owned by China Shipping Container Lines, which are expected to be delivered by the end of 2015 (bbc.com). The Globe reigned as the world’s biggest cargo ship for only two months. In January 2015 in fact, the Mediterranean Shipping Company launched MSC Oscar, which is able to carry 19.224 20’ containers.

The following table summarizes the dimensions of the main ships classes introduced in the maritime industry over the years.

	Length [m]	Beam [m]	Draft [m]	TEU
Early Containerships	137	17	9	500 - 800
Fully cellular	215	20	10	1.000 – 2.500
Panamax	294,13 (max)	32,31 (max)	12,04 (max)	4.500
New Panamax	366	49	15,2	12.500

Post Panamax	285	40	13	4.000 – 5.000
Post Panamax Plus	300	43	14,5	6.000 – 8.000
Post New Panamax	397	56	15,5	15.000
Triple-E	400	59	15,5	18.000
The Globe	400	59	16	19.100
MSC Oscar	395	59	16	19.224

Table 1: ships classes - dimensions

1.4.2. Other types of liner vessels

As explained at the beginning of the chapter, liner vessels include primarily container ships but also other types of vessels, which belong to the category of roll-on/roll-off ships. RoRo vessels were being built in the 19th century to transport trains, too wide for the bridges, across rivers. The rails were laid on the ship so that it could be connected to the ones on the land. A train would then simply roll onto the ship and then roll off at the other end (marineinsight.com). In general RoRo vessels are used to transport wheeled cargo which is loaded and unloaded by means of built in ramps. Two are the main categories considered: Pure Car and Truck Carriers (PCTC) and Pure Car Carriers (PCC), designed exclusively for transporting trucks and passenger vehicles across oceans; these vessels can often also accommodate tractors, buses and the like. According to Marine Insight, the largest RoRo passenger ferry is MS Color Magic: 223,70 m long, 35 m wide, with a capacity of 550 cars. Considering the car-carrying capacity instead, the biggest RoRo passenger ferry is the Ulysses: 209,02 m long, 31,84 m wide and a capacity of 1.342 cars (Figure 13).

Figure 13: Ulysses
Source: Wikipedia

Roll-on/roll-off ships are different from lift-on/lift-off ships (LoLo ships) which use cranes to load the cargo; container vessels belong to this last category. Compared to other ships, RoRo vessels offer various advantages. Given that vehicles can drive straight on to the ship and drive off upon arrival in few minutes, the shipper saves a lot of time; as a consequence, expensive loading equipment and staff is not needed: this makes the process safer, cheaper and more efficient. In addition to this, thanks to RoRo vessels, passengers can easily take their car from one country to the other by sea: this means of transportation significantly contributed to the growth of tourism. As regards disadvantages, RoRo vessels are characterised by inefficient volume utilisation. Vehicles cannot be stacked on top of each other and a lot of space is needed for loading and unloading in order to maneuver the cargo.

1.5 Types of containers

Containers are relatively uniform boxes designed for an easy and fast handling of freight. There is a variety of different types of containers, which are used to satisfy specific transportation needs. The following sections are dedicated to a detailed description of eight container's types, their construction materials, dimensions and use, according to a classification proposed in the web site tis-dgv.de. In particular, Table 2 summarizes containers' external dimensions expressed in meters, their capacity in cubic meters and weight, distinguishing between tare weight and payload in kgs (Nicolosi, P., 2013, p. 25-26).

According to the web site shippingandfreightresource.com, the payload is defined as the maximum weight that a container can carry, excluding the tare weight of the container. The payload that the container is allowed to carry is reflected in the CSC plate, abbreviation for container safety convention. The small metal plate fixed to the container's door, indicates that the container has been tested by a qualified individual and is structurally safe and sound to accept the weight of cargo stated.

CSC SAFETY APPROVAL

APPROVAL REFERENCE : D-HH-0169/FC2078
DATE MANUFACTURED : 4 /1989
IDENTIFICATION NO. : HSMT 7 1 5 2 5
MAXIMUM GROSS WEIGHT : 30,480kg - 67,200lbs
ALLOWABLE STACKING WEIGHT FOR 1.8g : 192,000kg-423,290lbs
RACKING TEST LOAD VALUE : 15,000kg - 33,070lbs

NEXT EXAMINATION DATE A 1994

ACEP — D
HH — 3

Figure 14: CSC plate
Source: novatransuk.co.uk

Type	External Dimensions [m]			Capacity [m3]	Weight [kg]	
	Length	Height	Width		Payload	Tare
Standard 20’	6,058	2,591	2,438	33,3	21.700-28.240	2.210-2.400
Standard 40’	12,192	2,591	2,438	67,7	26.740-26.850	3.630-3.740
High Cube 40’	12,192	2,896	2,438	76,5	26.580-26.600	3.880-3.900
Open top 20’	6,058	2,591	2,438	31,8-32,9	21.770-28.230	2.230-2.250
Open top 40’	12,192	2,591	2,438	67,1	26.830	3.650
Flat rack 20’	6,058	2,591	2,438		17.859-30.150	2.350-2.500
Flat rack 40’	12,192	2,591	2,438		40.100	4.900
Platform 20’	5,630	2,230	2,200		27.722	2.749
Platform 40’	12,060	1,950	2,080		38.918	5.800
Reefer 20’	6,058	2,591	2,438	26,2-28,3	17.090-27.280	2.850-3.500
Reefer 40’	12,192	2,591	2,438	57,5-58,7	25.080-25.980	4.500-5.400
Ventilated 20’	6,058	2,591	2,438	32,2-33,8	21.350-27.000	2.160-2.780
Bulk 20’	5,934*	2,340*	2,358*	33	21.550	2.450
Tank 20’	6,058	2,591	2,438	24	30.480	3.159

Table 2: characteristics of the main container types

* internal dimensions

1.5.1 Standard containers

Standard containers are general purpose containers used mainly for dry cargo; they are closed on all sides with the possibility of having doors at one or both end(s) and/or on one or both side(s). Containers also differ in dimensions and weight: the 20 and 40 feet (20’ and 40’) long containers are the most used.

Figure 15: standard 40’ container
Source: mashupstudio.pbworks.com

However, the trend nowadays is to resort to even longer and higher containers for voluminous cargo: the High Cube Container (40’ or 45’ long and 9,6’ high) is used for this purpose.

A common measurement unit used in the container shipping industry is the TEU, acronym for twenty feet equivalent unit. Bigger containers are measured by multiplying this unit (e.g. 40' and 45' containers are referred as 2 TEU).

Figure 16 shows the typical dimensions of the three containers' type mentioned so far.

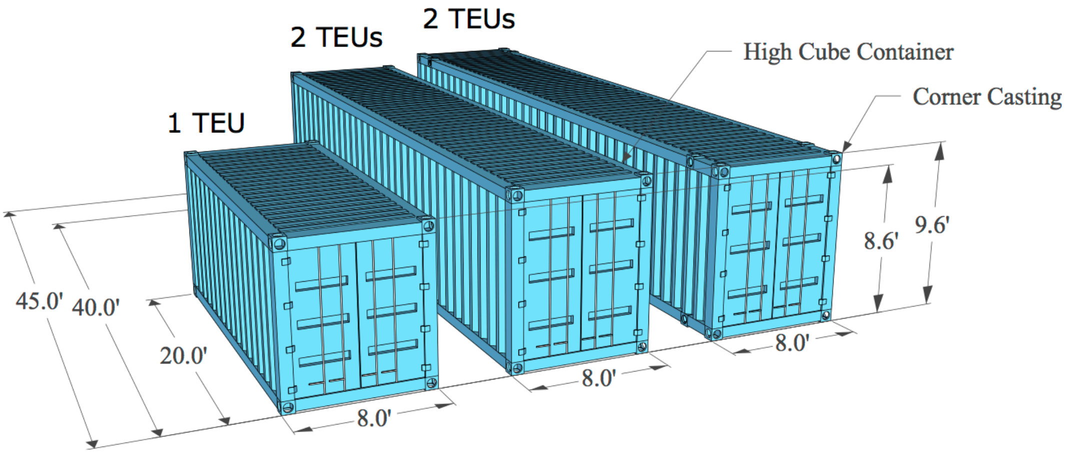


Figure 16: 20', 40' and 45' containers
Source: DTU Transport, Maritime Logistics course

As concerns the construction materials, the frame and the bottom cross members of standard containers are made of steel while the floor is generally made of wood. The walls instead, can be made of steel sheets, aluminium sheets or plywood with glass fiber-reinforced plastic coating.

1.5.2 Open Top Containers

This type of container is used for over-sized cargo, which exceeds the usual height of a standard container. Open top containers are available in lengths of 20' and 40' and are equipped with removable roof bows and tarpaulin covers; furthermore one of the two doors can also be opened, as shown in Figure 17.

Figure 17: open top container
Source: hapag-lloyd.com

The walls of an open top container are usually made of steel while the floor is made of wood. Open top containers are used for dry cargo particularly tall and above all, when there's the need of packing and unpacking from above or through the door by crane.

1.5.3. Flat racks

Flat racks are used for heavy cargo that requires particular attention or exceeds the dimensions of a standard container. From a structural point of view, a flat rack has a steel frame, a softwood floor and two end walls, which can be fixed or collapsible to convert the rack into a platform. The high stability of these end walls allows stacking several flat racks on top of one another. Flat racks are available in 20' and 40' sizes.
This type of container is suitable for top or side loading and ideal for transporting boats, pipes and heavy machineries, which are generally secured with lashing rings.

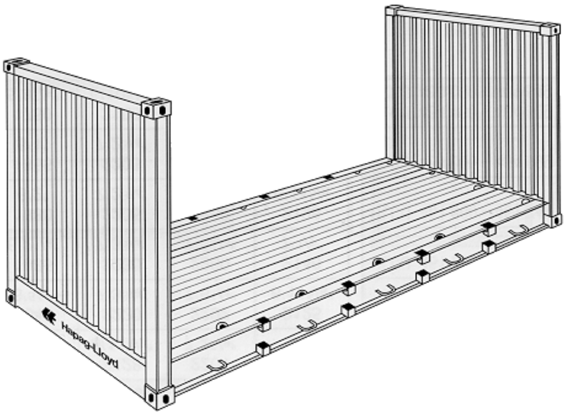


Figure 18: flat rack
Source: hapag-lloyd.com

1.5.4 Platforms

Platforms are used for very heavy and oversized cargo. They consist only of a wooden floor structure with a steel frame. Platforms' peculiarity is their extremely high loading capacity, which permits to concentrate heavy weights on small areas.
This type of equipment can be available in 20' and 40' sizes.

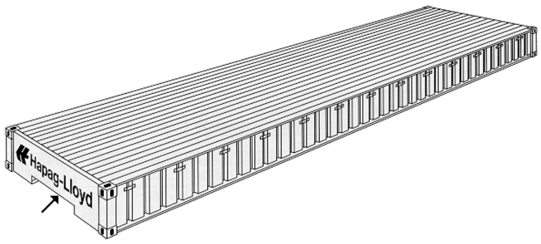


Figure 19: platform
Source: hapag-lloyd.com

1.5.5 Refrigerated and insulated containers

These types of containers are utilized when the goods' temperature must be kept constant around the freezing point. The main frozen or chilled products transported in these types of containers are fruit and vegetables, meat (sometimes hanged to the ceiling thanks to dedicated hook rails), butter, cheese, etc. If goods have to be stored in the container in a specific atmosphere for a longer period, special controlled atmosphere refrigerated containers are used. The atmosphere required is obtained by flushing the container with nitrogen and CO_2. During these operations, special attention must be paid in order not to let oxygen penetrate in the container.

Two different types of reefer containers are available: integral units and porthole containers. The first type contains an integral refrigeration unit, which controls the temperature inside the container. In order for the unit to work, it has to be connected to the on-board ship's power supply system, during the whole journey. The number of refrigerated containers which may be connected depends on the capacity of the supply system. When the vessel arrives at the container terminal, reefer containers are connected to the terminal's power supply system. In those routes where containers have to be transported by trucks or trains, integral units are operated by a generator (Figure 21).

Figure 20: reefer container
Source: klingecorp.com

Figure 21: integral unit operated by a generator
Source: tis-gdv.de

On the other hand, porthole containers are not considered refrigerated containers but mostly insulated containers because they do not contain the integral unit. The desired temperature is obtained by blowing cold air at the bottom of the container via the vessel's cooling plant. Warm air instead, is removed at the top of the container. Since there’s no integral unit inside the container, porthole containers are characterised by a larger internal available volume and payload.

Figure 22: insulated container
Source: rainbow-containers.com

1.5.6 Ventilated containers

This type of container is used when the cargo has to be naturally ventilated while being transported. The main commodity shipped with a ventilated container is green coffee beans, this is the reason why these containers are also called coffee containers.
The ventilation is provided by openings in the top and bottom section of the container as indicated in the figures. The common dimensions for a coffee container is 1 TEU.

Figure 23: ventilated container
Source: hapag-lloyd.com

Figure 24: openings in a ventilated container
Source: hapag-lloyd.com

1.5.7 Bulk containers

Bulk containers are used for transporting bulk cargo, such as grain, feedstuffs, spices. However, they may also be used for transporting general cargo. As regards their structure, bulk containers have three loading hatches in their roof with a diameter of approximately 45,5 cm each. Two discharge hatches are set on the door side; short tubes are typically used to discharge the cargo from the hatches.

Figure 25: bulk container
Source: hapag-lloyd.com

1.5.8 Tank containers

Tank containers are used for liquid cargoes such as fruit juices, spirits, oil, or chemicals such as fuels, toxic substances, corrosion protection agents, etc. These types of containers have to be used in particular conditions: on one hand, they must be at least 80% full in order to prevent dangerous surging of the liquids, on the other hand they cannot be more than 95% full, otherwise the ullage space for thermal expansion would be compromised.

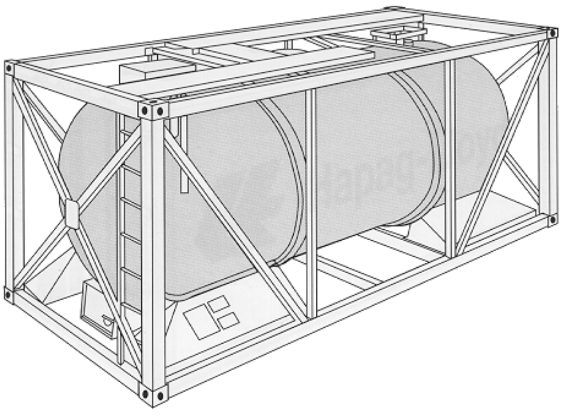


Figure 26: tank container
Source: hapag-lloyd.com

In details, tank containers which transport foodstuffs must be labelled "Potable Liquids only". If the cargo requires temperature-controlled transport, tank containers can be equipped with insulation or heating. The temperature of the cargo may be precisely controlled using temperature sensors.

1.6 Container shipping costs

The price to ship a container can vary from month to month and it depends on various factors, primarily the volume of goods transported and the distance between the origin and destination harbour.

According to the approached proposed by Maersk Line, the total price for a shipment can be broken down in three components: a basic rate, mandatory surcharges and extra services (maerskline.com).

The Basic Ocean Freight is a transportation rate for moving a cargo, it is determined by varying factors such as the cargo type and the origin-destination distance.

Mandatory surcharges are applicable to every shipment and constitute a part of the rate which is not covered by the Basic Ocean Freight. Examples of mandatory surcharges are reported in the following list:

- Terminal Handling Charge (THC): this fee covers the terminal's expenses related to containers (work to load and unload the container, storing the container for a certain period of time, handling and stacking the container on the yard, etc.). The charge, calculated per container, is divided into Origin and Destination Terminal Handling Charge (ITHC and DTHC respectively); the terminal applies the fee on the carrier, which subsequently applies it on the shipper.
- Bunker Adjustment Factor: charge which accounts for the fluctuations in bunker costs (oil used by the vessels) that changes on quarterly basis.
- Documentation Charges: service which provides the necessary transport documents at the origin and destination based on shipping instructions.
- Port security charges.

Finally, in the category Extra Services, the followings can be included: container cleaning, need for controlled atmosphere inside the container, cold treatments, garments on hangers, etc.

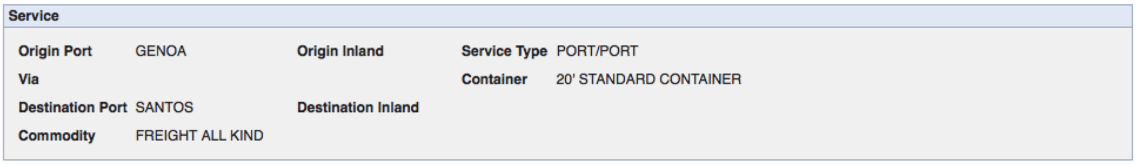
In a real situation, five entities are usually involved in the shipment of a container: the shipper, the carrier, the freight forwarder, the consignee and the notify party (kkfreight.com). The shipper is the company that supplies or owns the goods which have to be transported. Acting on behalf of either the seller or the buyer, the freight forwarder arranges the transport. Shared shipping is a convenient practice, the freight forwarder resort to in many cases: combining several small shipments into a larger one reduces the overall costs for the shipper. However, an increase in the delivery time must be expected since the container will not be shipped before enough items have been stored inside it.

The carrier is the company that physically transport goods and that is responsible for any possible loss during transportation. In most cases the freight forwarder will assume the legal liabilities of acting as a carrier (kkfreight.com). When goods arrive at the destination harbour, they are delivered to the consignee, party indicated in the bill of lading. Finally, the notify party is the person or company which must be informed by the carrier that goods arrived at destination.

In a realistic case, in order for the shipper to determine the freight rate, the following elements must be indicated: origin and destination country and city, container size (20’, 40’, 45’), the type of commodity (frozen food, machinery, office and school supplies, etc.), the need of a refrigerated container and the type of load (full container load or less than container load). As concerns the last specification, further details are here provided. If the shipper has enough items to store in one full container, it is indeed convenient to book a full container load (FCL). Whereas if the shipper does not have enough goods to accommodate in one full container, the less than a container load (LCL) shipment is chosen. The freight forwarder consoles goods from different shippers whit a common destination and arranges a fully loaded container. Each shipment is then separated at the container terminal once the container arrives at the port.

Many shipping companies offer the possibility to calculate freight rates applied to a given shipment directly from their website. An example is here provided considering the following scenario: generic goods have to be transported in 20’ standard containers from the port of Genoa in Italy to the Brazilian port of Santos. The shipper decides to address its request to the global liner shipping company Hapag-Llyod.

A summary of the data provided to the search engine is here reported (hapag-llyod.com).

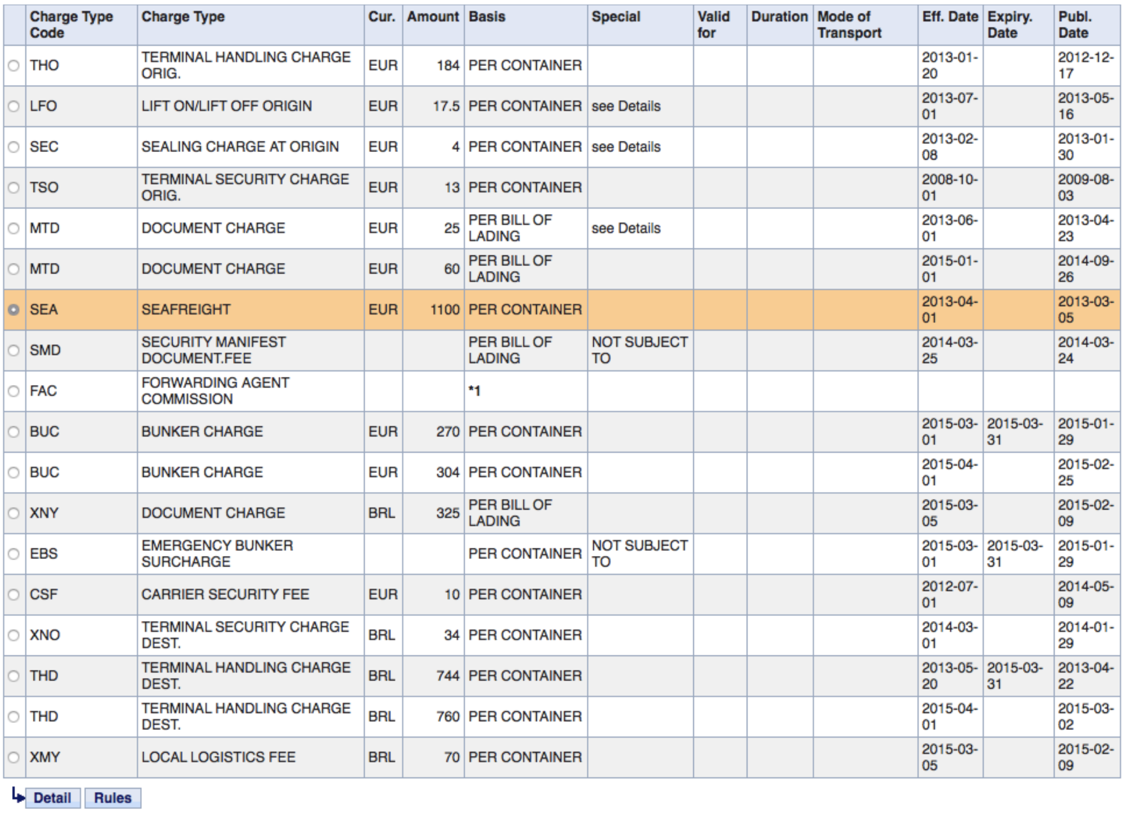


Service

Origin Port	GENOA	**Origin Inland**		**Service Type**	PORT/PORT
Via				**Container**	20' STANDARD CONTAINER
Destination Port	SANTOS	**Destination Inland**			
Commodity	FREIGHT ALL KIND				

Figure 27: input data to calculate freight rates
Source: hapag-lloyd.com

Figure 28 shows the different types of charges expressed in Euro or Brazilian real. It must be said that these prices are just estimates, hence subject to change. They are offered to the shipping public as a reference and will be verified and consolidated before shipment.



	Charge Type Code	Charge Type	Cur.	Amount	Basis	Special	Valid for	Duration	Mode of Transport	Eff. Date	Expiry. Date	Publ. Date
○	THO	TERMINAL HANDLING CHARGE ORIG.	EUR	184	PER CONTAINER					2013-01-20		2012-12-17
○	LFO	LIFT ON/LIFT OFF ORIGIN	EUR	17.5	PER CONTAINER	see Details				2013-07-01		2013-05-16
○	SEC	SEALING CHARGE AT ORIGIN	EUR	4	PER CONTAINER	see Details				2013-02-08		2013-01-30
○	TSO	TERMINAL SECURITY CHARGE ORIG.	EUR	13	PER CONTAINER					2008-10-01		2009-08-03
○	MTD	DOCUMENT CHARGE	EUR	25	PER BILL OF LADING	see Details				2013-06-01		2013-04-23
○	MTD	DOCUMENT CHARGE	EUR	60	PER BILL OF LADING					2015-01-01		2014-09-26
●	SEA	SEAFREIGHT	EUR	1100	PER CONTAINER					2013-04-01		2013-03-05
○	SMD	SECURITY MANIFEST DOCUMENT.FEE			PER BILL OF LADING	NOT SUBJECT TO				2014-03-25		2014-03-24
○	FAC	FORWARDING AGENT COMMISSION			*1							
○	BUC	BUNKER CHARGE	EUR	270	PER CONTAINER					2015-03-01	2015-03-31	2015-01-29
○	BUC	BUNKER CHARGE	EUR	304	PER CONTAINER					2015-04-01		2015-02-25
○	XNY	DOCUMENT CHARGE	BRL	325	PER BILL OF LADING					2015-03-05		2015-02-09
○	EBS	EMERGENCY BUNKER SURCHARGE			PER CONTAINER	NOT SUBJECT TO				2015-03-01	2015-03-31	2015-01-29
○	CSF	CARRIER SECURITY FEE	EUR	10	PER CONTAINER					2012-07-01		2014-05-09
○	XNO	TERMINAL SECURITY CHARGE DEST.	BRL	34	PER CONTAINER					2014-03-01		2014-01-29
○	THD	TERMINAL HANDLING CHARGE DEST.	BRL	744	PER CONTAINER					2013-05-20	2015-03-31	2013-04-22
○	THD	TERMINAL HANDLING CHARGE DEST.	BRL	760	PER CONTAINER					2015-04-01		2015-03-02
○	XMY	LOCAL LOGISTICS FEE	BRL	70	PER CONTAINER					2015-03-05		2015-02-09

Figure 28: calculation of freight rates
Source: hapag-lloyd.com

As we can see, some of the charges are calculated per container transported, some others per bill of lading. The latter is a legal document between the shipper of a particular good and the carrier detailing the type, quantity and destination of the good being carried. The bill of lading also serves as a receipt of shipment when the good is delivered to the predetermined destination (investopedia.com).

In addition to this we can distinguish the main components mentioned at the beginning of the section: Seafreight e.g. Basic Ocean Freight, Origin and Destination Terminal Handling Charges, Documentation Charges, Bunker Charges and Terminal Security Charges.

CHAPTER 2
Container Terminal Logistics

2.1 Terminal structure

In the literature, container terminals are defined as open systems of material flow with two external interfaces (Steenken et al., 2004). As we can see in Figure 29, three are the main areas which characterize a container terminal: the ship operation area, the yard and the truck and train operation area. Container flows are indicated with arrows; the transport between the different areas is carried out by vertical and horizontal handling equipment, which will be described in Section 2.3. In general, the layout of a container terminal depends on the available area, the number of containers to be handled and the mode of hinterland transport.

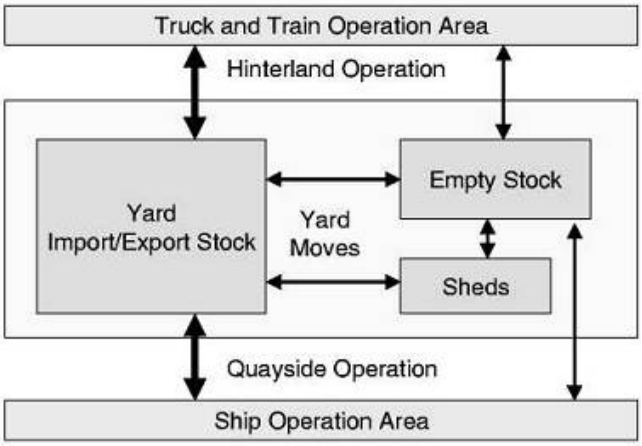


Figure 29: container terminal layout
Source: container-transportation.com

Two are the main goals for the management of a container terminal: keep the berthing time as short as possible and at the same time decrease the cost of operations. This leads to a win-win solution where the customer is satisfied with the quality of the service provided and the terminal becomes an efficient system able to optimize operations, hence reduce costs. In order to achieve these goals the performance of loading and discharging processes must increase as well as the logistic capabilities of the horizontal transport equipment. First and foremost though, it is fundamental that the three operational areas are tuned to each other.

2.1.1 The ship operation area

In the ship operation area, vessels are processed by quay cranes. Once a container vessel arrives at the port, a specific berthing position is assigned as well as a certain number of quay cranes which will unload the containers. Import containers are moved towards the yard by horizontal transport means; at the same time, export containers are moved towards the shore in order for the cranes to load them into the vessel. Container vessels are the only ships that can be loaded and discharged at the same time. This handling procedure requires good planning of the terminal equipment for the container delivery as well as for the container stacking in the yard and on the vessel (Brinkmann, 2011).

2.1.2 The yard

The yard is where containers are stored in stacks: blocks of containers defined by bays, rows and tiers.

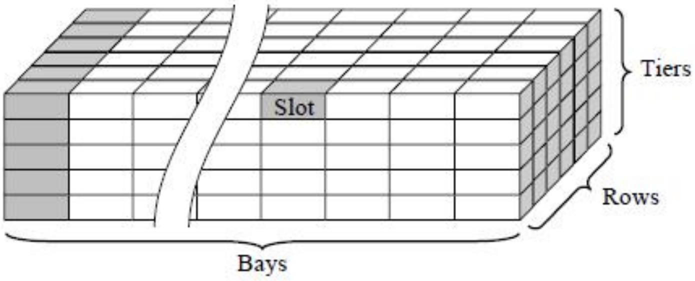


Figure 30: container block
Source: iemsjl.org

According to the type of container, yards can be divided into different sections. Some stack areas are reserved for import and export containers: import containers, discharged from vessels, can be forwarded to another vessel (transhipment), trucks or trains; export containers are usually delivered by train or truck and have to be loaded on vessels. Typically, sections for reefer containers which need electrical connection can be found as well as areas for containers with dangerous goods, overweight or overwidth containers. Furthermore, container terminals' yards usually have areas for empty containers as well as sheds where maintenance and repair operations take place or where goods are stored before putting them into the containers or after stripping the containers. The container terminal yard is an intermediate storage facility, in which the containers remain from a couple of hours to some weeks (Brinkmann, 2011).

According to Brinkmann (2011) three are the possible layouts for the stacking yard: block stacks, linear stacks and high-bay racking. Block stacking is preferred when the available area is very compact: gantry cranes are then used to stack the containers delivered by horizontal means of transport.

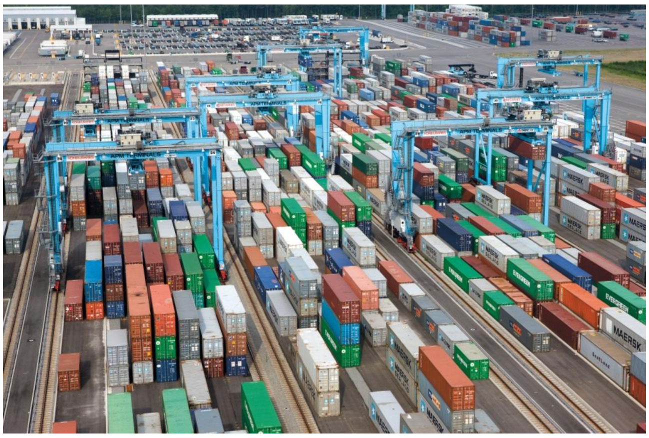


Figure 31: block stacking
Source: konecranes.com

In bigger terminals, an alternative is linear stacking. Space is required between container rows in order for straddle carriers to stack the containers up to a pile of 4.

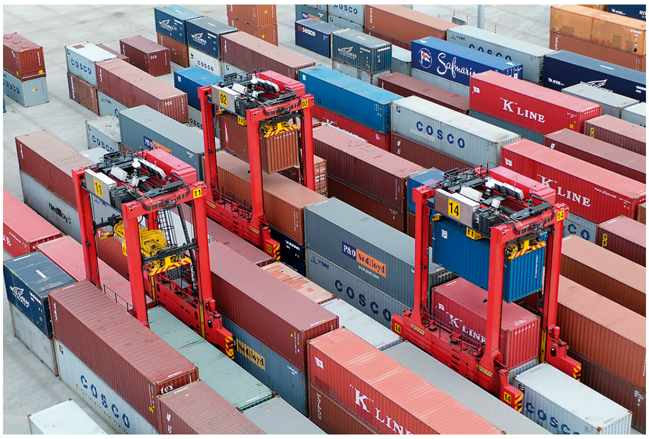


Figure 32: linear stacking
Source: portstrategy.com

The third rarely applied alternative is the high-bay racking, used for terminals with high throughput requirements but very small available area. An example is Hong Kong with high-bay racks up to 12 container tiers.

2.1.3 The truck and train operation area

Behind the yard, trucks and trains connect the container terminal with hinterland destinations. In those terminals where truck operations predominate, this area is usually integrated in the yard area. Straddle carriers or other dedicated equipment load and unload containers in and from the trucks, either on dedicated spaces at the end of the stacking yard or in the middle of the yard itself. Trucks have a capacity of up to three TEU. At container terminals they are directed to transfer points where they are loaded and unloaded (Steenken et al., 2004).

In case of rail operations, the loading and unloading should take place outside the yard to avoid that rail tracks interfere with the yard equipment. This in turn increases safety and efficiency on the terminal. The capacity of one train is about 120 TEU (Steenken et al., 2004). Yard equipment or gantry cranes combined with appropriate horizontal transport vehicles carry out the loading/unloading operations; once ready, trains connect the terminal with specific hinterland destinations. The transportation of a container using multiple modes, in this case ships and trains or trucks, without any handling of the goods when changing modes, is a growing logistics practice called intermodal freight transportation.

Figure 33: truck loading
Source: silive.com

Figure 34: Hamburg rail
Source: container-mag.com

2.2 Top container terminals

The American Association of Port Authorities produced a world ranking of the top 100 container ports based on container traffic measured in TEU. Table 3 shows a list of the 20 most active terminals in 2011, 2012 and 2013 (The Journal of Commerce annual top 50 World Container Ports, Lloyd's List annual Top 100 Ports, AAPA World Port Rankings and individual port websites).

Shanghai and Singapore rank as number one and two respectively in all the three years considered. As regards Europe in 2013, three harbours rank amongst the top 20: Rotterdam in the Netherlands, Hamburg in Germany and Antwerp in Belgium. In the 44th position ranks the Italian port of Gioia Tauro with a volume of 3,09 million TEU in 2013. Both in 2012 and 2013, China ports account for 70% of the top 10 ports in the world. Despite the U.S. being the world's largest importer, American ports do not rank with the world's largest. The biggest container terminal in the country is Los Angeles seaport, number 19 in the 2013 ranking, with a volume of 7,87 million TEU.

The top 50 container ports in 2013 represent over 30 countries demonstrating the truly global nature of the liner shipping business and the importance of the network of ports that facilitate timely and efficient ship and cargo movement. (worldshipping.org)

Rank	Port, Country	Volume 2013 (Million TEU)	Volume 2012 (Million TEU)	Volume 2011 (Million TEU)
1	Shanghai, China	33,62	32,53	31,74
2	Singapore, Singapore	32,6	31,65	29,94
3	Shenzhen, China	23,28	22,94	22,57
4	Hong Kong, China	22,35	23,12	24,38
5	Busan, South Korea	17,69	17,04	16,18
6	Ningbo-Zhoushan, China	17,33	16,83	14,72
7	Qingdao, China	15,52	14,50	13,02
8	Guangzhou Harbor, China	15,31	14,74	14,42
9	Jebel Ali, Dubai, United Arab Emirates	13,64	13,30	13,00
10	Tianjin, China	13,01	12,30	11,59
11	Rotterdam, Netherlands	11,62	11,87	11,88
12	Dalian, China	10,86	8,92	6,40
13	Port Kelang, Malaysia	10,35	10,00	9,60
14	Kaohsiung, Taiwan, China	9,94	9,78	9,64
15	Hamburg, Germany	9,30	8,89	9,01
16	Antwerp, Belgium	8,59	8,64	8,66
17	Keihin ports, Japan	8,37	7,85	7,64
18	Xiamen, China	8,01	7,20	6,47

19	Los Angeles, U.S.A.	7,87	8,08	7,94
20	Tanjung Pelepas, Malaysia	7,63	7,70	7,50

Table 3: top 20 container terminals by annual TEU volume

Figure 35: Shanghai container terminal
Source: forbes.com

Figure 36: Singapore container terminal
Source: forbes.com

2.3 Types of cranes and other handling equipment

According to Steenken et al. (2004), container terminals consist of two components: stocks and transport vehicles. Yard stacks, vessels, trains and trucks belong to the first category: stocks are entities used to store containers. Instead, transport vehicles are used to move containers. Vertical transport means (cranes) and horizontal transport means belong to this category. A detailed classification of the main transport vehicles used in container terminals is presented in this section.

2.3.1 Vertical transport means

Vertical transport means or cranes are divided in two categories: quay cranes and gantry cranes. Quay cranes are used to load and unload containers to and from ships, they are positioned in the ship operation area. Generally, they are mounted on rails so that they can move along the quay and align with the containers in the ship. Two types of quay cranes can then be distinguished: single-trolley cranes and dual-trolley cranes. Trolleys travel along the crane's arm and are equipped with spreaders, specific devices that pick up the containers. Single trolley cranes are manual and the most used at container terminals. This type of crane moves containers from the vessel to the shore, putting them on the quay or on a horizontal vehicle and vice versa. On the other hand, dual-trolley cranes, semi-automatic, represent a higher performance system only used in very few terminals. In this modern version, two trolleys are used: the main trolley is man-driven and moves containers from the ship to a platform, a second automatic trolley moves the container from the platform to the shore.

Figure 37: quay cranes
Source: flickr.com

Quay cranes can have a single or dual hoist. QC with a single hoist picks up either a single 20', 40', 45' or two 20 (twin 20') under a single spreader. To the contrary dual hoist QC includes two hoisting systems on the main trolley and can handle either two 40' or four 20' for each lift (Bartosek and Marek, 2013). Dual arrangements can almost double the productivity of the quay cranes. Further details about quay crane productivity will be given in Section 2.4.

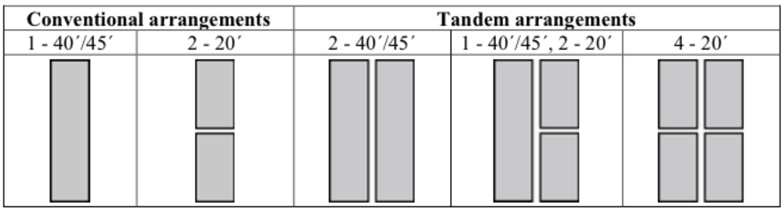


Figure 38: single and dual hoist configurations
Source: Bartosek A., Marek O., 2013

The gantry crane is another type of vertical transport means used at container terminals. In particular, gantry cranes move containers stacked in the yard and can be used to load/unload trains for hinterland transportation. Two types of gantry cranes can be considered: rail mounted (RMG) and rubber tyred (RTG). Practically, as shown in the following figures, RMGs are mounted on fixed rail tracks while RTGs are mobile cranes with rubber wheels.

Figure 39: RMG
Source: cnbmengineering.en.alibaba.com

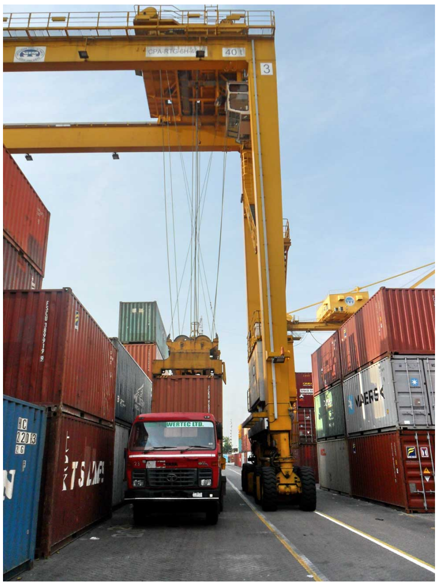


Figure 40: RTG
Source: saifpowertecltd.com

Adavntages and disadvantages of the two vertical transport means are presented in Table 4 (Brinkmann, 2011).

	Advantages	Disadvantages
RTGs	-smaller and lighter -high flexibility as they can be transported to other areas -medium investments	-heavy concrete paving is necessary to support the heavy wheels
RMGs	-more durable and reliable -easier to automate	-more expensive to install because of the tracks

	-they stack higher and span wider (up to 7 tiers and 12 rows) -higher stacking density (storage capacity in a small area) -moderate maintenance and repair costs	-if a crane stops, more operations are affected -rigidity and higher difficulty to change the layout in the yard

Table 4: advantages and disadvantages of RTGs and RMGs

2.3.2 Horizontal transport means

Horizontal transport means are used both for ship to shore transportation and for hinterland operations. The literature distinguishes between active and passive vehicles according to their ability of lifting a container by themselves.

Forklifts, straddle carriers and reachstackers belong to the category of active vehicles. Straddle carriers are the most important active vehicles because of their flexibility and dynamicity. They can transport containers and stack them in the yard, having free access to containers independent of their position. The straddle carrier' spreader can transport either 20' or 40' containers; they are usually man driven and able to stack a container on top of two or three other containers. the maximum stacking height is 4-high (Brinkmann, 2011).

Figure 41: straddle carrier
Source: directindustry.com

The straddle carriers are independent from any other equipment and are able to perform all the different handling operations: transport, stacking and the loading/unloading of trucks and rail cars (B. Brinkmann). Straddle carriers are advantageous systems especially for medium and large size terminals where high accessibility to the containers and high flexibility in the stacking yard are required. In case a vehicle breaks down, the impact on the other operations is relatively low; furthermore, the use of this system allows to easily alter the terminal's layout if necessary. The containers can be dropped on the ground so that no (or only short) waiting times for handling equipment occur. This kind of container handover enables quay cranes to operate with a high productivity while using a comparatively low number of straddle carriers per crane (B. Brinkmann).

Straddle carriers present some disadvantages though: they require high investments, high maintenance and energy costs; they can't be used for long travelling distances because of their high costs and slowness compared for example to trucks with trailers.

Forklifts and reachstackers are similar in their appearance, they are both rubber-tyred vehicles that are usually powered by diesel engines and equipped with a driver cabin in the rear of the vehicle (Kalmar, 2011). These two vehicles are mainly used in small – medium terminals for stacking operations; they are able to quickly transport one container at a time for a short distance and pile them if required. Figure 43 shows a particular case of forklift transporting two empty containers.

Figure 42: reachstacker
Source: wijayaequipments.indonetwork.co.id

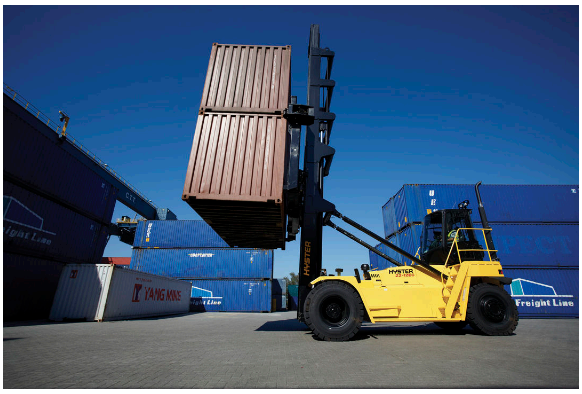


Figure 43: forklift transporting an empty container
Source: directindustry.com

Nowadays reachstackers are preferred by most operators because of their flexibility and higher storage capacity than forklifts: for instance, a container block can be kept thanks to second row access. These vehicles can be used not only for stacking in the yard but also for loading/unloading trucks and trains on first rail. Amongst the advantages, these systems are characterised by low investments and low operating costs of equipment; moreover, because of their easy transportation between terminals (or terminal areas) reachstackers could be used to cover temporary peak requirements (Brinkmann, 2011).

As concerns passive vehicles, that is to say vehicles that cannot lift a container by themselves, two means are commonly used in container terminals: automatic guided vehicles (AGVs) and trucks with trailers or multi-trailers.

Quay cranes or gantry cranes load and unload these vehicles.

Figure 44: AGVs
Source: bildarchiv-hamburg.de

Figure 45: truck with trailer
Source: universalcargo.com

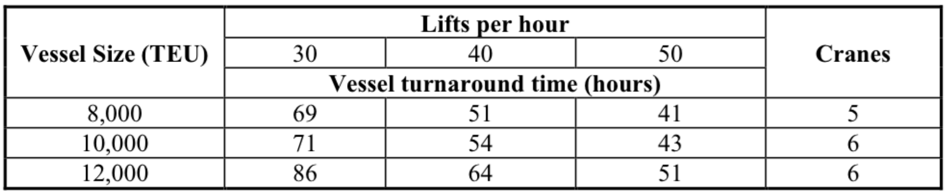
AGVs are robotics able to drive on a road network which consists of electric wires or transponders in the ground to control the position of the AGVs. AGVs can either load one 40'/45' container or two 20' containers: in the latter case multiple load operation is possible (Steenken et al., 2004). AGVs are used at the port of Rotterdam and Hamburg in combination with automatic gantry cranes.

A truck with trailer consist of a tractor that pulls one or more trailers (multi-trailer) each one with a carrying capacity of two TEU. Solutions with even four or five trailers are possible. On its journey across the container terminal, several destinations are visited by these vehicles where some containers may be discharged and some new containers may be loaded (Kemme, 2013).

2.4 The productivity of the quay cranes

Quay crane's productivity is a crucial component of the overall terminal productivity. Being the focus of this Thesis, the topic is analysed from a logistics point of view in this section; the concept of quay crane productivity will then be used in Chapter 4 for the explanation of the Berth Allocation and Quay Crane Assignment problem.

The productivity is measured by the number of cycles or container moves that the crane is able to perform in one hour. Typically, a quay crane cycle consists of four steps: the spreader moves towards the container's location in the vessel, the container is picked, hoisted back to the wharf and finally set down. QCs are currently able to realize about 30-50 moves per hour in practice. Almost all terminals are able to achieve maximum productivity as low as 70% and as high as 80% of the computed number. QCs do not achieve the technically possible productivity due to productivity losses caused by operational disturbances (Bartosek and Marek, 2013). Figure 46 shows the typical vessels turnaround times according to the number of containers which have to be handled, the number of lifts per hour and the number of quay cranes used. Bigger vessels mean longer handling cycles for each container: this in turn has significant effect on quay crane productivity.



Vessel Size (TEU)	Lifts per hour			Cranes
	30	40	50	
	Vessel turnaround time (hours)			
8,000	69	51	41	5
10,000	71	54	43	6
12,000	86	64	51	6

Figure 46: vessel turnaround time
Source: Bartosek A., Marek O., 2013

The concept of vessel turnaround time or processing time will be of fundamental importance in Chapter 4, where the Berth Allocation and Quay Crane Assignment problem is explained. The turnaround time can approximately be calculated dividing the total quay crane hours required and the number of available quay cranes. Quay crane hour requirements to process a vessel depend in turn on the number of containers and the technical capabilities of the quay crane itself.

Nowadays, many terminals are seeking an increase in quay crane productivity through the use of dual hoists and technological improvements which aim for instance at raising up speeds and accelerations.

2.5 Container terminal management

Managing a container terminal implies coordinating all the activities which take place in the three main areas: ship operation area, stacking yard and trucks and trains operation area. Let us consider the simple ship unloading cycle represented in Figure 47. Using quay cranes, trucks with trailers and rubber-tyred gantry cranes, the cycle is composed of 4 steps (eventi.unicas.it):

- Once the vessel berths, the quay crane unloads the container.
- The import container is transferred towards the yard by a truck.
- The gantry crane stocks the container in the pre-defined position in the yard.
- After a certain time the gantry crane picks up the container again and loads it on another vehicle directed inland.

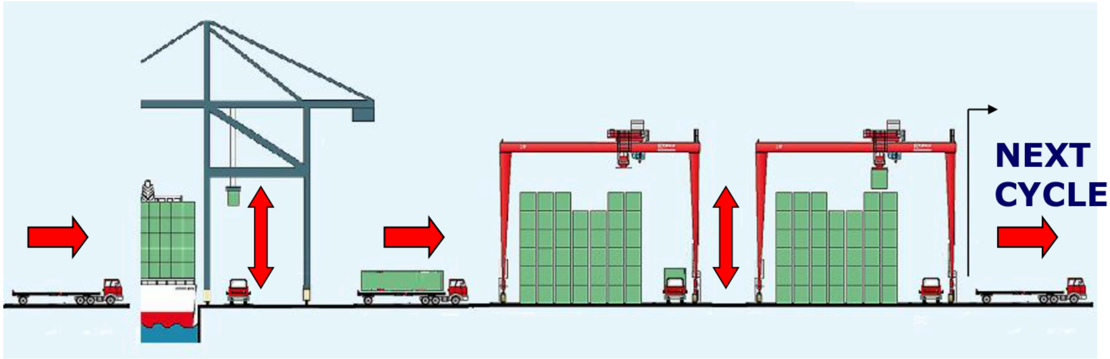


Figure 47: ship unloading cycle
Source: eventi.unicas.it

The ship loading cycle is obtained going through the four steps backwards.

Considering a timeframe of one week, the unloading cycle is repeated for almost all the containers in the vessel and then for all the vessels that visit the harbour within the week. Statistics proposed in the web site worldshipping.org say that container ships make about 9.000 port calls, and vehicle vessels about 1.000 port calls per week, meaning that workers at ports and handling systems worldwide load and unload more than 10.000 liner ship stops per week. The average ship makes about 2 port calls per week. Managing such high container volumes, different handling systems, the container terminal's staff and above all guaranteeing reasonable service levels to customers is undoubtedly very complex. Each operational area in a container terminal is characterised by specific logistic problems which have to be optimised: the berth allocation and the assignment of quay cranes to unload and load the vessel, the determination of the specific slot in the yard where the container must be stored and all the activities related to planning the movements of transport means. Planning problems within container terminals will be described in details in Chapter 3.

Furthermore, not only these single criticalities must be taken into consideration: being the container terminal a system of interconnected areas, it is fundamental to balance and synchronize all the interfaces in order to have an efficient goods flow.

With the aim to have a well managed container terminal, which is cost efficient and offers a good service performance to its customers, some major operational goals should be considered and achieved:

- Fast discharging and loading of containers.
- Minimum port stay for vessels.
- High level of accuracy of the information used by various departments of the terminal and consistent communication with the other entities the terminal interacts with (transport companies and shipping lines above all).
- Good monitoring of the storage of containers in the yard.
- Efficient use of yard container stacking space.
- Minimum un-necessary container shifting operations.
- Minimum bottleneck situations which affect the flow of goods from the vessel to the inland.
- High productivity of handling systems.
- High safety standards.
- Reduced manual efforts and paper flows.
- Fast invoicing system.
- Fast responses to a variety of customers inquiries.

All these goals cannot be achieved without computerization. Information technology is an essential element to efficiently manage container terminal operations, given their complexity and the large volumes of information which are handled. Container Terminal Management Systems are powerful software which address this purpose.

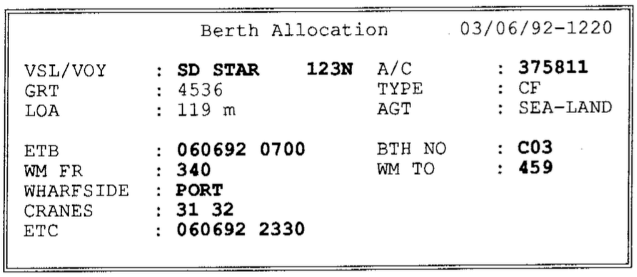
2.5.1 Container Terminal Management Systems

A Container Terminal Management System (CTMS) is a sophisticated information system that manages and optimizes processes and resources in a container terminal (ant-tech.ru). CTMS allow terminal managers to efficiently handle all the criticalities listed above, hence improve terminals' competitiveness. The Port of Singapore

Authority (PSA) has invested over a hundred million Singapore dollars to build up its present suite of computer applications to support container terminal management and operations. Every year, tens of millions of dollars are also spent to maintain these applications to keep them up-to-date with the operational requirements (UNCTAD Monographs on Port Management, 1993). A CTMS is characterised by various modules: therefore, each terminal can configure the system package according to its needs and to the scale of the terminal. UNCTAD distinguishes four core functions in a container terminal which are computerized in CTMS: logistics control, container control, ship operations control, container terminal performance control. The last part of this chapter provides an outline of these functions and their applications modules. A real example of CTMS is then presented with its software components and main features.

2.5.1.1 Logistics control: application modules

Logistics control involves maintenance, planning and controlling the use of the expensive resources of the terminal such as berths, container stacking yard, container handling equipment and manpower (UNCTAD Monographs on Port Management, 1993).
One of the most important modules is the berth allocation module, which tracks information about planned occupancy of berths and assist the berth assignment process. Samples of computer screens that CTMS allow to visualise are given below.
Figure 48 captures the details of berth assignment to a vessel. The meanings of the abbreviations used are reported in Appendix A.



```
                Berth Allocation        03/06/92-1220

VSL/VOY      : SD STAR    123N  A/C        : 375811
GRT          : 4536             TYPE       : CF
LOA          : 119 m            AGT        : SEA-LAND

ETB          : 060692 0700      BTH NO     : C03
WM FR        : 340              WM TO      : 459
WHARFSIDE    : PORT
CRANES       : 31 32
ETC          : 060692 2330
```

Figure 48: berth allocation
Source: Hui Ying P., Lui E., 1993

Figure 49 shows a typical layout of vessel assignments to available berths: both the time and space dimensions are represented.

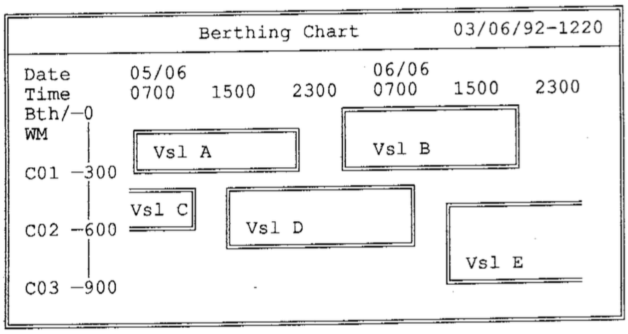
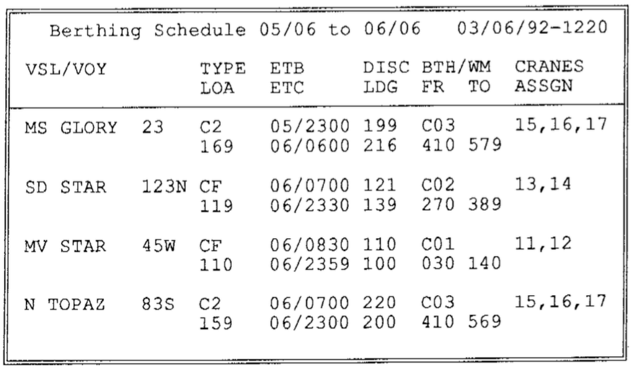


Figure 49: berthing chart
Source: Hui Ying P., Lui E., 1993

The last example related to the berth allocation module shows the schedule of vessels that berth at the harbour in chronological order of estimated time of berthing.

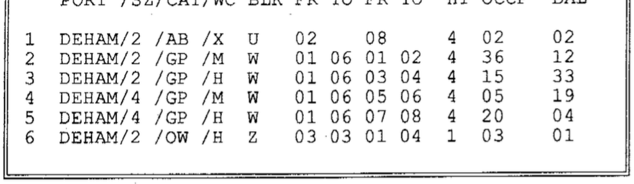


```
 Berthing Schedule 05/06 to 06/06    03/06/92-1220

VSL/VOY          TYPE  ETB       DISC BTH/WM   CRANES
                 LOA   ETC       LDG  FR  TO   ASSGN

MS GLORY  23     C2    05/2300   199  C03      15,16,17
                 169   06/0600   216  410 579

SD STAR   123N   CF    06/0700   121  C02      13,14
                 119   06/2330   139  270 389

MV STAR   45W    CF    06/0830   110  C01      11,12
                 110   06/2359   100  030 140

N TOPAZ   83S    C2    06/0700   220  C03      15,16,17
                 159   06/2300   200  410 569
```

Figure 50: berthing schedule
Source: Hui Ying P., Lui E., 1993

Another fundamental module for the logistics control is the yard allocation module which maintains a profile of all the yard space in the terminal and information on the allocation of yard space to ships. Inputs to the module will include the profile of yard space in the terminal, yard space allocation to incoming ships and yard space freed by outgoing ships (UNCTAD Monographs on Port Management, 1993).

Figure 51 shows which slots in the yard have been allocated to a vessel. The types of containers (20' or 40'), their category (general purpose, overwidth, etc.) and their weight class are indicated. Furthermore, the screen shows the number of slots occupied and the ones which are left free for incoming containers.

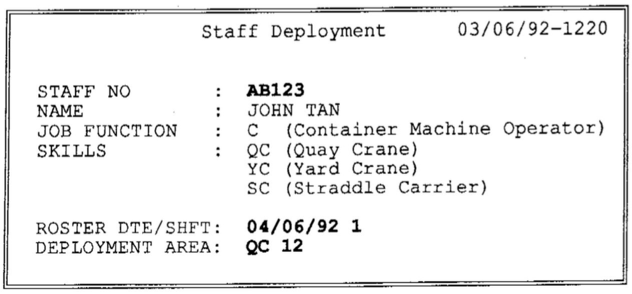


```
      Yard Allocated and Balance      03/06/92-1220

VSL/VOY : SD STAR     123
                     YD   ROW   SLOT        NO. SLOTS
   PORT /SZ/CAT/WC  BLK  FR TO  FR TO   HT  OCCP  BAL

1  DEHAM/2 /AB /X    U   02     08      4   02     02
2  DEHAM/2 /GP /M    W   01 06  01 02   4   36     12
3  DEHAM/2 /GP /H    W   01 06  03 04   4   15     33
4  DEHAM/4 /GP /M    W   01 06  05 06   4   05     19
5  DEHAM/4 /GP /H    W   01 06  07 08   4   20     04
6  DEHAM/2 /OW /H    Z   03 03  01 04   1   03     01
```

Figure 51: yard allocation and balance
Source: Hui Ying P., Lui E., 1993

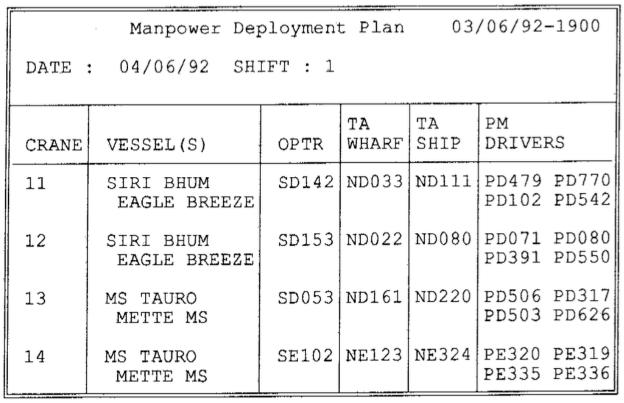
In a container terminal it is important to keep track of the work done by staff members (it facilitates remuneration) and to maintain a roster of the staff available for deployment.

Figure 52 is an example of staff deployment screen while Figure 53 shows the overall deployment of operations staff to support terminal operations in a shift.



```
                 Staff Deployment       03/06/92-1220

 STAFF NO         :  AB123
 NAME             :  JOHN TAN
 JOB FUNCTION     :  C  (Container Machine Operator)
 SKILLS           :  QC (Quay Crane)
                     YC (Yard Crane)
                     SC (Straddle Carrier)

 ROSTER DTE/SHFT:    04/06/92 1
 DEPLOYMENT AREA:    QC 12
```

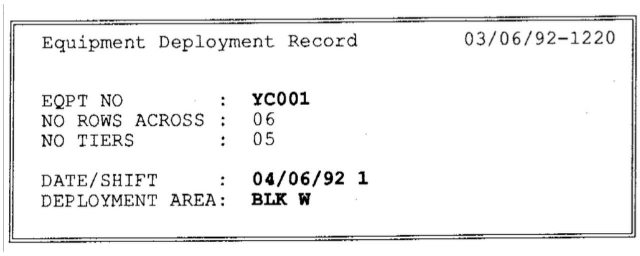
Figure 52: staff deployment
Source: Hui Ying P., Lui E., 1993



```
          Manpower Deployment Plan     03/06/92-1900

 DATE :   04/06/92  SHIFT : 1

                                   TA    TA    PM
 CRANE  VESSEL(S)           OPTR   WHARF SHIP  DRIVERS

 11     SIRI BHUM           SD142  ND033 ND111 PD479 PD770
          EAGLE BREEZE                         PD102 PD542

 12     SIRI BHUM           SD153  ND022 ND080 PD071 PD080
          EAGLE BREEZE                         PD391 PD550

 13     MS TAURO            SD053  ND161 ND220 PD506 PD317
          METTE MS                             PD503 PD626

 14     MS TAURO            SE102  NE123 NE324 PE320 PE319
          METTE MS                             PE335 PE336
```

Figure 53: manpower deployment plan
Source: Hui Ying P., Lui E., 1993

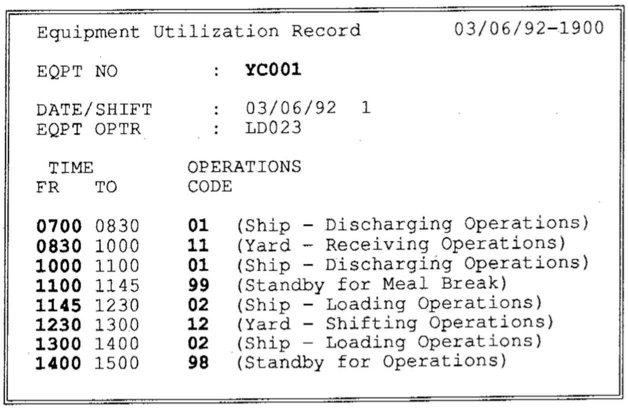
Container Terminal Management Systems have also modules for equipment deployment. Figure 54 captures information related to a yard crane.



```
 Equipment Deployment Record             03/06/92-1220

 EQPT NO          :  YC001
 NO ROWS ACROSS   :  06
 NO TIERS         :  05

 DATE/SHIFT       :  04/06/92 1
 DEPLOYMENT AREA:    BLK W
```

Figure 54: equipment deployment
Source: Hui Ying P., Lui E., 1993

The following screen instead shows details of equipment utilisation during one operational shift.



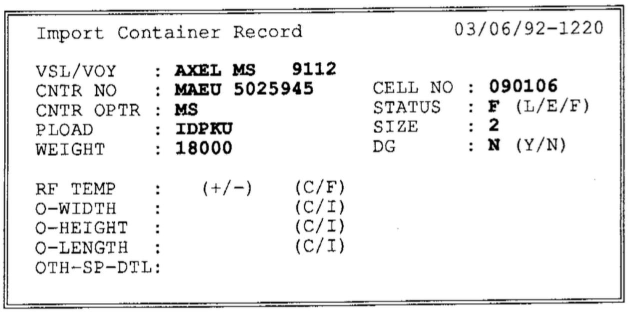
```
Equipment Utilization Record          03/06/92-1900

EQPT NO          :  YC001

DATE/SHIFT       :  03/06/92  1
EQPT OPTR        :  LD023

 TIME            OPERATIONS
FR   TO          CODE

0700 0830        01  (Ship - Discharging Operations)
0830 1000        11  (Yard - Receiving Operations)
1000 1100        01  (Ship - Discharging Operations)
1100 1145        99  (Standby for Meal Break)
1145 1230        02  (Ship - Loading Operations)
1230 1300        12  (Yard - Shifting Operations)
1300 1400        02  (Ship - Loading Operations)
1400 1500        98  (Standby for Operations)
```

Figure 55: equipment utilization
Source: Hui Ying P., Lui E., 1993

2.5.1.2 Container control: application modules

Container control involves the receiving of export container from inland and import container discharged from ships at a port. It also involves the releasing of import containers to consignee and loading of the export container onto ships at a port (UNCTAD Monographs on Port Management, 1993). Thanks to CTMS for example, the identification of a specific container within the terminal becomes faster thanks to an updated inventory of containers' locations. Container control is realised with three main application modules: container documentation, yard management and gate management.

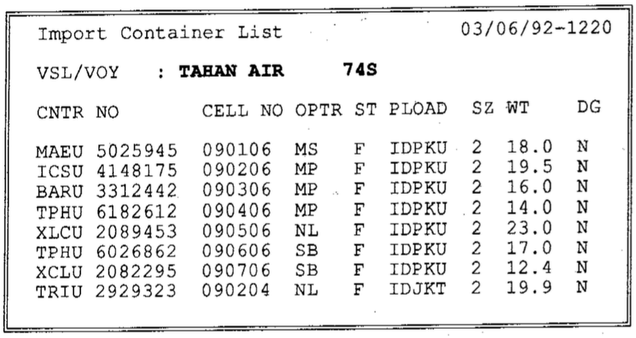
Container documentation modules capture the details of all import and export containers at the terminal. The following figure is a typical import container record screen.



```
Import Container Record                    03/06/92-1220

VSL/VOY     : AXEL MS   9112
CNTR NO     : MAEU 5025945       CELL NO : 090106
CNTR OPTR   : MS                 STATUS  : F (L/E/F)
PLOAD       : IDPKU              SIZE    : 2
WEIGHT      : 18000              DG      : N (Y/N)

RF TEMP     :    (+/-)    (C/F)
O-WIDTH     :             (C/I)
O-HEIGHT    :             (C/I)
O-LENGTH    :             (C/I)
OTH-SP-DTL:
```

Figure 56: import container record
Source: Hui Ying P., Lui E., 1993

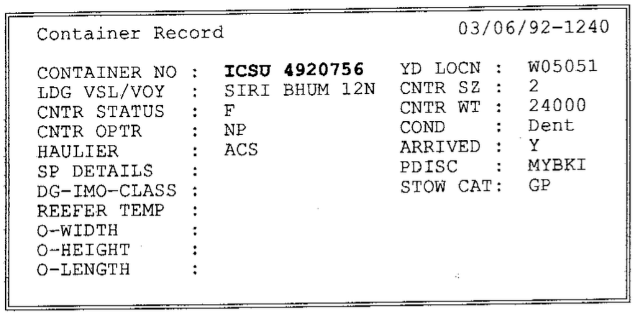
Figure 57 shows the containers which have to be unloaded from a specific vessel.



```
Import Container List                    03/06/92-1220

VSL/VOY   : TAHAN AIR      74S

CNTR NO         CELL NO OPTR ST PLOAD  SZ WT     DG

MAEU 5025945    090106  MS   F  IDPKU  2  18.0   N
ICSU 4148175    090206  MP   F  IDPKU  2  19.5   N
BARU 3312442    090306  MP   F  IDPKU  2  16.0   N
TPHU 6182612    090406  MP   F  IDPKU  2  14.0   N
XLCU 2089453    090506  NL   F  IDPKU  2  23.0   N
TPHU 6026862    090606  SB   F  IDPKU  2  17.0   N
XCLU 2082295    090706  SB   F  IDPKU  2  12.4   N
TRIU 2929323    090204  NL   F  IDJKT  2  19.9   N
```

Figure 57: import container list
Source: Hui Ying P., Lui E., 1993

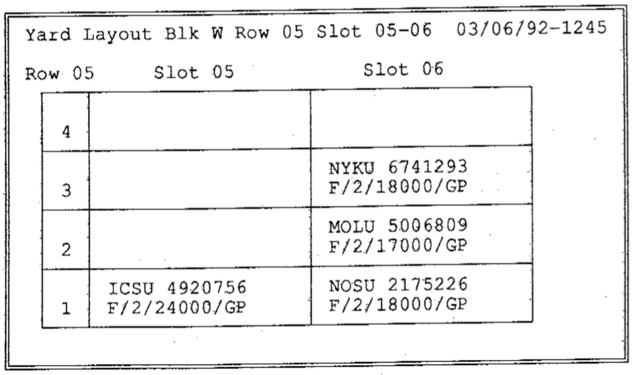
An application module for yard management maintains record of containers stacked in the yard. Figure 58 is an example of container record screen.



```
Container Record                          03/06/92-1240

CONTAINER NO :  ICSU 4920756    YD LOCN  :  W05051
LDG VSL/VOY  :  SIRI BHUM 12N   CNTR SZ  :  2
CNTR STATUS  :  F               CNTR WT  :  24000
CNTR OPTR    :  NP              COND     :  Dent
HAULIER      :  ACS             ARRIVED  :  Y
SP DETAILS   :                  PDISC    :  MYBKI
DG-IMO-CLASS :                  STOW CAT:   GP
REEFER TEMP  :
O-WIDTH      :
O-HEIGHT     :
O-LENGTH     :
```

Figure 58: container record
Source: Hui Ying P., Lui E., 1993

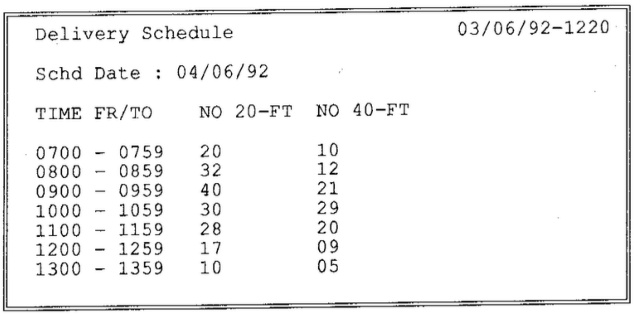
Figure 59 instead visualises how containers are positioned within a specific yard section.



```
Yard Layout Blk W Row 05 Slot 05-06   03/06/92-1245

Row 05      Slot 05            Slot 06
 ____________________________________________
|   |                  |                     |
| 4 |                  |                     |
|___|__________________|_____________________|
|   |                  | NYKU 6741293        |
| 3 |                  | F/2/18000/GP        |
|___|__________________|_____________________|
|   |                  | MOLU 5006809        |
| 2 |                  | F/2/17000/GP        |
|___|__________________|_____________________|
|   | ICSU 4920756     | NOSU 2175226        |
| 1 | F/2/24000/GP     | F/2/18000/GP        |
|___|__________________|_____________________|
```

Figure 59: yard layout
Source: Hui Ying P., Lui E., 1993

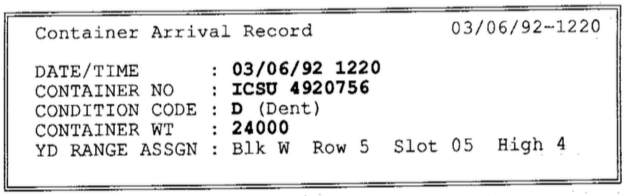
CTMS usually offers modules for gate management whose main goal is to record anything that enters or comes out of terminal gates (containers, trucks, trains, personnel, private vehicles, visitors, etc.). For instance, the following figure shows a delivery schedule screen with the number and type of containers which will leave the terminal in each time slot.



```
Delivery Schedule                          03/06/92-1220

Schd Date : 04/06/92

TIME FR/TO     NO 20-FT  NO 40-FT

0700 - 0759    20        10
0800 - 0859    32        12
0900 - 0959    40        21
1000 - 1059    30        29
1100 - 1159    28        20
1200 - 1259    17        09
1300 - 1359    10        05
```

Figure 60: delivery schedule
Source: Hui Ying P., Lui E., 1993

Figure 61 captures the details of a container which arrived at the gate and have to be stored in a specific slot in the yard.



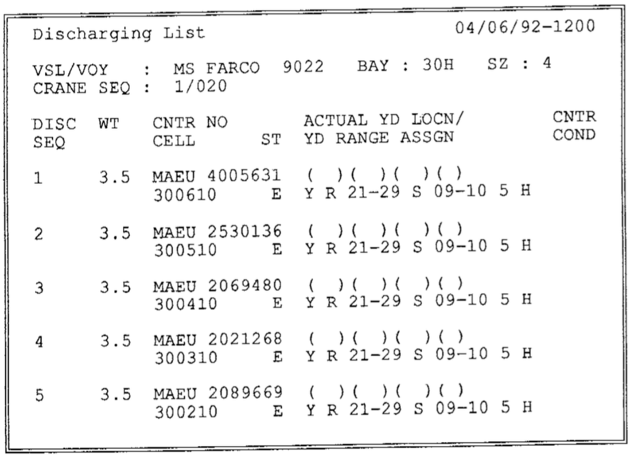
```
Container Arrival Record                   03/06/92-1220

DATE/TIME        : 03/06/92 1220
CONTAINER NO     : ICSU 4920756
CONDITION CODE   : D (Dent)
CONTAINER WT     : 24000
YD RANGE ASSGN   : Blk W  Row 5  Slot 05  High 4
```

Figure 61: container arrival record
Source: Hui Ying P., Lui E., 1993

2.5.1.3 Ship operations control: application modules

Ship operations control involves planning, executing and monitoring the loading/discharging operations of ships at port (UNCTAD Monographs on Port Management, 1993). These operations have to be planned in advance making sure that the vessels remains stable whilst alongside.

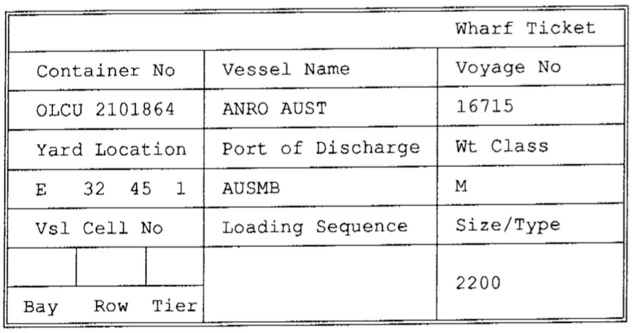
The discharge planning module defines the sequence of containers which have to be unloaded from the ship considering the stowage plan and the structure of the ship. Figure 62 shows a typical discharging list.



```
Discharging List                                04/06/92-1200

VSL/VOY    :  MS FARCO  9022   BAY : 30H    SZ : 4
CRANE SEQ  :  1/020

DISC   WT    CNTR NO        ACTUAL YD LOCN/           CNTR
SEQ          CELL       ST  YD RANGE ASSGN            COND

1      3.5   MAEU 4005631   (  )(  )(  )( )
             300610      E  Y R 21-29 S 09-10 5 H

2      3.5   MAEU 2530136   (  )(  )(  )( )
             300510      E  Y R 21-29 S 09-10 5 H

3      3.5   MAEU 2069480   (  )(  )(  )( )
             300410      E  Y R 21-29 S 09-10 5 H

4      3.5   MAEU 2021268   (  )(  )(  )( )
             300310      E  Y R 21-29 S 09-10 5 H

5      3.5   MAEU 2089669   (  )(  )(  )( )
             300210      E  Y R 21-29 S 09-10 5 H
```

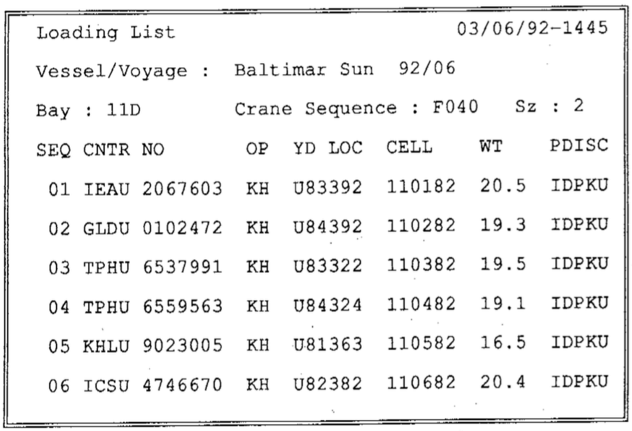
Figure 62: discharging list
Source: Hui Ying P., Lui E., 1993

The stowage planning module is another fundamental tool which supports an efficient container terminal management. Thanks to this module the planner is assisted in the process of picking containers from the yard and loading them onto the vessel. Two are the main outputs which can be generated from this module: wharf tickets and loading lists. A wharf ticket contains relevant information related to each container which has to be loaded onto the ship. The vessel cell location and the loading sequence are automatically determined by the CTMS software. The loading list defines the sequence of picking containers from the yard and loading them to specific slots in the vessel. The following figures show the two reports described.



		Wharf Ticket
Container No	Vessel Name	Voyage No
OLCU 2101864	ANRO AUST	16715
Yard Location	Port of Discharge	Wt Class
E 32 45 1	AUSMB	M
Vsl Cell No	Loading Sequence	Size/Type
Bay Row Tier		2200

Figure 63: wharf ticket
Source: Hui Ying P., Lui E., 1993



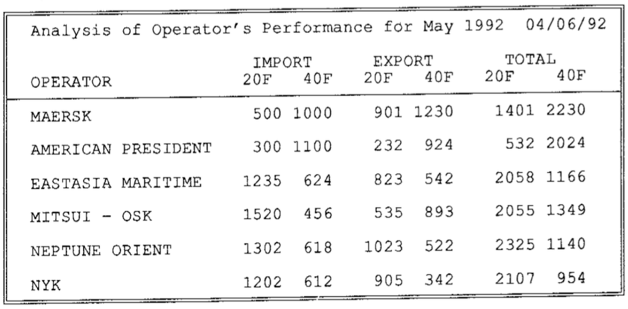
```
Loading List                                03/06/92-1445
Vessel/Voyage :   Baltimar Sun   92/06
Bay : 11D         Crane Sequence : F040    Sz : 2
SEQ CNTR NO        OP  YD LOC  CELL    WT    PDISC
 01 IEAU 2067603   KH  U83392  110182  20.5  IDPKU
 02 GLDU 0102472   KH  U84392  110282  19.3  IDPKU
 03 TPHU 6537991   KH  U83322  110382  19.5  IDPKU
 04 TPHU 6559563   KH  U84324  110482  19.1  IDPKU
 05 KHLU 9023005   KH  U81363  110582  16.5  IDPKU
 06 ICSU 4746670   KH  U82382  110682  20.4  IDPKU
```

Figure 64: loading list
Source: Hui Ying P., Lui E., 1993

2.5.1.4 Container terminal performance control: application modules

Monitoring the performance of a container terminal is undoubtedly the overall priority for terminal managers. Container terminals are highly capital intensive therefore it is necessary to well utilise all the resources. In addition to this, managers need to monitor customer service levels as well as key performance indicators in order to take actions in case targets are not met. Staff should also be informed regularly about the performance achieved: good performances should be recognised with incentives, which in turn motivate workers to aim to even better results.

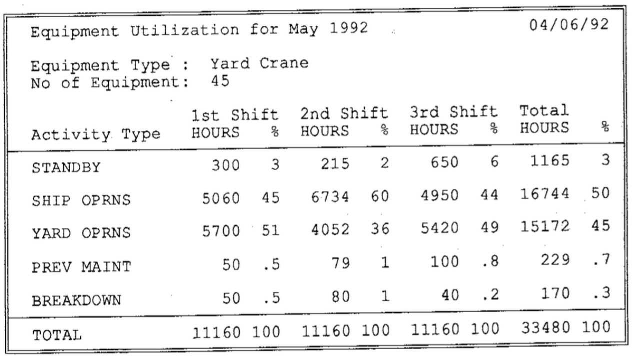
An application module for container terminal performance control gives various reports in output. The container throughput report summarises the volumes of containers handled at the terminal for each shipping line (Figure 65). The report distinguishes between import/export container and 20'/40' containers.



```
Analysis of Operator's Performance for May 1992  04/06/92

                           IMPORT      EXPORT       TOTAL
OPERATOR                 20F   40F   20F   40F   20F   40F

MAERSK                   500  1000   901  1230   1401  2230

AMERICAN PRESIDENT       300  1100   232   924    532  2024

EASTASIA MARITIME       1235   624   823   542   2058  1166

MITSUI - OSK            1520   456   535   893   2055  1349

NEPTUNE ORIENT          1302   618  1023   522   2325  1140

NYK                     1202   612   905   342   2107   954
```

Figure 65: analysis of operator's performance
Source: Hui Ying P., Lui E., 1993

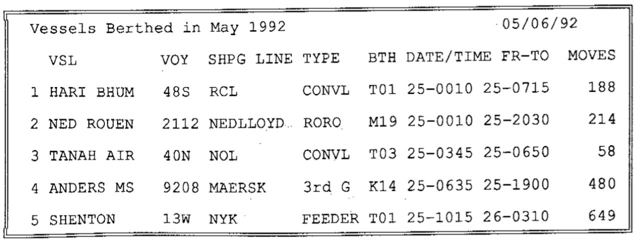
The equipment utilisation report shows the type of activity carried out by a certain equipment type and their workload in hours per shift.



```
Equipment Utilization for May 1992                        04/06/92

Equipment Type  :  Yard Crane
No of Equipment:  45

                1st Shift   2nd Shift   3rd Shift   Total
Activity Type   HOURS   %   HOURS   %   HOURS   %   HOURS    %

STANDBY           300   3     215   2     650   6    1165    3

SHIP OPRNS       5060  45    6734  60    4950  44   16744   50

YARD OPRNS       5700  51    4052  36    5420  49   15172   45

PREV MAINT         50  .5      79   1     100  .8     229   .7

BREAKDOWN          50  .5      80   1      40  .2     170   .3

TOTAL           11160 100   11160 100   11160 100   33480  100
```

Figure 66: equipment utilization
Source: Hui Ying P., Lui E., 1993

Finally, the vessels berthed report analyses the frequency of berthing and the port stay of the vessels.



```
Vessels Berthed in May 1992                          05/06/92
  VSL           VOY  SHPG LINE TYPE   BTH DATE/TIME FR-TO  MOVES
1 HARI BHUM     48S  RCL       CONVL  T01 25-0010 25-0715    188
2 NED ROUEN     2112 NEDLLOYD  RORO   M19 25-0010 25-2030    214
3 TANAH AIR     40N  NOL       CONVL  T03 25-0345 25-0650     58
4 ANDERS MS     9208 MAERSK    3rd G  K14 25-0635 25-1900    480
5 SHENTON       13W  NYK       FEEDER T01 25-1015 26-0310    649
```

Figure 67: vessels berthed
Source: Hui Ying P., Lui E., 1993

2.5.1.5 CTMS: a real example

Various CTMS software solutions are available on the market and can be customised according to terminals' specific needs. The MES Container Terminal Management System is here reported as an example, with the aim to visualise the modules previously described and new functionalities. The package is developed by the Japanese company Mitsui Engineering & Shipbuilding Co.,Ltd. (mes.co.jp).

As we can see in Figure 68, 8 are the main software components:

Figure 68: MES CTMS
Source: mes.co.jp

- Yard Planning and Control System: an online real time system that controls all the information required for the container terminal.
- WWW Inquiry: a web platform where all the information managed can be retrieved; through this module, the terminal accepts entries from ship's agents and forwarders.
- Vessel Planning System: it supports vessel planning in container terminals using powerful graphic user interfaces; modules related to berth allocation, discharge planning and stowage planning are included in this system.
- Yard Planning System: it supports container location control, automatically determines yard slots for import containers and provides a real-time graphic display of the yard status.
- Yard Operation System: this system supports the allocation of container handling equipment; it also allows detect the position of the vehicles in the terminal thanks to Radio Data Transmission Systems.
- Integrated Gate System: it ensures that gate management procedures are performed smoothly.

- Container Truck Distribution System: it manages truck dispatch through mobile telecommunications.
- Container Terminal Simulation System: this 3D simulator support the prediction of future yard situations, including traffic congestion and allows an early response to those conditions; input parameters include terminal layout, number of containers, performance and number of yard equipment, etc.

A CTMS supports the terminal management in the optimisation of all the operations that occur at the terminal. Having explained the different interfaces and modules functionalities, it is important to know that at the basis of any CTMS there are mathematical models that describe the various optimisation problems. The resolution of these models through Operations Research methods, gives all the reports and screens detailed in the previous sections as output.

Having done an introduction about the container shipping industry and the logistics criticalities in container terminals, this Thesis will now focus on the main planning problems which occur at container terminals; in particular, one specific problem will be analysed in details from a mathematical perspective: the Berth Allocation with Quay Crane Assignment Problem, known as BACAP.

CHAPTER 3
Planning Problems within Container Terminals

3.1 Introduction

The logistics of container terminals has become very complex in recent years, because of the various operations which can take place at the terminal, the different layouts and equipment used. Furthermore, the dynamicity of a container terminal makes hard to predict for a long planning horizon the numerous processes occurring. To deal with this complexity and with the need of real time optimization and decisions, resorting to Operations Research methods becomes necessary. In addition to this, simulation methods are usually also used to test the optimization algorithms before implementing them into real systems. The 3D simulator for container terminals presented in the previous chapter is an example of this trend.

In the different areas of a container terminal, seaside, yard and landside, many processes occur. At the seaside, three main operations are taken into account: the allocation of berths to the incoming ships, the stowage planning, (the determination of an optimal position for the containers in the vessel) and the assignment and scheduling of the quay cranes, which load and unload the containers in and from the vessel. In the yard of a container terminal instead, the main issue is the determination of the specific slot where each container has to be stored. Furthermore, all the operations regarding horizontal transport are considered, as well as the scheduling of the yard cranes operating in the stacks. Finally, landside processes mainly regard the movement of the containers from the storage area to the trucks and trains operation area. Understanding these problems means understanding the major criticalities that terminal managers have to face when making logistics choices.

The chapter is organized as follows. The next section reports a classification of the main optimization problems within container terminals. In the subsections *3.2.1-2-3* the ship planning processes, storage and stacking operations as well as transport operations are described in details.

3.2 Classification of planning problems

In this section we classify the main logistics processes which take place in a container terminal and which can be optimized using Operations Research.

Three macro areas are considered for this purpose:

- The ship planning process
- Storage and stacking
- Transport operations

Each area includes specific processes, which in turn refer to the three main sections a container terminal is divided into: the seaside, the yard and the landside. The following figure visualizes the different sections and their processes.

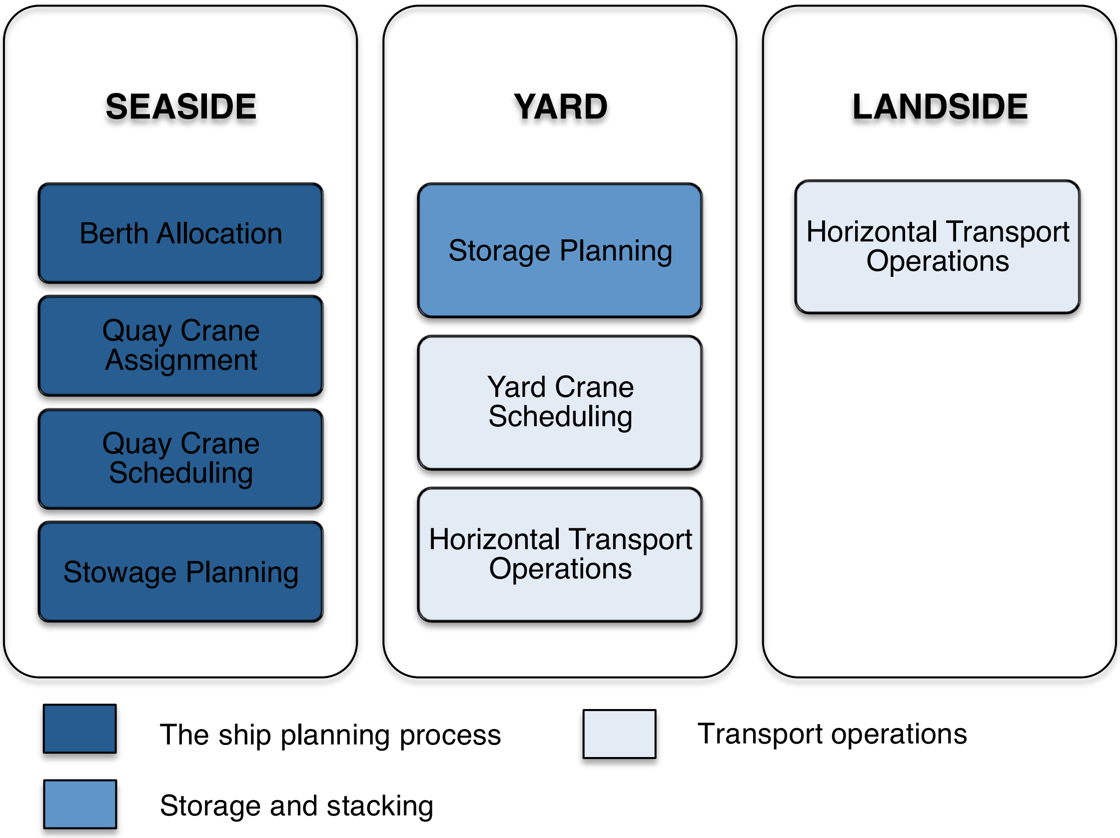


Figure 69: main processes in a container terminal

3.2.1 The ship planning process

The ship planning process includes four sub-processes: the berth allocation, the quay crane assignment and scheduling and the stowage planning. The related optimization problems are here described in detail, underlying their features, constraints and objectives. Particular relevance will be given to the integration of berth allocation and quay crane assignment, focus of this Thesis and the next chapter.

3.2.1.1 The Berth Allocation Problem

As regards the seaside operations' planning, the first main issue is the assignment of a berth and a berthing time to all the vessels which are planned to arrive at the harbour in a specific time interval. This problem is known as Berth Allocation Problem (BAP).

Practically, the berth allocation starts when the first containers assigned to the vessel arrive at the terminal, that is to say two or three weeks before the ship's arrival. Instead, the information about the arrival of the vessel is usually known one year in advance approximately. The main advantage of having an optimized and possibly automatic system which handle this process, rises up when ships' delays occur.

Different objectives for the BAP are proposed in the Literature:

- The minimization of the port stay time for the vessel.
- The minimization of the sum of the seaside to yard distances for the containers loaded and unloaded.
- The minimization of the workload of terminal resources.
- The minimization of the number of rejected vessels at the terminal.

The main information usually given for this problem is related to the number of vessels which have to be berthed in the planning horizon, the vessels' length and draft, the expected time of arrival, the vessel handling time, the latest departure time and the berth layout.

As concerns berthing times, Imai et al. (2001) distinguish two situations:

- Dynamic arrival: the arrival time of all the vessels is known and has to be respected, not allowing a vessel to berth before that time.
- Static arrival: the arrival times are not given, therefore it is assumed that the vessel can berth immediately.

Furthermore, the Literature defines 5 types of handling times for vessels:

- Fixed: they are known in advance and considered unchangeable.
- They depend on the berthing position of the vessel.
- They depend on the number of quay cranes assigned to the vessel.
- They depend on the schedule of the quay cranes.
- They are a combination of the three previous modes.

The latest departing time for a vessel can also be provided and be equal to:

- The sum of the expected berthing time, a waiting time and the handling time.
- The end of the time window in the specific dynamic case quoted above.

Finally, different types of berth layout can be considered for the problem. Imai et al. (2005) distinguish between:

- Discrete layout: the quay is divided into defined berthing sections called berths.
- Continuous layout: there are no sections in the quay, the vessel can therefore berth at arbitrary position.
- Hybrid layout: the quay is divided into sections with the possibility for big vessels to occupy more than one berth or for small ones to share the berth with another ship.

Figure 70 visualises the three types of layout: (a) and (b) represent a discrete layout, (c) a continuous layout while (d), (e) and (f) are examples of hybrid layout.

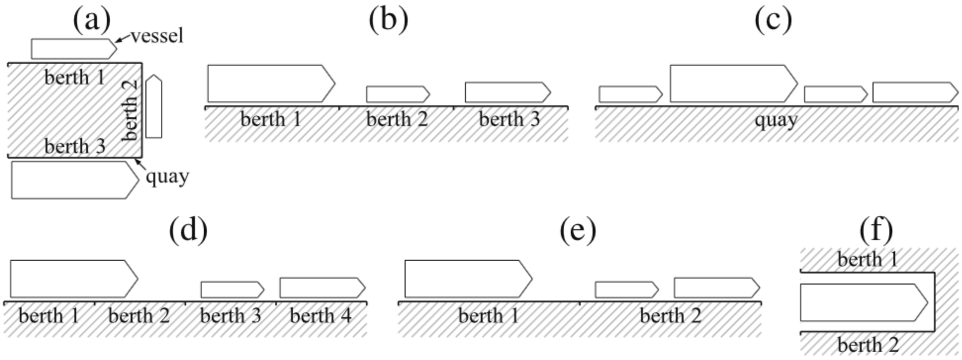


Figure 70: berth layouts
Source: Bierwirth C., Meisel F., 2009

In addition to initial data and objectives, the formulation of the BAP includes typical constraints such as: the impossibility that two vessels occupy the same berthing position at the same time, the respect of arrival and departure times and the observance of the quay boundaries and the water depth.

The output of the problem is a berth plan, which can be represented in a space-time diagram. Each vessel is represented by a rectangle where the horizontal dimension expresses the port stay time and the vertical dimension the length of the vessel. Figure 71 is a simple example of berth plan; these types of diagrams are the typical output of the Berth Allocation application module in a Container Terminal Management System.

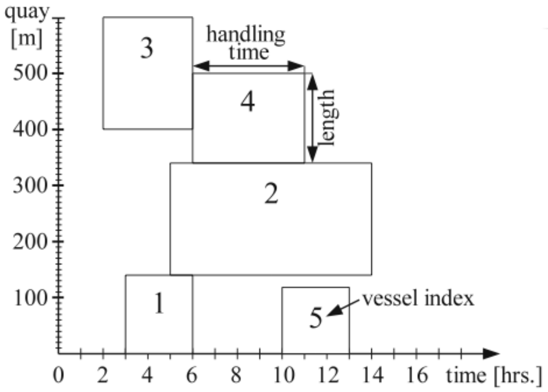


Figure 71: example of berth plan
Source: Bierwirth C., Meisel F., 2009

3.2.1.2 The Quay Crane Assignment Problem

The problem known as QCAP, deals with the determination of the optimal number of quay cranes or the optimal set of specific cranes assigned to a vessel, such that all the operations of unloading and loading the containers can be fulfilled.

The common objectives proposed in the Literature are:

- The minimization of the sum of the delays of all ships.
- The minimization of crane productivity losses through the reduction of the crane travel times and the number of setups at vessels.
- The maximization of a ship's performance.
- A well-balanced utilization of the cranes.

In the QCAP, the typical initial information provided is the set of available quay cranes at the harbour, a feasible berth plan, the minimum and the maximum number of cranes which can be assigned simultaneously to each vessel and finally the volume of containers which have to be unloaded and loaded, usually expressed in quay-crane hours. The limit number of quay-cranes which can operate a vessel depends in particular on the ship's length: commonly, three to five cranes operate at one oversea vessel while feeder ships are operated with one to two cranes (Stenkeen et al., 2004).

The Literature distinguishes then between time-invariant assignment and a variable-in-time assignment. In the first case, the number of quay-cranes assigned to a vessel, doesn't change throughout its handling time: the processing time is therefore known and included in the problem's data. In the second approach, the number of cranes can be different from hour to hour during the handling time, which becomes a decision variable of the problem.

Two main constraints characterize the formulation of the QCAP:

- The impossibility of exceeding the total number of cranes available at the terminal in each hour of the planning horizon.
- The respect of the quay-crane hour requirements defined for each vessel.

The formulation of the problem is usually based on common assumptions, for instance:

- It takes no time to move a QC from one vessel to another vessel.
- Vessels are served without preemption, i.e., once started to serve a vessel the process is not interrupted until the service is completed.
- Every crane has the technical capability to serve every vessel. Furthermore, the cranes are identical, i.e., they have the same maximum productivity.

The output of the problem is the quay crane-to-vessel assignment, which can be shown in a time-space diagram. As before, each vessel is represented by a rectangle where the horizontal dimension expresses the port stay time and the vertical dimension the length of the vessel. In addition to this, the figure indicates the number of quay cranes which are assigned to the ship hour by hour. An example of time-invariant assignment is shown by vessels 1, 4 and 5 in Figure 72: the number of cranes which process the vessel (1 crane for vessel 1 and 5, 2 cranes for vessel 4) doesn't change during the handling time. In contrast, a variable-in-time assignment is shown for vessel 2 and 3. For vessel 3 for instance, 3 quay cranes are used for the first three hours, while just 1 quay crane handles the vessel in the last three hours. As we can also notice, in every hour each quay crane (identified with numbers from 1 to 4) is serving a different vessel.

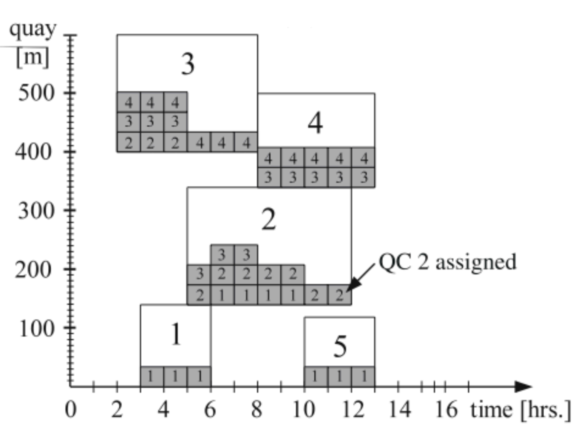


Figure 72: example of quay crane assignment
Source: Bierwirth C., Meisel F., 2009

3.2.1.3 The Quay Crane Scheduling Problem

Given the berth allocation plan, the stowage plan and the quay crane assignment, the aim of the quay crane scheduling problem (QCSP) is to define a schedule for the quay cranes assigned to the vessel. In details, once a reasonable berth schedule is determined, port operators attempt to allocate available quay cranes to vessels that are planned to berth simultaneously. Once cranes are assigned, the actual berthing and completion times of vessels are determined with more precision (Aykagan Ak, 2008). Known the number of cranes that have to process the ship hourly, the exact position of every crane with respect to the vessel has to be determined, along with the staying time in that specific position. It is usually assumed that each vessel is divided along its length into holds or bays, each one including a certain number of container rows. Practically, quay cranes are mounted on the same tracks along the same berth: this forbids them from crossing each other at any instant while a vessel is operated. In addition to this, it is assumed that cranes simultaneously processing adjacent holds on single vessels may need to be scheduled carefully so that no safety distances are compromised while they work on nearby containers within their assigned holds (Aykagan Ak, 2008). Compared with the processing time of a ship bay, the travel time of a quay crane between two bays is generally small, hence not considered. Another common assumption is that no interruptions occur during the quay crane operations, moreover it is clear that the vessel can leave the harbour only after every bay is processed.

According to the method used to assign cranes to vessels, two types of quay crane scheduling problems may arise. On one hand, the terminal operator can assign a certain number of quay cranes to every vessel moored at the harbour. There, cranes can operate just the specific vessel they have been assigned to. This approach is called dedicated crane assignment and the resulting scheduling problem is called dedicated quay crane scheduling problem. On the other hand, cranes assigned to a certain vessel, if necessary can move and operate also other vessels simultaneously berthed. This method is called roaming crane assignment and the resulting problem roaming quay crane scheduling problem.

In general, in the QCSP a set of tasks is considered, representing transhipment operations for a vessel on a set of assigned quay cranes. Precedence relations among tasks can be given to ensure that unloading precedes loading and to represent the stacking of containers as defined by the stowage plan. Every task must be processed once by a quay crane, while a quay crane can process at most one task at a time. A solution to the problem, called a quay crane schedule, defines a starting time for every task on a crane (Bierwirth and Meisel, 2010).

According to Bierwirth and Meisel (2010), the most common objective function of this planning problem deals with the minimization of the makespan of the quay crane schedule. This serves the purpose of having short vessel handling times and therefore allows the earliest possible departures.

The major problem's constraints are hereunder reported (Lee and Chen, 2009):

- At any instant, quay cranes should not cross over each other.
- Safety margins between adjacent cranes have to be respected.
- Each ship hold is only handled by one quay crane during the planning horizon.
- For all the time intervals, the movement of the quay cranes must not be interfeared by the presence of other quay cranes in the rail. The violation of this condition is shown in figure 73.
- Quay cranes don't have to be driven out of the vessel boundary in order to avoid their crossing. The violation of this condition is represented in figure 74.

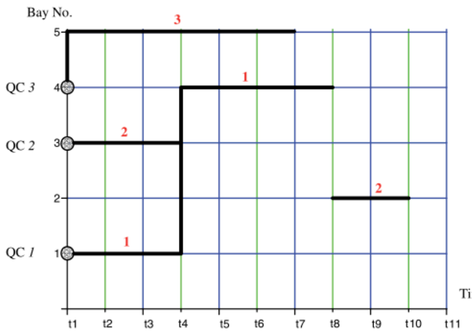


Figure 73: quay crane interference
Source: Lee D-H., Hang Chen J., 2009

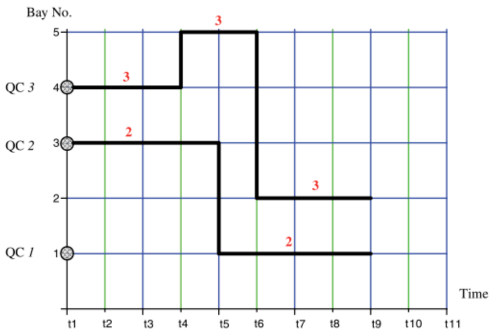


Figure 74: quay cranes out of the boundaries
Source: Lee D-H., Hang Chen J., 2009

The solution of the problem can be visualized in a space-time diagram which indicates in which bay each quay crane operates and in which time steps within the planning horizon.

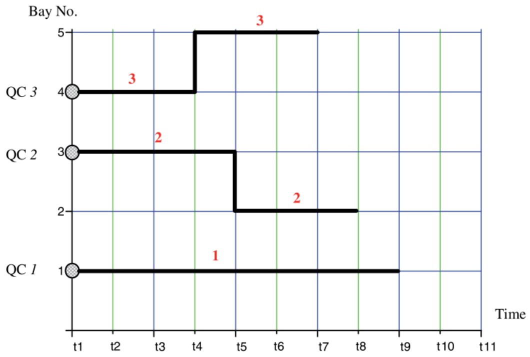


Figure 75: example of quay crane schedule
Source: Lee D-H., Hang Chen J., 2009

3.2.1.4 The Berth Allocation with Quay Crane Assignment Problem

Despite the Literature differentiates the problems of Berth Allocation, Quay Crane Assignment and Scheduling, in a realistic context the three planning problems are inter-related as we can see in the following figure.

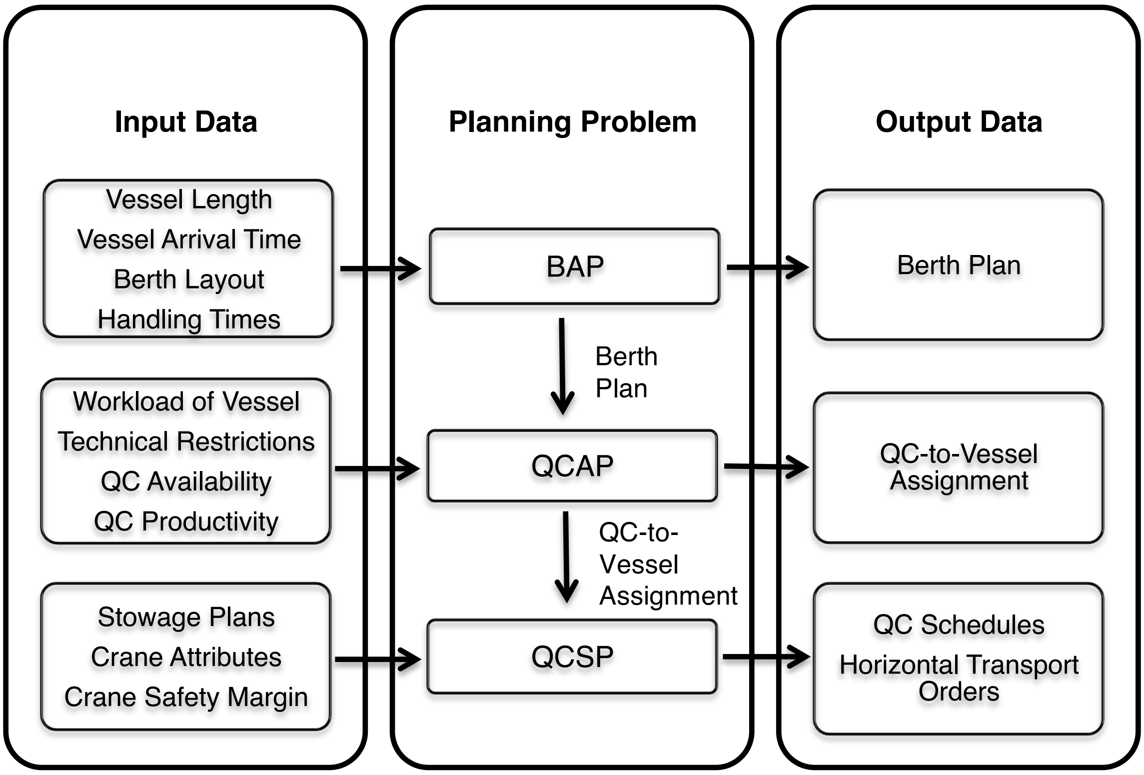


Figure 76: input and output data for BAP, QCAP and QCSP
Source: Bierwirth C., Meisel F., 2009

Berth allocation, quay crane assignment and quay crane scheduling can be made in sequence: the berth plan, output of the BAP is given as input to the QCAP; subsequently, the quay crane – to – vessel assignment is the input of the QCSP which in turn provides quay crane schedules and horizontal transport orders in output. Moving from the BAP to the QCSP, the availability of input data increases while the uncertainty of input data decreases. The berth plan is therefore generated with few and generally not certain data.

Even though more realistic, considering the BAP, QCAP and QCSP as a unique optimization problem would lead to huge models, which are basically impossible to solve. The recent research's focus is the definition of integrated problems: the combination of Berth Allocation and Quay Crane Assignment is the most important example of this trend. The discussed problem consists of determining a berthing position in the quay for a set of incoming vessels and a berthing time across a planning horizon of a certain length. The problem also deals with the determination of the number of quay cranes serving each vessel during each time slot. Figure 77 shows an example of a complete berth plan with quay crane assignment.

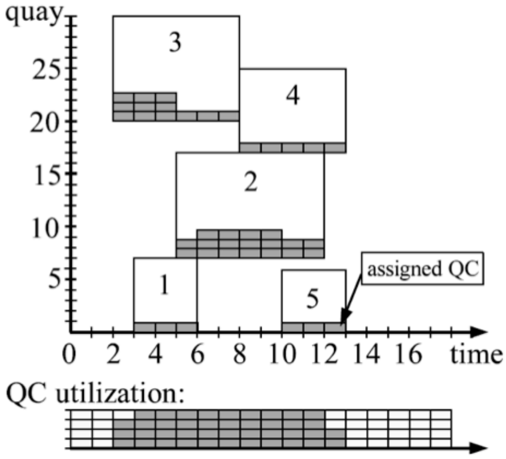


Figure 17: example of berth plan with quay crane assignment
Source: Bierwirth C., Meisel F., 2008

A classification scheme for the integration of BAP and QCAP is proposed in the paper "A survey of berth allocation and quay crane scheduling problems in container terminals" (Bierwirth and Meisel, 2009). Problems are classified according to four attributes. The spatial attribute concerns the berth layout and water depth restrictions. The temporal attribute describes the temporal constraints for the service process of vessels. The handling time attribute determines the way vessel handling times are considered in the problem. The fourth attribute defines a performance measure for evaluating possible solutions to a problem (Bierwirth and Meisel, 2009).

	Value	Description
SPATIAL ATTRIBUTE	disc	The quay is partitioned in discrete berths.
	cont	The quay is assumed to be a continuous line.
	hybr	The hybrid quay mixes up properties of discrete and continuous berths.
	draft	Vessels with a draft exceeding a minimum water depth cannot be berthed arbitrarily.
TEMPORAL ATTRIBUTE	stat	In static problems there are no restrictions on berthing times.
	dyn	In dynamic problems arrival times restrict the earliest berthing times.
	due	Due dates restrict the latest allowed departure times of vessels.

HANDLING TIME ATTRIBUTE	fix	The handling time of a vessel is considered fix.
	pos	The handling time of a vessel depends on its berthing position.
	QCAP	The handling time of a vessel depends on the assignment of quay cranes.
	QCSP	The handling time of a vessel depends on a quay crane operation schedule.
PERFORMANCE MEASURE	wait	Waiting time of a vessel.
	hand	Handling time of a vessel.
	compl	Completion time of a vessel.
	speed	Speedup of a vessel to reach the terminal before the expected time of arrival.
	tard	Tardiness of a vessel against the given due date.
	order	Deviation between the arrival order of vessels and the service order.
	rej	Rejection of a vessel.
	res	Resource utilization effected by the service of a vessel.
	pos	Berthing of a vessel apart from its desired berthing position.
	misc	Miscellaneous.

Table 5: classification scheme for the integration of BAP and QCAP

From a mathematical point of view, the problem's constraints and assumptions are an integration of the ones presented for the two sub-problems (BAP and QCAP).

Pertaining to the objective function, in general the most utilized deal with the minimization of one or more of the performance measures reported in the above table. Further details on the BACAP will be presented in Chapter 4.

3.2.1.5 Stowage Planning

Stowage planning is one of the core and most complex ship planning processes. A stowage plan defines the precise position of each container in the vessel. In this context, containers are not usually identified with numbers: they belong instead to specific categories defined by two or more attributes (destination port, weight class, length or type of container, etc.). A practical example is here reported with the aim to understand the whole process easily. Let us suppose that a vessel is travelling on a route which involves four harbours in northern Europe: Hamburg, Esbjerg, Aarhus and Copenhagen. The ship is docked in Hamburg and the containers destined for the three other harbours have to be loaded on the vessel. The stowage plan is designed by the shipping line taking into account various information:

- The layout of the ship (number of bays, rows and tiers).
- The type of container which can be stored in each slot.
- The attributes of each container (its destination, weight, dimensions, need for electrical power in the vessel in case of reefer container, etc.).
- The approximate time for loading a container in a specific slot.

In order to find a feasible loading plan, some major constraints must be taken into account:

- A 40' container cannot be placed on top of a 20' container.
- All containers need to have a support from below, e.g. they cannot be placed on top of empty cells.
- Reefer containers must be placed on reefer slots.
- A heavier container cannot be stored upon a lighter container.
- If container A has to be discharged before container B, then container A shouldn't be stored below B: this principle is fundamental to avoid or at least minimize reloading operations due to overstowage.
- The balance of the vessel must be respected, both rows and bays wise.
- The line of sight for an optimal visual perspective.

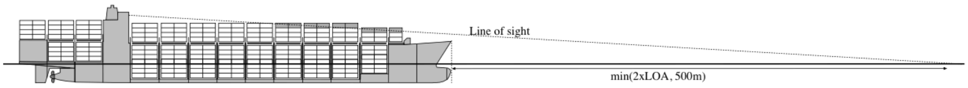


Figure 78: line of sight
Source: DTU Transport, Maritime Logistics Course

All these constraints are fundamental to work on the mathematical model which describes the problem.

The typical objectives for this planning problem are here listed:

- Minimization of the loading time.
- Maximisation of robustness by keeping bottom space free and reefer plugs free.
- Minimization of overstowage.

Going back to our example, once the vessel arrives at the second harbour, containers with that destination are unloaded and new containers might be loaded: the stowage plan has to be revised and updated always taking into consideration all the constraints listed above.

3.2.2 Storage and Stacking

Due to the continuous container traffic growth, much more importance has been given to storage and stacking logistics. This field deals with the determination of an optimal block and slot in the yard for all the containers that flow through the terminal.

In storage or yard planning systems, stack areas and storage capacities are allocated to a ship's arrival in advance according to the number of import and export containers expected (Steenken et al., 2004). The most used strategy for export containers is to reserve rows for containers of the same type and destination port. In addition to this, heavier containers are usually stacked on top of lighter containers: in so doing heavier containers will be loaded first onto the vessel and they will occupy the lowest positions. On the other hand, for import containers discharged from vessels, a common practice is to assign a certain yard capacity of adequate dimension, without further differentiation. This is because data and transport means of delivery generally are unknown at the time of discharge. If the transport mode is known, import areas can be subdivided according to them (Steenken et al., 2004).

The main objectives of yard planning problems are here reported:

- Minimisation of reshuffles.
- Minimisation of transport distances.
- Minimisation of bottleneck situations.
- Minimisation of waiting times for quay cranes.

As regards the first objective, we know that a reshuffle is necessary when a container, which has to be moved from its position in the yard, is not directly accessible. This non value added activity requires resources and implies a waste of time. Reshuffles mainly occur because of wrong or inaccurate data about containers. At European terminals 30-40% of the export containers arrive at the terminal lacking accurate data for the respective vessel, the discharge port, or container weight – data which are necessary to make a good storage decision. For import containers unloaded from ships the situation is even worse: the landside transport mode is known in at most 10-15% of all cases at the time of unloading a ship, e.g., when a location has to be selected in the yard (Steenken et al., 2004).

Pertaining to the second objective, in order to minimise transportation distances, it is a good logistics practice to place containers close to the future loading place and in such an order that it fits the loading plan.

An easy access to containers in the yard, with minimum or no reshuffles reduces bottlenecks and allows vehicles to efficiently transport the containers towards the quay cranes which can therefore optimise their productivity.

3.2.3 Transport Operations

The different means of transportation, which are used in container terminals, can be divided into two categories: vertical transport means (quay cranes and gantry cranes) and horizontal transport means (straddle carriers, AGVs, forklifts, trucks with trailers, reachstackers). A detailed description of this equipment is provided in Chapter 2. Within transport operations, three main optimization possibilities can be identified: as concerns horizontal transport, optimization problems refer both to the quayside-yard transport and the landside transport; as regards vertical transport means, another interesting area of optimization is related to the gantry crane transport. The three problems are presented in the subsections hereunder.

3.2.3.1 Quayside-Yard Transport

This area of optimization refers to the movement of containers from the yard to the ship and vice versa. The typical means of transportation used for this purpose are AGVs, truck with trailers, multi trailers or straddle carriers.

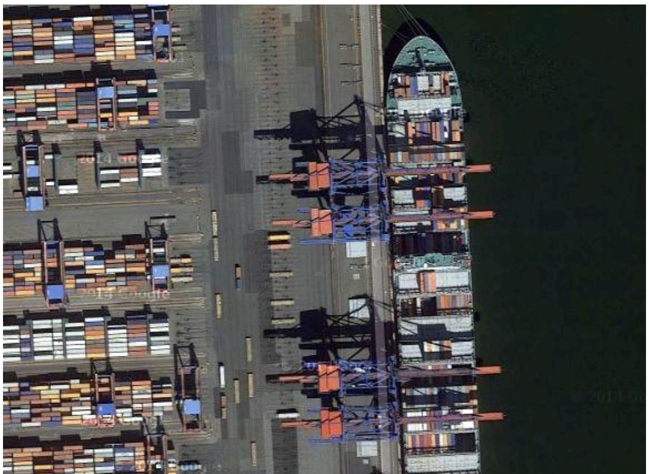


Figure 79: quayside-yard area
Source: maps.google.it

Different objectives can be considered for this problem:

- The maximization of the quay cranes productivity.
- The minimization of congestions in the area between the yard and the quay.
- The minimization of travelling times.
- The synchronization of the containers' transport with the handling activities performed by the quay cranes.

The first goal can be achieved minimizing breaks during shifts, moves of hatch covers, technical or operational disturbances and horizontal transports means' congestions.

The minimization of congestions is a goal itself, which can be reached finding out the optimal number of vehicles operating between the quay and the yard. The speed of the vehicles has to be optimized as well, with the aim of increasing the efficiency of the whole system.

In order to specify the third goal considered for this type of problem, we have to distinguish between two different modalities, vehicles can be allocated to the quay cranes. In the single-cycle mode, the vehicles serve only one crane; in the dual-cycle mode, the transport vehicles serve several cranes, thus combining the transport of export and import containers (Steenken et al., 2004).

In the single-cycle mode, the travelling time refers to the transport of either export containers (from the yard to the ship) or import containers (from the ship to the yard). In an import cycle, the only possibility for minimizing the travelling times is selecting containers' locations in the yard, which are close to the quayside. However, as we have seen in the previous section, this task is already included in the storage planning process. As concerns export cycles, the possibilities for optimization are higher. The transport time of containers from their position in the yard towards the quay cranes depends for example on reshuffles which have to be done in the yard, or on the need of particular equipment, which has to be set before the transportation of special containers. All these non-value added activities contribute to increase the total transportation time and have therefore a potential for optimization.

In the dual-cycle mode, the greater complexity reduces the possibility for optimization; however, the model itself is still more efficient than the single-cycle one. In this scenario in fact, each vehicle can serve more cranes operating at the same vessel or at other ships moored at the quay. In so doing, the combination of export and import containers' transport can be performed, empty travels are reduced and the efficiency of the system increased.

3.2.3.2 Landside Transport

The landside transport generally includes three types of operations: rail operations, truck operations and internal transports.

As regards rail operations, containers are transported between the stack and the railhead with straddle carriers, trucks or trailers; gantry cranes usually load and unload the containers to and from the trains. Buffers can be created alongside the railhead or directly on trailers. Two optimization opportunities can be identified: on one hand for the terminal operator it is important to minimize the reshuffles of containers in the yard, the crane waiting times and the empty transport distances of gantry cranes and transport vehicles; on the other hand the rail operator aims at minimizing shunting activities during train transport. Optimization at the railhead is facilitated if only a stowage instruction is sent to the terminal operator which indicates the wagon position for container attributes instead of specific positions for each container (Steenken et al., 2004).

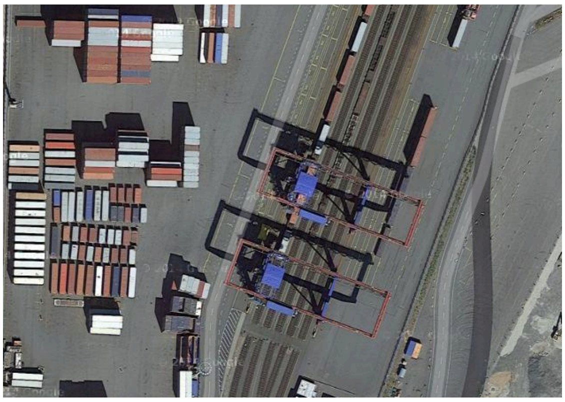


Figure 80: rail operations
Source: maps.google.it

Figure 81: rail freight terminal
Source: warrenlane.co.uk

Along with trains, trucks are also used for transporting containers in and out of the terminal. Trucks drive to transition points where the containers are loaded and unloaded by internal equipment. In this context, the objectives of optimization are the minimization of empty distances and travel times. The first goal can be achieved if the transport of import containers from the yard to the transition point is combined with the transport of export containers from the transition point to the yard. Because of the permanently changing traffic volume, optimization has to be very flexible and fast. Online optimisation is demanded (Steenken et al., 2004).

Finally, the third area of optimization within landside transport is related to internal movements which should be minimized. Internal transports may be necessary because of different reasons. When a ship is overbooked, some containers have to be left at the terminal, this requires a reorganisation of the yard, therefore additional transport. Empty containers play a crucial role too. They are needed to adjust imbalances problems in vessels, trains or trucks, thus they have to be transported to specific yards or transition points. If depots for empty containers exist at the terminal, additional transport have to be carried out. In addition to this, there might be import containers which have to be stripped and moved to assigned sheds or packed containers which have to be driven to the export stock. In general, all these types of internal movements are less critical than those associated to ships load and unload or truck operations, therefore they are performed mainly during low workload periods (Steenken et al., 2004).

3.2.3.3 Gantry Crane Transport

As described in Chapter 2, gantry cranes allow an efficient management of container stackyards. They represent the link between quayside and landside equipment such as ship loading and unloading cranes, vehicles for horizontal container transport and road trucks. The main optimization possibility is the minimization of the waiting times of the transport vehicles at the stack interfaces and the stacking cranes' total transfer times, including set-up and travel times. In practice, sequences of jobs have to be calculated and jobs have to be assigned to the respective crane; furthermore, priority of jobs have to be taken into account too. Because the traffic at the interfaces change rapidly, online optimization is demanded and job sequences have to be recalculated whenever a new job arises (Steenken et al., 2004).

CHAPTER 4
The Berth Allocation Problem with Quay Crane Assignment

4.1 Introduction

As introduced in the previous chapter, the Berth Allocation and Quay Crane Assignment Problem (BACAP) is one of the main problems which container terminals have to face. The problem is the integration of two sub-problems: the Berth Assignment Problem (BAP) and the Quay Crane Assignment Problem (QCAP). The first deals with the determination of the optimal berthing position and time for a vessel, the latter aims at allocating to the vessel the optimal number of quay cranes for loading and unloading the containers. Referring to Container Terminal Management Systems, the output of the BAP and QCAP (berth plan and QC-to-vessel assignment respectively) is produced by the application module for berth allocation.

Being the BACAP the focus of this Thesis, a deep analysis of all the aspects related to the problem has been performed. Firstly, a Literature Review has been carried out to understand the general characteristics of the problem and investigate which are the solutions proposed so far. Various mathematical models have been studied in details, trying to identify the differences and common features in terms of equations and inequalities, decision variables, types of objective function and constraints. It was interesting to find out how a specific concept (the minimization of the total costs, the non-overlapping of vessels in the quay, etc.) can be expressed in many different mathematical terms. According to the author, one or more inequalities can be used, as well as variables with single or multiple dimensions. Subsequently, six specific models with similar formulations have been chosen for a deeper investigation, improvement and comparison. The main aim of this work is to show how the BACAP can be approached and solved in different ways, resorting to similar mathematical formulations.

All the mathematical models which are proposed in the following sections, were written and tested using IBM® ILOG® CPLEX® Optimization Studio. In the first place, models were tested with small set of instances in order to verify their feasibility; in the second place, larger instances were solved, in order to assess the limits of the models. The six formulations have then been compared from a mathematical point of view and for what concerns the results obtained. A sensitivity analysis shows the relationship between the input data and the output of the different models.

Chapter 4 is organized as follows. The next section is devoted to a Literature review of the BACAP. In Section 4.3 we present the optimization software used in this work. The mathematical models considered for a deeper analysis and comparison are presented in Section 4.4 while the computational results are shown in Section 4.5. Finally, Section 4.6 presents a detailed study of the results obtained.

4.2 BACAP: Literature Review

The integration of berth allocation and quay crane assignment has received less attention in the scientific literature, compared to the single problems (BAP, QCAP, QCS, etc.). However, given its importance for the improvement of the operational efficiency of container terminals, more and more authors have recently focused their studies on the BACAP. The following table summarizes the major models proposed in the literature so far. For each model, the characteristics of the objective function are reported as well as a hint of the methodology utilised.

Model	Characteristics	Method
Park and Kim (2003)	Minimization of penalty costs and number of quay cranes setups.	Lagrangean relaxation, subgradient optimization technique, dynamic programming.
Meisel and Bierwirth (2006)	Minimization of quay cranes idle time.	Heuristic scheduling algorithm based on priority – rules methods.
Lee et al. (2006)	Minimization of the sum of total completion time of all the vessels and the completion time for all the quay cranes.	Genetic algorithm.
Liu, Wan and Wang (2006)	Minimization of the tardiness of vessels departures.	

Imai et al. (2008)		Genetic – algorithm based heuristic.
Giallombardo et al. (2008)	Maximisation of the total value of chosen quay crane profiles, minimisation of transhipment costs.	Mixed integer quadratic programming formulation (MIQP) and a linearization of the MIQP (mixed integer linear program – MILP).
Meisel and Bierwirth (2008)	Minimization of total service costs.	Construction heuristic, local refinement procedures, two meta – heuristics.
Chang et al. (2010)	Minimization of the total berthing location deviation, total penalty costs and the energy consumption of quay cranes.	Dynamic allocation, heuristic algorithm, parallel genetic algorithm, simulation.
Turkogullari et al. (2013)	Minimization of total costs	Binary integer linear programming formulation.

Table 6: BACAP models

A more detailed description of each model follows hereunder.

Park and Kim (2003) have firstly considered the possibility of integrating the BAP and the QCAP. Their model entails a continuous layout and considers the scheduling of quay cranes as well. The integrated problem is formulated as an integer program and a two-phase solution procedure is presented to solve the model. In the first phase, the berthing time and position of vessels and the number of quay cranes assigned to each vessel at each time step, are determined using Lagrangean relaxation and a subgradient optimization technique; the objective is to minimize the sum of penalty costs over all ships. In the second phase, cranes are scheduled along the quay via dynamic programming with the objective of minimizing the number of setups (Giallombardo et al., 2008). Furthermore, the assignment of quay cranes to vessels is allowed to change during the handling time. The authors consider specific parameters in their formulation such as a lower bound and upper bound in the number of quay cranes which can be assigned to a vessel, the desired berthing position for each ship, penalty costs associated to earlier or later mooring time and later departure. For reasons of simplicity Park and Kim (2003) assume that the crane productivity is proportional to the number of quay cranes that simultaneously serve a vessel. (Meisel and Bierwirth, 2008). Cordeau et al. (2005) criticised this assumption, underlying the importance of considering interference effects, which may decrease the quay cranes' productivity.

Meisel and Bierwirth (2006) proposed a dynamic variant of the BACAP focusing on the reduction of quay cranes idle times, one of the primary objectives for terminal operators. In this approach, each vessel represents an activity which can be performed in 8 different modes, each mode representing a given quay crane – to – vessel assignment over time (Giallombardo et al., 2008).

Lee et al. (2006) presented a method for scheduling berth and quay cranes with the objective of minimizing the sum of total completion time of all the vessels and the completion time for all the quay cranes (Boile, Theofanis, Golias, 2006). Given a number of quay cranes available at a berth, no crane assignment is necessary. A Genetic Algorithm is used to obtain berth plans, which are evaluated by generating a feasible work plan for the cranes that serve a vessel. In lack of a suitable scheduling algorithm for the generation of work plans, only a single problem instance of small size is investigated (Meisel and Bierwirth, 2008).

In the model proposed by Liu, Wan, and Wang (2006), the optimal berthing times and crane numbers is determined without however including any information about the vessels' berthing position. For this specific reason, the BACAP model is considered weaker compared to other formulations (Turkogullari et al., 2014).

Imai et al. (2008) studied the simultaneous berth – crane allocation and quay crane scheduling problem. A physical constraint characterizes the model: quay cranes cannot move freely among berths since they are mounted on the same track and cannot bypass each other (Giallombardo et al., 2008).

Giallombardo et al. in the paper "The Tactical Berth Allocation Problem with Quay Crane Assignment and Quadratic Transshipment-Related Quadratic Yard Costs" (2008), dealt with the combination of BAP and QCAP at a tactical level, from the perspective of a transshipment terminal. In addition to this, the authors introduced the concept of quay crane profile, which is undoubtedly the peculiarity of the model. Tactical level, characteristics of a transhipment terminal and quay crane profile are here explained in details.

The Tactical Berth Allocation Problem (TBAP) differs from the Operational Berth Allocation Problem (OBAP or simply BAP) in many ways. The planning horizon for the TBAP consists of months while the one for the BAP is shorter and generally consists of one week. Pertaining to ships arrival times, in the TBAP it is up to the shipping line to communicate a time window for the expected arrival time of the vessel (e.g. wednesday afternoon with a weekly frequency). In the BAP instead, the vessel arrival time is known precisely. Furthermore, while the objective function for the BAP deals with the minimization of the waiting times to moor, the TBAP aims at assessing if a customer request can be satisfied and what are the correlated impacts on the whole terminal performances (yard costs and quay crane utilization). Another important difference between the two problems concerns handling times: the BAP works with deterministic handling times while the TBAP implies a negotiation between the shipping lines and the terminal's management about reserved assignment of quay cranes along work shifts.

Giallombardo et al. (2008) adopt the perspective of the transhipment terminal where containers are unloaded from the inbound vessels, temporarily stored in the yard and then loaded again in the outbound vessels. When unloading a vessel, the discharged containers must be allocated to yard positions close enough to the vessel berthing point in order to speed up the vessel handling. However when the departure position of a container is far from its yard position, the container must be reallocated before the arrival of the outbound vessel (Giallombardo et. al, 2008). The process of moving a container from a current yard position to a new one, which is closer to the outgoing berth is called housekeeping. In details, according to Giallombardo et al. (2008), three different situations can occur according to the distance along the quay between the incoming and outgoing berths. If the distance is below 600 meters, the housekeeping is not performed: a container will be moved from the ship to its established position in the yard and then from this position to the quay, for the loading operations in a new vessel. Straddle carriers are usually used for these operations. If the distance between the incoming and outgoing berths is between 600 and 1100 meters, the housekeeping operations are carried out using straddle carriers. Finally, if the distance is greater than

1100 meters, the housekeeping is performed using the less expensive multi trailer vehicles with a higher capacity than the straddle carriers.

Giallombardo et al. (2008) model is also characterised by the concept of quay crane profile. A quay crane profile is the combination of work shifts and the number of quay cranes which operate during the shifts. According to the quay crane hours, which are necessary to unload and load the vessel (in turn depending on the number of containers and the productivity of the quay cranes available), different profiles can be proposed. For example, terminal managers receive a request for a ship which requires 6 quay crane hours. Two profiles could be suggested: an intensive quay crane profile (3 quay cranes each one operating for two hours) or a long quay crane profile (2 quay cranes operating for 3 hours each). Each profile has its own advantages and disadvantages. The fast profile would satisfy both the customer and the terminal: the handling time is lower and the availability of the berths increases too. On the other hand, a slow profile could be preferred by the terminal management as well, if the priority is avoiding bottlenecks by always having available quay cranes. Similarly, customers could ask for a faster handling for mother vessels and a slower handling for feeders.

Taking into consideration quay crane profiles, the approach proposed by Giallombardo et al. (2008) differs from the ones described above, where quay cranes are usually assigned hour by hour. As mentioned, the concept of “mode” in Meisel and Bierwirth (2006) is somehow similar to the concept of quay crane profile, but the authors do not provide enough details to allow comparisons (Giallomardo et al., 2008).

Additional constraints and characteristics connected to the profiles are presented hereby. Different feasible quay crane profiles can be associated to a given vessel, each profile is defined by a value which reflects technical aspects such as the resources utilized by the profile and the type of vessel which will use the profile. Specific operational constraints are taken into account in the model too: a quay crane cannot be moved from one vessel to another at whatever moment, but only between two shifts. This constraint can be easily handled by forcing profiles to maintain exactly the same number of quay cranes during a shift. Another good practice is to keep the distribution of quay cranes as much regular as possible among active shifts; a variance of one or at most two quay cranes can be considered acceptable (Giallombardo et al., 2008).

As concerns time constraints, both the time horizon and the working shifts are discretized in time steps. A profile can start at every time step of the shift complying with the arrival time of the vessel itself at the harbour.

Pertaining to the objective function, the model proposed aims, on one hand, at maximizing the total value of the selected quay crane profiles and on the other hand, at minimizing the housekeeping costs arising from the transshipment of containers between vessels.

Meisel and Bierwirth (2008) worked on the integration of BAP and QCAP focusing on quay cranes productivity and their effects, aspect ignored for example in the model provided by Park and Kim (2003). The model aims at determining the berthing time and position for the vessels as well as the number of quay cranes that serve a ship within the handling period. In particular, the objective function minimizes the total costs involved: the cost for berthing later than the expected time of arrival, the penalty cost which arises for finishing later than a given time and the operation cost related to the quay crane utilisation.

One of the first constraints of the model ensures that every vessel receives the required quay crane capacity with respect to productivity losses by quay crane interference and the chosen berthing position (Meisel and Bierwirth, 2008). An interference exponent and a berth deviation factor are introduced for this purpose. Another peculiarity of this formulation is that a vessel can be speed up to at most the earliest starting time of the operations: this makes the BACAP a dynamic problem according to the classification proposed by Imai et al. (2005).

Chang et al. (2010) propose a model whose aim is to minimize three factors: the total penalty for delayed berthing and departure time of vessels, the total energy consumption of quay cranes and the total deviation between the actual and best berthing locations of ships. A multi-objective function takes into account these three aspects, each one weighted conveniently. The authors employ a rolling-horizon strategy (Zhang et al., 2003), trade off between a short planning horizon, less predictable and accurate and a long planning horizon which suffers from computational uncertainty and unfeasibility. In details, a planning horizon of 3 days is set and divided into six periods of 12 hours each; the two daily periods are set from 9 a.m. to 9 p.m. and from 9 p.m. to 9 a.m., respectively. In the start of the first period, the BAP and QCAP plans are established for these six periods of three days. Upon completion of each period, a new 3-day plan is thereafter formed (Chang et al, 2010).

One of the most recent BACAP models is the one proposed by Turkogullari et al. (2013). The formulation presented in the paper "*Optimal berth allocation and time-invariant quay crane assignment in container terminals*" consider a continuous berth layout and dynamic vessel arrivals, meaning respectively that vessels can berth at arbitrary positions and cannot moor before the expected time of arrival. The aim here is to find an optimal berthing time and section for each ship as well as an optimal number of quay cranes assigned to the vessels. The objective function pursues the minimization of the total costs involved in the problem: the cost for deviating from the desired berth section, the cost of berthing one period later than the expected time of arrival and the cost of departing later that the desired due time of vessels. The geniality of the formulation proposed, stays on the fact that just one binary variable is used and only three constraints are defined. Because of this, the model contains a significant number of binary variables: however, it has a special form that increases the efficiency of the solution procedure (Turkogullari et al., 2013).

4.3 The Optimization Tool

IBM® ILOG® CPLEX® Optimization Studio is the software utilized to test the mathematical models in this work. More precisely, it is an analytical decision support toolkit composed by an integrated development environment (IDE), ILOG CPLEX optimizer solvers and the Optimization Programming Language (OPL), which will be analysed in the next paragraph in detail. As concerns the solvers, we distinguish between IBM ILOG CPLEX Optimizer, which solves difficult discrete optimization problems and IBM ILOG CPLEX CP Optimizer for hard combinatorial problems.

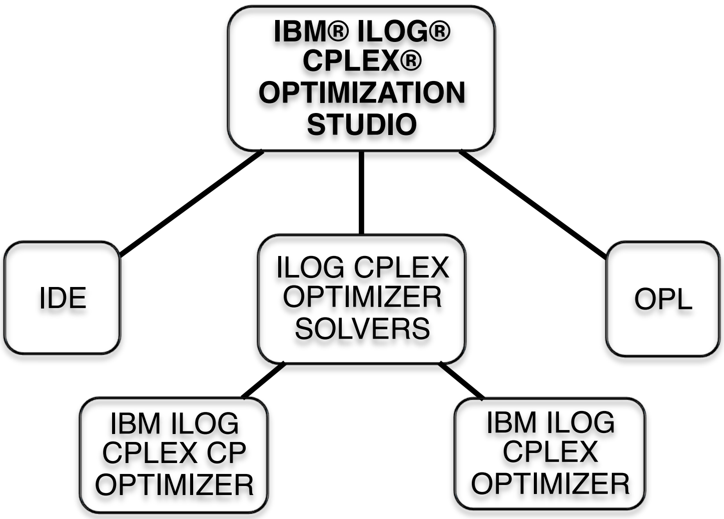


Figure 82: IBM® ILOG® CPLEX® Optimization Studio

In general, IBM® ILOG® CPLEX® Optimization Studio main functions are (ibm.com):

- Optimize business decision.
- Quickly develop optimization models.
- Create real-world applications.

4.3.1 Optimization Programming Language

OPL mathematically describes optimization models. Its powerful syntax supports all expressions needed to model and solve problems using both mathematical programming and constraint programming (ibm.com).

OPL main features are presented below:

- Compact language.
- Handling of mixed integer linear programming (MIP) Problems, where some of the decision variables are constrained to be integer values at the optimal solution.
- Handling of Constraint Programming (CP) Problems, which require assignment of symbolic values to variables that satisfy certain constraints.
- Utilization of real or integer variables.
- Representation of detailed scheduling problems.
- Import of data and export of optimal solutions to databases and Microsoft Excel spreadsheets.

4.4 Presentation of the models for the BACAP

4.4.1 Introduction

In this Section, core part of this Thesis, we present six different models, which aim to optimally solve the BACAP. Some models were taken directly from the Literature, others were adjusted for this specific work. In order to compare the results obtained in each model, common assumptions were made as well as some simplifications of the reference models.

The following table summarizes the main differences between the models, which from now on, will be identified using the lettering M-Number.

Model	Formulation	Number of Quay Cranes	Length of the Vessels	Reference Literature
M1	Arc based	Fixed	1	R1
M2	Arc based	Variable	1	R1
M3	Compact	Fixed	Specific	R2
M4	Compact	Variable	Specific	R3
M5	Compact	Variable	1	R3
M6	Compact	Fixed	Specific	R3

Table 7: main differences between the six BACAP models

The first two models are characterized by an arc formulation, which is translated in the utilisation of tuples in the coding part. All the other models are coded using a compact formulation.

As concerns the number of quay cranes, two cases are analysed. In the so called "Fixed" scenario, the number of quay cranes assigned to a vessel doesn't change during its stay at the berth (time-invariant assignment). As a consequence, the processing time of the vessel is known for each possible quay crane requirement. In the "Variable" scenario instead, the number of quay cranes can change through the processing time, which is therefore not known a priori.

The length of the vessel is a critical parameter of the problem. As we can see, in the different models we can have vessels of length 1 or vessels with a specific length. A vessel with length 1 is a vessel, which perfectly fits in a berth section. Here we assume that the berths are long enough to accept all the vessels arriving at the harbour, no matter their length. In a more realistic scenario instead, a vessel has its specific length, which is usually expressed in meters. Since we consider a discrete layout and will then suppose that the berth sections are equal-sized, having vessels with a length expressed in meters would turn the problem into a continuous problem. To avoid this, we define the length of a vessel as the number of berth sections, which will be occupied along the quay, according to the vessels' real length.

Models M1 and M2 refer to the paper "The Tactical Berth Allocation Problem with Quay Crane Assignment and Quadratic Transshipment-Related Quadratic Yard Costs", by Giallombardo et al. (2008). Model M3 is directly drawn from the paper by Turkogullari et al. (2013), "Optimal berth allocation and time-invariant quay crane assignment in container terminals". Models M4, M5 and M6 make reference to "Heuristics for the integration of crane productivity in the berth allocation problem" by Meisel and Bierwirth (2008). All the three papers have been deeply analysed and synthetized in the Literature review.

The following assumptions clarify the common characteristics of the models:

- The partition of the quay where the vessels can berth is discrete: vessels cannot berth at arbitrary positions but have to be assigned to a specific section of the quay, which is called berth. The berth sections are equal-sized.
- The planning horizon is divided into equal-sized time periods.
- Each berth section is occupied by at most one vessel in each time period.
- Each quay crane can be assigned to at most one vessel in each time period.
- Each vessel has a minimum and maximum number of quay cranes which can be assigned to it.
- There are no disruptions during the processing of a vessel: the operations start when the vessel berth at the quay and go on continuously till the departure of the vessel.

As we will see in the following sections, all the models pursue the minimization of 3 major costs considered in this context: the cost for berthing later than the expected time of arrival provided, the operational costs which arise when using the quay cranes and the cost for berthing far from the desired position.

Shipping lines usually request a berthing time in the container terminal in advance; when the vessel is close to calling at the terminal, this time could also be revised. In container shipping it is fundamental to respect schedules: berthing later than expected may result in a late departure and consequently late arrival at the next port. After repeated delays at calling ports, ships suffer from a substantial delay at the final port to be called during a specific voyage, but even more important is that those containers that need to be transhipped to other vessels at hubs may lose their planned connection (plagrave-journals.com). The models proposed in this work, take into consideration penalty costs that arise for the container terminal whenever a vessel is not able to berth at its desired arrival time.

In addition to this, shipping lines specifies a preferred berthing location along the quay. The desired position is usually close to the dedicated yard areas for import and export containers: in so doing, the workload of horizontal transport means is minimal. If the actually chosen berthing position is apart from the desired position, the load of the horizontal transport increases (Meisel and Bierwirth, 2009). All the six models propose to penalize apart berthing positions through additional costs that the terminal has to face.

All in all, the container terminal reaches a perfect service quality and minimum or no costs when desired berthing time and berthing position are respected.

The third cost considered takes into account the quay crane hours required to process each vessel. The minimization of this cost implies a quick service time for the vessel, which in turn increases customer's satisfaction.

4.4.2 Presentation of Model M1

Model M1 is drawn from the paper "The Tactical Berth Allocation Problem with Quay Crane Assignment and Quadratic Transshipment-Related Quadratic Yard Costs", by Giallombardo et al. (2008).

This formulation for the BACAP is characterized by vessels of length 1 and a time-invariant assignment: the number of quay cranes which process a vessel doesn't change during its stay at the berth. Thanks to this assumption, which is added to the general ones, the vessel's processing time is known, for each quay crane assignment.

Model M1 takes also into consideration the schedule of ships in each berth and a time window associated to each berthing section. To comply with these peculiarities, the mathematical model was translated into the coding language using an arc formulation.

Parameters and Sets used in the Mathematical Model

v : the number of vessels
s : the number of berth sections
k : the number of available quay cranes
t : the number of time periods
M : a big positive real number

$V = \{1 \ldots v\}$: the set of vessels
$S = \{1 \ldots s\}$: the set of berth sections
$K = \{1 \ldots k\}$: the set of available quay cranes
$T = \{1 \ldots t\}$: the set of all time periods

e_i : the desired arrival time for vessel $i \in V$
LB_i : the lower bound on the number of cranes that can be assigned to vessel $i \in V$
UB_i : the upper bound on the number of cranes that can be assigned to vessel $i \in V$
d_i : the desired berth for vessel $i \in V$

p_i^k : the processing time of vessel $i \in V$ if $k \in K$ quay cranes are assigned to it

a_z : the start of availability time of berth $z \in S$

b_z : the end of availability time of berth $z \in S$

ϕ_{i1} : the cost of one unit deviation from the desired berth section for vessel $i \in V$

ϕ_{i2} : the cost of berthing one period later than the desired berthing time of vessel $i \in V$

ϕ_{i3} : the cost of using one quay crane to process vessel $i \in V$

We then define a graph $G^z = (V^z, A^z) \;\; \forall \; z \in S$, characterized by vertices and arcs, where $V^z = V \cup \{o(z), d(z)\}$, with $o(z)$ and $d(z)$ additional vertices representing berth z and $A^z \subseteq V^z \times V^z$.

Decision Variables used in the Mathematical Model

x_{ij}^z : equal to 1 if vessel i is scheduled before vessel j at berth $z, \forall \; (i,j) \in A^z, z \in S,$ 0 otherwise

y_{it}^k : equal to 1 if $k \in K$ quay cranes are assigned to vessel $i \in V$ at time $t \in T,$ 0 otherwise

z_i^k : equal to 1 if $k \in K$ quay cranes are assigned to vessel $i \in V$ through the processing time, 0 otherwise

w_i^z : equal to 1 if vessel $i \in V$ is assigned to berth $z \in S,$ 0 otherwise

r_{it} : equal to 1 if at least one quay crane is assigned to vessel $i \in V$ at time $t \in T,$ 0 otherwise

δ_i : the berthing time for vessel $i \in V$

$\tau_{o(z)}$: the starting operation time for berth $z \in S$

$\tau_{d(z)}$: the ending operation time for berth $z \in S$

Optimization Model

We formulate the BACAP as follows:

$$\sum_{i=1}^{V} \sum_{z=1}^{S} \sum_{k=LB_i}^{UB_i} \phi_{i1} | \, z - \, d_i \, | w_i^z + \, \phi_{i2}(\delta_i - \, e_i) + \, \phi_{i3} \, k \, p_i^k \tag{1.1}$$

subject to

$$\sum_{z=1}^{S} w_i^z = 1 \qquad \forall\, i \in V \tag{1.2}$$

$$\sum_{j=1}^{V \cup \{d(z)\}} x_{ij}^z = w_i^z \qquad \forall\, i \in V, z \in S \tag{1.3}$$

$$\sum_{j=1}^{V \cup \{d(z)\}} x_{o(z)j}^z = 1 \qquad \forall\, z \in S \tag{1.4}$$

$$\sum_{i=1}^{V \cup \{o(z)\}} x_{id(z)}^z = 1 \qquad \forall\, z \in S \tag{1.5}$$

$$\sum_{j=1}^{V \cup \{o(z)\}} x_{ji}^z = \sum_{j=1}^{V \cup \{d(z)\}} x_{ij}^z \qquad \forall\, z \in S, i \in V \tag{1.6}$$

$$\sum_{k=LB_i}^{UB_i} z_i^k = 1 \qquad \forall\, i \in V \tag{1.7}$$

$$\sum_{k=LB_i}^{UB_i} y_{it}^k = r_{it} \qquad \forall\, i \in V, t \in T \tag{1.8}$$

$$\sum_{t=1}^{T} r_{it} = \sum_{k=LB_i}^{UB_i} p_i^k z_i^k \qquad \forall\, i \in V \tag{1.9}$$

$$\sum_{i=1}^{V} \sum_{k=LB_i}^{UB_i} k\, y_{it}^k \leq K \qquad \forall\, t \in T \tag{1.10}$$

$$\sum_{t=1}^{T} \sum_{k=LB_i}^{UB_i} (k\, y_{it}^k - k\, p_i^k z_i^k) \leq 0 \qquad \forall\, i \in V \tag{1.11}$$

$$y_{it}^{k} \leq \ z_{i}^{k} \qquad \forall\ i \in V, t \in T, k \in \{UB_i \dots\ LB_i\} \tag{1.12}$$

$$\delta_i\ \geq\ e_i \qquad \forall\ i \in V \tag{1.13}$$

$$\delta_i + \sum_{k=\ LB_i}^{UB_i} p_i^k\ \leq T \qquad \forall\ i \in V \tag{1.14}$$

$$t\ \ r_{it}\ + T(1 -\ r_{it}\ ) \geq\ \delta_i \qquad \forall\ i \in V, t \in T \tag{1.15}$$

$$(t+1)\, r_{it}\ \leq\ \delta_i + \sum_{k=\ LB_i}^{UB_i} p_i^k \qquad \forall\ i \in V, t \in T \tag{1.16}$$

$$\delta_i + \sum_{k=\ LB_i}^{UB_i} p_i^k -\ \delta_j \leq \left(1 - x_{ij}^{z}\right) M \qquad \forall\ i \in V, z \in S, j \in V \cup \{d(z)\} \tag{1.17}$$

$$\tau_{o(z)} -\ \ \delta_j \leq \left(1 - x_{o(z)j}^{z}\right) M \qquad \forall\ z \in S, j \in V \tag{1.18}$$

$$\tau_{o(z)}\ \geq\ a_z \qquad \forall\ z \in S \tag{1.19}$$

$$\tau_{d(z)}\ \leq\ b_z \qquad \forall\ z \in S \tag{1.20}$$

$$x_{ij}^{z} \in \{0,1\} \qquad \forall\ (i,j) \in A^z, z \in S \tag{1.21}$$

$$y_{it}^{k} \in \{0,1\} \qquad \forall\ i \in V, t \in T, k \in \{UB_i \dots\ LB_i\} \tag{1.22}$$

$$z_{i}^{k} \in \{0,1\} \qquad \forall\ i \in V, k \in \{UB_i \dots\ LB_i\} \tag{1.23}$$

$$w_{i}^{z} \in \{0,1\} \qquad \forall\ i \in V, z \in S \tag{1.24}$$

$$r_{it} \in \{0,1\} \qquad \forall\ i \in V, t \in T \tag{1.25}$$

$$\delta_i \geq 0 \qquad \forall\ i \in V \tag{1.26}$$

$$\tau_{o(z)}, \tau_{d(z)} \geq 0 \qquad \forall\ z \in S \tag{1.27}$$

Explanation of the above formulation

Model M1, as all the other models, pursues the minimization of the total costs involved in the problem, that is to say the cost which arises for not berthing in the desired position, the cost for berthing later than the planned arrival time and the cost associated to the utilization of the quay cranes to operate the vessel.

The first five constraints are expressed with an arc formulation.

Constraint (1.2) makes sure that each ship berths in just one section of the quay.

The link between the two binary variables x_{ij}^{z} and w_{i}^{z} is defined in (1.3).

Constraints (1.4) and (1.5) define the outcoming and incoming flows from and to the depots.

The flow conservation for all the vertices, apart from the ones representing the berths, is ensured by (1.6).

The next part of the model, until Constraint (1.16), refers mainly to the quay-crane assignment.

Each ship can have just one quay crane assignment, this is guaranteed in Constraint (1.7).

The link between the two binary variables y_{itk} and r_{it} is defined in (1.8).

Constraint (1.9) sets the processing time for each vessel as the difference from the departure time and the berthing time of the vessel. In so doing, each ship i has its specific crane profile, that is to say a certain number of quay cranes k, which all operate for the processing time p_{i}^{k}.

Constraint (1.10) ensures that the quay crane hours required by each vessel are provided.

Constraint (1.11) characterizes the formulation and ensures that the number of quay cranes which process the vessel doesn't change during the time.

The link between the two binary variables y_{it}^{k} and $z_{i}^{k}$is expressed in Constraint (1.12).

An assumption on the arrival time of the vessel is defined in Constraint (1.13): the berthing time cannot be lower than the desired value provided.

A time limit for the processing of a vessel is set in Constraint (1.14).

Constraint (1.15) instead, guarantees that the processing hours do not precede the berthing time.

Constraint (1.16) ensures that each processing hour for a vessel doesn't go beyond the departing time of the vessel.

The model ends with four constraints which are typical of the arc formulation.

Precedences related to the berthing times of the scheduled vessels are defined in constraints (1.17) and (1.18).

Time windows on berths' availabilities are stated in constraint (1.19) and (1.20).

Constraints (1.21)-(1.27) define the domain of the decision variables.

4.4.3 Presentation of Model M2

Model M2, like Model M1, is inspired by the paper "The Tactical Berth Allocation Problem with Quay Crane Assignment and Quadratic Transshipment-Related Quadratic Yard Costs", by Giallombardo et al. (2008).

As in the previous model, we consider vessels of length 1. However, we here introduce the possibility of having a different number of quay cranes, which process the vessel from hour to hour. This approach is known as variable in time assignment, different from the previous approach known as time invariant assignment.

Under this scenario the processing time becomes a decision variable; in addition to this, in order to decide upon the optimal quay-crane assignment, the total quay crane hours required for each vessel are also provided.

The model reflects the same considerations concerning the ships' schedule and berths' time windows, which were introduced for Model M1.

Parameters and Sets used in the Mathematical Model

v : the number of vessels

s : the number of berth sections

k : the number of available quay cranes

t : the number of time periods

M : a big positive real number

$V = \{1 \dots v\}$: the set of vessels

$S = \{1 \dots s\}$: the set of berth sections

$K = \{1 \dots k\}$: the set of available quay cranes

$T = \{1 \dots t\}$: the set of all time periods

e_i : the desired arrival time for vessel $i \in V$

LB_i : the lower bound on the number of cranes that can be assigned to vessel $i \in V$

UB_i : the upper bound on the number of cranes that can be assigned to vessel $i \in V$

d_i : the desired berth for vessel $i \in V$

h_i : the number of quay crane hours required to process vessel $i \in V$

a_z : the start of availability time of berth $z \in S$

b_z : the end of availability time of berth $z \in S$

ϕ_{i1} : the cost of one unit deviation from the desired berth section for vessel $i \in V$

ϕ_{i2} : the cost of berthing one period later than the desired berthing time of vessel $i \in V$

ϕ_{i3} : the cost of using one quay crane to process vessel $i \in V$

We then define a graph $G^z = (V^z, A^z)\ \forall\ z \in S$, characterized by vertices and arcs, where $V^z = V \cup \{o(z), d(z)\}$, with $o(z)$ and $d(z)$ additional vertices representing berth z and $A^z \subseteq V^z \times V^z$.

Decision Variables used in the Mathematical Model

x_{ij}^z : equal to 1 if vessel i is scheduled before vessel j at berth z, $\forall\ (i,j) \in A^z, z \in S$, 0 otherwise

y_{it}^k : equal to 1 if $k \in K$ quay cranes are assigned to vessel $i \in V$ at time $t \in T$, 0 otherwise

w_i^z : equal to 1 if vessel $i \in V$ is assigned to berth $z \in S$, 0 otherwise

r_{it} : equal to 1 if at least one quay crane is assigned to vessel $i \in V$ at time $t \in T$, 0 otherwise

δ_i : the berthing time for vessel $i \in V$

γ_i : the ending time of the operations for vessel $i \in V$

$\tau_{o(z)}$: the starting operation time for berth $z \in S$

$\tau_{d(z)}$: the ending operation time for berth $z \in S$

Optimization Model

We formulate the BACAP as follows:

$$\min \sum_{i=1}^{V}\sum_{t=1}^{T}\sum_{z=1}^{S}\sum_{k=LB_i}^{UB_i} \phi_{i1} \mid z - d_i \mid w_i^z + \phi_{i2}\ (\delta_i - e_i) + \phi_{i3}\, k\, y_{it}^k \tag{2.1}$$

subject to

$$\sum_{z=1}^{S} w_i^z = 1 \qquad \forall\, i \in V \tag{2.2}$$

$$\sum_{j=1}^{V \cup \{d(z)\}} x_{ij}^z = w_i^z \qquad \forall\, i \in V, z \in S \tag{2.3}$$

$$\sum_{j=1}^{V \cup \{d(z)\}} x_{o(z)j}^z = 1 \qquad \forall\, z \in S \tag{2.4}$$

$$\sum_{i=1}^{V \cup \{o(z)\}} x_{id(z)}^z = 1 \qquad \forall\, z \in S \tag{2.5}$$

$$\sum_{j=1}^{V \cup \{o(z)\}} x_{ji}^z = \sum_{j=1}^{V \cup \{d(z)\}} x_{ij}^z \qquad \forall\, z \in S, i \in V \tag{2.6}$$

$$\sum_{k=LB_i}^{UB_i} y_{it}^k = r_{it} \qquad \forall\, i \in V, t \in T \tag{2.7}$$

$$\sum_{t=1}^{T} r_{it} = \gamma_i - \delta_i \qquad \forall\, i \in V \tag{2.8}$$

$$\sum_{i=1}^{V} \sum_{k=LB_i}^{UB_i} k\, y_{it}^k \le K \qquad \forall\, t \in T \tag{2.9}$$

$$\sum_{t=1}^{T} \sum_{k=LB_i}^{UB_i} k\, y_{it}^k \ge h_i \qquad \forall\, i \in V \tag{2.10}$$

$$\delta_i \ge e_i \qquad \forall\, i \in V \tag{2.11}$$

$$\delta_i + \sum_{t=1}^{T} \sum_{k=LB_i}^{UB_i} y_{it}^{k} \leq T \qquad \forall\, i \in V \tag{2.12}$$

$$t\ r_{it} + T(1 - r_{it}) \geq \delta_i \qquad \forall\, i \in V, t \in T \tag{2.13}$$

$$(t+1)\, r_{it} \leq \gamma_i \qquad \forall\, i \in V, t \in T \tag{2.14}$$

$$\delta_i + \sum_{t=1}^{T} \sum_{k=LB_i}^{UB_i} y_{it}^{k} - \delta_j \leq \left(1 - x_{ij}^{z}\right) M \qquad \forall\, i \in V, z \in S, j \in V \cup \{d(z)\} \tag{2.15}$$

$$\tau_{o(z)} - \delta_j \leq \left(1 - x_{o(z)j}^{z}\right) M \qquad \forall\, z \in S, j \in V \tag{2.16}$$

$$\tau_{o(z)} \geq a_z \qquad \forall\, z \in S \tag{2.17}$$

$$\tau_{d(z)} \leq b_z \qquad \forall\, z \in S \tag{2.18}$$

$$x_{ij}^{z} \in \{0,1\} \qquad \forall\, (i,j) \in A^{z}, z \in S \tag{2.19}$$

$$y_{it}^{k} \in \{0,1\} \qquad \forall\, i \in V, t \in T, k \in \{UB_i \dots LB_i\} \tag{2.20}$$

$$w_i^{z} \in \{0,1\} \qquad \forall\, i \in V, z \in S \tag{2.21}$$

$$r_{it} \in \{0,1\} \qquad \forall\, i \in V, t \in T \tag{2.22}$$

$$\delta_i, \gamma_i \geq 0 \qquad \forall\, i \in V \tag{2.23}$$

$$\tau_{o(z)}, \tau_{d(z)} \geq 0 \qquad \forall\, z \in S \tag{2.24}$$

Explanation of the above formulation

As in Model M1, the objective function (2.1) pursues the minimization of the total costs involved in the problem.

The first five constraints are typical of the arc formulation.

Constraint (2.2) makes sure that each ship berths in just one section of the quay.

The link between the two binary variables x_{ij}^{z} and w_{i}^{z} is defined in (2.3).

Constraints (2.4) and (2.5) define the outcoming and incoming flows from and to the depots.

The flow conservation for all the vertices, apart from the ones representing the berths, is ensured by (2.6).

From Constraint (2.7) to Constraint (2.14) the formulation refers mainly to the quay-crane assignment.

The link between the two binary variables y_{itk} and r_{it} is defined in (2.7).

Constraint (2.8) sets the processing time for each vessel as the difference from the departure time and the berthing time of the vessel.

Constraint (2.9) is related to the availability of the quay cranes at the container terminal. In particular it is guaranteed that in each time period, the number of quay cranes utilized by the vessels being processed, does not exceed the available number of cranes.

Constraint (2.10) ensures that the quay crane hours required by each vessel are provided.

An assumption on the arrival time of the vessel is defined in Constraint (2.11): the berthing time cannot be lower than the desired value provided.

A time limit for the processing of a vessel is set in Constraint (2.12).

Constraint (2.13) instead, guarantees that the processing hours do not precede the berthing time.

Constraint (2.14) ensures that each processing hour for a vessel doesn't go beyond the departing time of the vessel.

The last inequalities are specific for the arc formulation.

Precedences related to the berthing times of the scheduled vessels are defined in constraints (2.15) and (2.16).

Time windows on berths' availabilities are stated in constraint (2.17) and (2.18).

Constraints (2.19)-(2.24) define the domain of the decision variables.

4.4.4 Presentation of Model M3

Model M3 is directly drawn from the reference paper "Optimal berth allocation and time-invariant quay crane assignment in container terminals" by Turkogullari et al. (2013). This formulation for the BACAP is characterized by a time-invariant assignment as in Model M1. The difference here concerns the lengths of the vessels, which are realistic and intended as the number of berth sections occupied by each vessel in the quay.

The distinctivenesses of the formulation proposed by Turkogullari et al. (2013) is the definition of a unique binary decision variable and the formulation of just three constraints. In detail, the variable takes into consideration the first berthing position of the vessel, its berthing time and the fixed number of quay cranes assigned for the handling operations.

Parameters and Sets used in the Mathematical Model

v : the number of vessels
s : the number of berth sections
k : the number of available quay cranes
t : the number of time periods
M : a big positive real number

$V = \{1 \ldots v\}$: the set of vessels
$S = \{1 \ldots s\}$: the set of berth sections
$K = \{1 \ldots k\}$: the set of available quay cranes
$T = \{1 \ldots t\}$: the set of all time periods

e_i : the arrival time for vessel $i \in V$
l_i : the length of vessel $i \in V$ expressed in number of berth sections needed by the vessel
LB_i : the lower bound on the number of cranes that can be assigned to vessel $i \in V$
UB_i : the upper bound on the number of cranes that can be assigned to vessel $i \in V$
d_i : the desired berth for vessel $i \in V$
p_i^k : the processing time of vessel $i \in V$ if $k \in K$ quay cranes are assigned to it
ϕ_{i1} : the cost of one unit deviation from the desired berth section for vessel $i \in V$
ϕ_{i2} : the cost of berthing one period later than the desired berthing time of vessel $i \in V$
ϕ_{i3} : the cost of using one quay crane to process vessel $i \in V$

Decision Variable used in the Mathematical Model

x_{ijt}^k : equal to 1 if vessel $i \in V$ berths at section $j \in S$ in time period $t \in T$ and $k \in K$ quay cranes are assigned to it for the whole processing time, 0 otherwise

Optimization Model

We formulate the BACAP as follows:

$$\min \sum_{i=1}^{V} \sum_{k=LB_i}^{UB_i} \sum_{j=1}^{S-l_i+1} \sum_{t=e_i}^{T-p_i^k+1} \{\phi_{i1}|j-d_i| + \phi_{i2}(t-e_i) + \phi_{i3}\, k\, p_i^k\}\, x_{ijt}^k \tag{3.1}$$

subject to

$$\sum_{j=1}^{S-l_i+1} \sum_{k=LB_i}^{UB_i} \sum_{t=e_i}^{T-p_i^k+1} x_{ijt}^k = 1 \qquad \forall\, i \in V \tag{3.2}$$

$$\sum_{i=1}^{V} \sum_{k=LB_i}^{UB_i} \sum_{t=\max(e_{i,}g-p_i^k+1)}^{\min(T-p_i^k+1,g)} \sum_{j=\max(1,f-l_i+1)}^{\min(S-l_i+1,f)} x_{ijt}^k \le 1 \qquad \forall\, g \in T, f \in S \tag{3.3}$$

$$\sum_{i=1}^{V} \sum_{k=LB_i}^{UB_i} \sum_{t=\max(e_{i,}g-p_i^k+1)}^{\min(T-p_i^k+1,g)} \sum_{j=1}^{(S-l_i+1)} k\, x_{ijt}^k \le K \qquad \forall\, g \in T \tag{3.4}$$

$$x_{ijt}^k \in \{0,1\} \qquad \forall\, i \in V, j \in \{1,\dots,S - l_i + 1\}, k \in \{UB_i \dots LB_i\},$$
$$\mathrm{t} \in \{e_i, \dots, T - p_i^k + 1\} \tag{3.5}$$

Explanation of the above formulation

As before, the objective function minimizes the total costs considered (cost for berthing far from the desired position, cost for berthing later than the expected arrival time and utilization cost of the quay cranes).

Constraint (3.2) makes sure that each vessel finds a unique berth section and berthing time; the number of quay cranes used to load or unload the containers lies between the minimum and maximum values provided.

Constraint (3.3) ensures the non overlapping of the vessels: at most one vessel can occupy a berth section in each time period.

Constraint (3.4) is related to the availability of the quay cranes at the container terminal. In particular, it is guaranteed that in each time period, the number of quay cranes utilized by the vessels being processed, does not exceed the available number of cranes.

Finally, the domain of the binary decision variable is specified.

4.4.5 Presentation of Model M4

The reference paper "Heuristics for the integration of crane productivity in the berth allocation problem" by Meisel and Bierwirth (2008) inspired the formulation of Model M4.

As in Model M3, the specific length of each vessel is taken into consideration and translated into the number of berth sections occupied in the quay. In this formulation, similarly to Model M2, the number of quay cranes which are assigned to the vessel is no more fixed during the processing time, which then becomes a decision variable. Furthermore, the formulation allows us to understand the relative position of two vessels in the quay as well as their dependency in terms of berthing time.

Parameters and Sets used in the Mathematical Model

v : the number of vessels

s : the number of berth sections

k : the number of available quay cranes

t : the number of time periods

$V = \{1 \ldots v\}$: the set of vessels

$S = \{1 \ldots s\}$: the set of berth sections

$K = \{1 \ldots k\}$: the set of available quay cranes

$T = \{1 \ldots t\}$: the set of all time periods

e_i : the arrival time for vessel $i \in V$

l_i : the length of vessel $i \in V$ expressed in number of berth sections needed

LB_i : the lower bound on the number of cranes that can be assigned to vessel $i \in V$

UB_i : the upper bound on the number of cranes that can be assigned to vessel $i \in V$

d_i : the desired berth for vessel $i \in V$

h_i : the number of quay crane hours required to process vessel $i \in V$

ϕ_{i1} : the cost of one unit deviation from the desired berth section for vessel $i \in V$

ϕ_{i2} : the cost of berthing one period later than the desired berthing time of vessel $i \in V$

ϕ_{i3} : the cost of using one quay crane to process vessel $i \in V$

Decision Variables used in the Mathematical Model

y_{it}^{k} : equal to 1 if $k \in K$ quay cranes are assigned to vessel $i \in V$ at time $t \in T$, 0 otherwise

b_i : the first berthing position of vessel $i \in V$

r_{it} : equal to 1 if at least one quay crane is assigned to vessel $i \in V$ at time $t \in T$, 0 otherwise

δ_i : the berthing time for vessel $i \in V$

γ_i : the ending time of the operations for vessel $i \in V$

z_{ij} : equal to 1 if the berthing time of vessel $j \in V$ is greater or equal than the finishing time of the operations for vessel $i \in V$, 0 otherwise

w_{ij} : equal to 1 if vessel $i \in V$ is berthed below vessel $j \in V$ in the quay, 0 otherwise

Optimization Model

We formulate the BACAP as follows:

$$\min \quad \sum_{i=1}^{V}\sum_{t=1}^{T}\sum_{k=LB_i}^{UB_i} \phi_{i1} \mid b_i - d_i \mid + \phi_{i2} \; (\delta_i - e_i) + \phi_{i3} \, k \, y_{it}^{k} \tag{4.1}$$

subject to

$$\sum_{i=1}^{V}\sum_{k=LB_i}^{UB_i} k \, y_{it}^{k} \le K \qquad \forall \, t \in T \tag{4.2}$$

$$\sum_{t=1}^{T}\sum_{k=LB_i}^{UB_i} k \, y_{it}^{k} \ge h_i \qquad \forall \, i \in V \tag{4.3}$$

$$\sum_{k=LB_i}^{UB_i} y_{it}^{k} = r_{it} \qquad \forall \, i \in V, t \in T \tag{4.4}$$

$$\sum_{t=1}^{T} r_{it} = \gamma_i - \delta_i \qquad \forall\, i \in V \tag{4.5}$$

$$\delta_i \geq e_i \qquad \forall\, i \in V \tag{4.6}$$

$$\delta_i + \sum_{t=1}^{T} \sum_{k=LB_i}^{UB_i} y_{it}^{k} \leq T \qquad \forall\, i \in V \tag{4.7}$$

$$t\ r_{it} + T(1 - r_{it}) \geq \delta_i \qquad \forall\, i \in V, t \in T \tag{4.8}$$

$$(t+1)\, r_{it} \leq \gamma_i \qquad \forall\, i \in V, t \in T \tag{4.9}$$

$$b_j + M\left(1 - w_{ij}\right) \geq b_i + l_i \qquad \forall\, i \in V, j \in V, i \neq j \tag{4.10}$$

$$\delta_j + M\left(1 - z_{ij}\right) \geq \gamma_i \qquad \forall\, i \in V, j \in V, i \neq j \tag{4.11}$$

$$w_{ij} + w_{ji} + z_{ij} + z_{ji} \geq 1 \qquad \forall\, i \in V, j \in V, i \neq j \tag{4.12}$$

$$y_{it}^{k} \in \{0,1\} \qquad \forall\, i \in V, t \in T, k \in \{UB_i \ldots LB_i\} \tag{4.13}$$

$$b_i \in \{1, \ldots S\text{-}l_i\} \qquad \forall\, i \in V \tag{4.14}$$

$$r_{it} \in \{0,1\} \qquad \forall\, i \in V, t \in T \tag{4.15}$$

$$\delta_i, \gamma_i \geq 0 \qquad \forall\, i \in V \tag{4.16}$$

$$z_{ij}, w_{ij} \in \{0,1\} \qquad \forall\, i \in V, j \in V \tag{4.17}$$

Explanation of the above formulation

As in the previous Models, the objective function minimizes the total cost.
The first part of the formulation, from Constraint (4.2) to Constraint (4.9), specifically refers to the quay-crane assignment.
Constraint (4.2) is related to the availability of the cranes at the container terminal.

In particular, it is guaranteed that in each time period, the number of quay cranes utilized by the vessels being processed, does not exceed the available number of cranes.

Constraint (4.3) ensures that the quay crane hours required by each vessel are provided.

The link between the two binary variables y_{it}^{k} and r_{it} is defined in (4.4).

Constraint (4.5) sets the processing time for each vessel as the difference from the departure time and berthing time of the vessel.

An assumption on the arrival time of the vessel is defined in Constraint (4.6): the berthing time cannot be lower than the desired value provided.

Constraint (4.7) guarantees that the operations taking place in a vessel don't end after the total available time.

Constraint (4.8) instead, guarantees that the processing hours do not precede the berthing time.

Constraint (4.9) ensures that each processing hour for a vessel doesn't go beyond the departing time of the vessel.

The last three inequalities characterize this model, taking into consideration the scheduling of the vessels, both in the time and the space dimension.

Constraint (4.10) makes sure that the space overlapping between vessels does not occur.

Constraint (4.11) avoids the vessels' overlapping in the time dimension.

Constraint (4.12) makes sure that either vessel i berths below vessel j, or viceversa and either the handling time of vessel i finishes no later than the handling time of vessel j starts, or viceversa.

Constraints (4.13)-(4.17) define the domain of the decision variables.

4.4.6 Presentation of Model M5

Model M5 has the same mathematical formulation as Model M4; however here we assume that the length of each vessel is 1. This will not change the inequalities and equations of the model, but only the values of the length parameter.

4.4.7 Presentation of Model M6

The reference paper “Heuristics for the integration of crane productivity in the berth allocation problem” by Meisel and Bierwirth (2008) inspired the formulation of Model M6.

As in the previous model, the specific length of each vessel is taken into consideration and translated into the number of berth sections occupied in the quay. In this formulation though, the number of quay cranes doesn’t change during the processing time.

Parameters and Sets used in the Mathematical Model

v : the number of vessels
s : the number of berth sections
k : the number of available quay cranes
t : the number of time periods

$V = \{1...v\}$: the set of vessels
$S = \{1...s\}$: the set of berth sections
$K = \{1...k\}$: the set of available quay cranes
$T = \{1...t\}$: the set of all time periods

e_i : the arrival time for vessel $i \in V$
l_i : the length of vessel $i \in V$ expressed in number of berth sections needed by the vessel
LB_i : the lower bound on the number of cranes that can be assigned to vessel $i \in V$
UB_i : the upper bound on the number of cranes that can be assigned to vessel $i \in V$
p_i^k: the processing time of vessel $i \in V$ if $k \in K$ quay cranes are assigned to it
d_i : the desired berth for vessel $i \in V$
ϕ_{i1} : the cost of one unit deviation from the desired berth section for vessel $i \in V$
ϕ_{i2} : the cost of berthing one period later than the desired berthing time of vessel $i \in V$
ϕ_{i3} : the cost of using one quay crane to process vessel $i \in V$

Decision Variables used in the Mathematical Model

y_{it}^{k} : equal to 1 if $k \in K$ quay cranes are assigned to vessel $i \in V$ at time $t \in T$, 0 otherwise

z_{i}^{k} : equal to1 if $k \in K$ quay cranes are assigned to vessel $i \in V$ through the processing time, 0 otherwise

b_i : the first berthing position of vessel $i \in V$

r_{it} : equal to 1 if at least one quay crane is assigned to vessel $i \in V$ at time $t \in T$, 0 otherwise

δ_i : the berthing time for vessel $i \in V$

g_{ij} : equal to 1 if the berthing time of vessel $j \in V$ is greater or equal than the finishing time of the operations for vessel $i \in V$, 0 otherwise

w_{ij} : equal to 1 if vessel $i \in V$ is berthed below vessel $j \in V$ in the quay, 0 otherwise

Optimization Model

We formulate the BACAP as follows:

$$\min \sum_{i=1}^{V} \sum_{t=1}^{T} \sum_{k=LB_i}^{UB_i} \phi_{i1} \mid b_i - d_i \mid + \phi_{i2} \; (\delta_i - e_i) + \phi_{i3} \, k \, p_i^k \tag{6.1}$$

subject to

$$\sum_{k=LB_i}^{UB_i} z_i^k = 1 \qquad \forall \, i \in V \tag{6.2}$$

$$\sum_{k=\,LB_i}^{UB_i} y_{it}^k = r_{it} \qquad \forall \, i \in V, t \in T \tag{6.3}$$

$$\sum_{t=1}^{T} r_{it} = \sum_{k=\,LB_i}^{UB_i} p_i^k z_i^k \qquad \forall \, i \in V \tag{6.4}$$

$$\sum_{i=1}^{V} \sum_{k=\,LB_i}^{UB_i} k\, y_{it}^{k} \; \leq K \qquad \forall\, t \in T \tag{6.5}$$

$$\sum_{t=1}^{T} \sum_{k=\,LB_i}^{UB_i} (k\, y_{it}^{k} - k\, p_i^{k} z_i^{k}) \; \leq \; 0 \qquad \forall\, i \in V \tag{6.6}$$

$$y_{it}^{k} \leq \; z_i^{k} \qquad \forall\, i \in V, t \in T, k \in \{UB_i \dots\, LB_i\} \tag{6.7}$$

$$\delta_i \; \geq \; e_i \qquad \forall\, i \in V \tag{6.8}$$

$$\delta_i + \sum_{k=\,LB_i}^{UB_i} p_i^{k} \; \leq T \qquad \forall\, i \in V \tag{6.9}$$

$$t\;\, r_{it} \;+ T(1 - \; r_{it}\,) \geq \; \delta_i \qquad \forall\, i \in V, t \in T \tag{6.10}$$

$$(t+1)\, r_{it} \; \leq \; \delta_i + \sum_{k=\,LB_i}^{UB_i} p_i^{k} \qquad \forall\, i \in V, t \in T \tag{6.11}$$

$$b_j + M\big(1 - w_{ij}\big) \geq \; b_i + \; l_i \qquad \forall\, i \in V, j \in V, i \; \neq j \tag{6.12}$$

$$\delta_j + M\big(1 - g_{ij}\big) \geq \; \delta_i + \sum_{k=\,LB_i}^{UB_i} p_i^{k} \qquad \forall\, i \in V, j \in V, i \; \neq j \tag{6.13}$$

$$w_{ij} + \; w_{ji} + \; g_{ij} + \; g_{ji} \; \geq 1 \qquad \forall\, i \in V, j \in V, i \; \neq j \tag{6.14}$$

$$y_{it}^{k} \in \{0,1\} \qquad \forall\, i \in V, t \in T, k \in \{UB_i \dots\, LB_i\} \tag{6.15}$$

$$z_i^{k} \in \{0,1\} \qquad \forall\, i \in V, k \in \{UB_i \dots\, LB_i\} \tag{6.16}$$

$$b_i \in \{1, \dots\, S\text{-}l_i\} \qquad \forall\, i \in V \tag{6.17}$$

$$r_{it} \in \{0,1\} \qquad \forall\, i \in V, t \in T \tag{6.18}$$

$$\delta_i \geq 0 \qquad \forall\, i \in V \tag{6.19}$$

$$g_{ij}, w_{ij} \in \{0,1\} \qquad \forall\, i \in V, j \in V \tag{6.20}$$

Explanation of the above formulation

As in all the other models, the objective function minimizes the total cost.
As in Model M4, the first part of the formulation refers mainly to the quay crane assignment.
Each ship can have just one quay crane assignment, this is guaranteed in Constraint (6.2).
The link between the two binary variables y_{it}^k and r_{it} is defined in (6.3).
Constraint (6.4) sets the processing time for each vessel as the difference from the departure time and berthing time of the vessel. In so doing, each ship i has its specific crane profile, that is to say a certain number of quay cranes k, which all operate for the processing time p_i^k.
Constraint (6.5) is related to the availability of the quay cranes at the container terminal. In particular it is guaranteed that in each time period, the number of quay cranes utilized by the vessels being processed, does not exceed the available number of cranes.
Constraint (6.6) characterizes the formulation and ensures that the number of quay cranes which process the vessel doesn't change during time.
The link between the two binary variables y_{it}^k and $z_i^k$is expressed in Constraint (6.7).
An assumption on the arrival time of the vessel is defined in Constraint (6.8): the berthing time cannot be lower than the desired value provided.
Constraint (6.9) guarantees that the operations taking place in a vessel don't end after the total available time.
Constraint (6.10) instead, guarantees that the processing hours do not precede the berthing time.
Constraint (6.11) ensures that each processing hour for a vessel doesn't go beyond the departing time of the vessel.
The last three inequalities characterize this Model and take into consideration the scheduling of the vessels both in the time and space dimension.
Constraint (6.12) makes sure that the space overlapping between vessels does not occur.

Constraint (6.13) avoids the vessels' overlapping in the time dimension.

Constraint (6.14) makes sure that either vessel i berths below vessel j, or viceversa and either the handling time of vessel i finishes no later than the handling time of vessel j starts, or viceversa.

Constraints (6.15)-(6.20) define the domain of the decision variables.

4.5 Computational Study

In the previous section, six mathematical formulations for the BACAP have been presented; subsequently, each model has been translated into the Optimization Programming Language (the code is reported in the Appendix B). Finally, in order to test the different models and get an optimal solution for the problem, computational experiments have been performed on a set of problem instances, drawn from the paper "Heuristics for the integration of crane productivity in the berth allocation problem" by Meisel and Bierwirth (2008) and adapted to this specific work.

Common data, which are provided in all the instances are:

- The number of vessels.
- The number of available quay cranes at the harbour, which is set to 10 for all the instances.
- A 1 km quay, which is divided into 20 discretized berth sections, each one 50 m long.
- A planning horizon of 168 hours (one week).
- The desired arrival time for each vessel, expressed in hours.
- The desired berthing section for each vessel.
- The minimum and maximum number of quay cranes which can process the vessel.
- The cost of one unit deviation from the desired berth, expressed in 1000 US$/unit of deviation.
- The cost of berthing later from the desired hour, expressed in 1000 US$/hour of deviation.
- The cost associated to the use of the quay-cranes, expressed in 1000 US$/quay crane hours. In particular, this cost is equal to 0,01 kUS$ for all the vessels and all the different instances tested.

Parameters that may be present or not, depending on the mathematical formulation are here reported:

- The length of the vessel, intended as the number of berth sections occupied.
- The quay crane demand of the vessel, expressed in quay crane hours.
- The processing time of each vessel which varies according to the possible number of quay cranes assigned: each value is calculated rounding up to the next integer value the ratio between the quay crane hour requirements and the real number of cranes assigned:

$$Processing\ Time = \frac{Quay\ Crane\ Hours\ _{Vessel\ i}}{Nr.of\ Quay\ Cranes\ Assigned}$$

- The time window for the availability of each berth.

4.5.1 First computational study

In the first place, the six BACAP models have been tested with a first instance of 20 vessels, whose parameters are reported in Appendix C, section C1. As specified before, not all the parameters are used in all the models.

The following Table summarizes the results obtained. In particular, for each model we specify the optimal objective value (in US$), which represents the total costs considered, the upper bound and lower bound, the percentage GAP, the root node lower bound and finally the solution time (in seconds).

Model	Optimal Objective Value [US$]	Upper Bound [US$]	Lower Bound [US$]	GAP %	Nodes	Root Node LB [US$]	Solution Time [s]
M1	4.000	4.000	4.000	0	0	2.928,2	6,57
M2	3.950	3.950	3.950	0	0	3.950	29,01
M3	17.030	17.030	17.030	0	0	16.530	18,03
M4	16.950	16.950	12.050	28,9	924.725	3.950	3.600,64
M5	3.950	3.950	3.950	0	0	3.950	3,53
M6	17.030	17.030	17.030	0	1.086	9.876,2	6,35

Table 8: results of the first computational study

Note: all the models have been tested with a time limit of 3.600 seconds.

4.5.2 Visualization of the optimal solutions found

Every solution can be visualized in a Time-Space diagram in order to clearly assess its feasibility. The 168-hours time horizon is represented in the X-axis; the Y-axis instead, reports the berth sections constituting the whole berth. In particular, we can see that for all the formulations, the vessels are not overlapping, neither in the time dimension nor in the space dimension. The real length of the ship is clearly represented for the three models which take into consideration this parameter. From a first visual comparison of the solutions found, almost all the vessels berth always at the same time and in the same berthing section.

Model M1

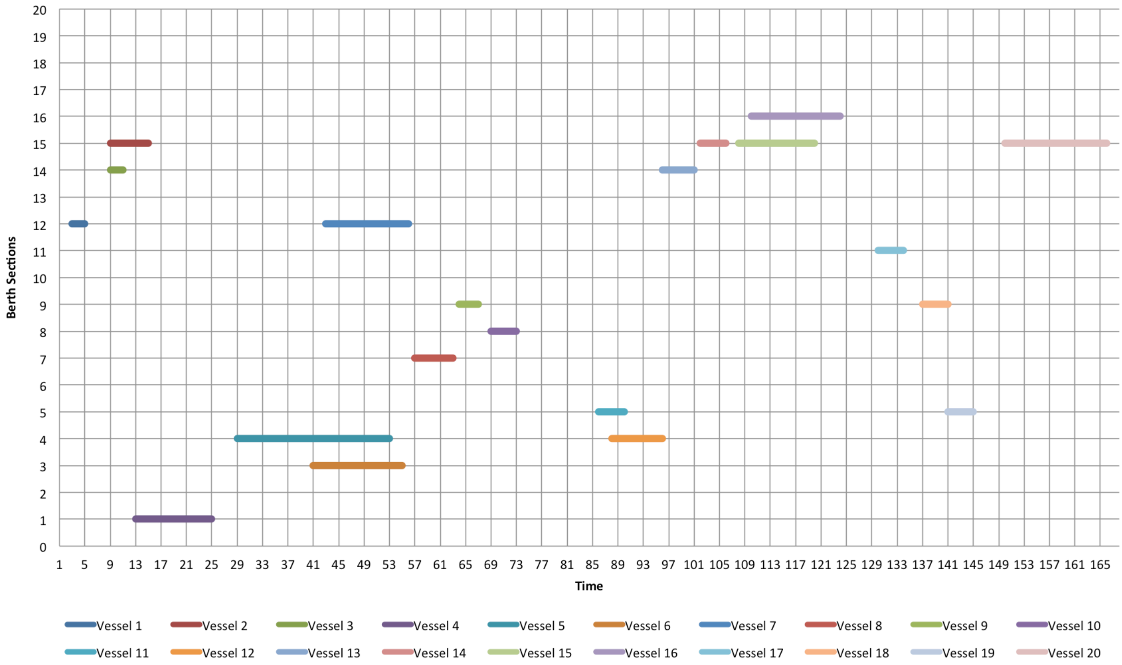


Figure 83: model M1, berth plan

Model M2

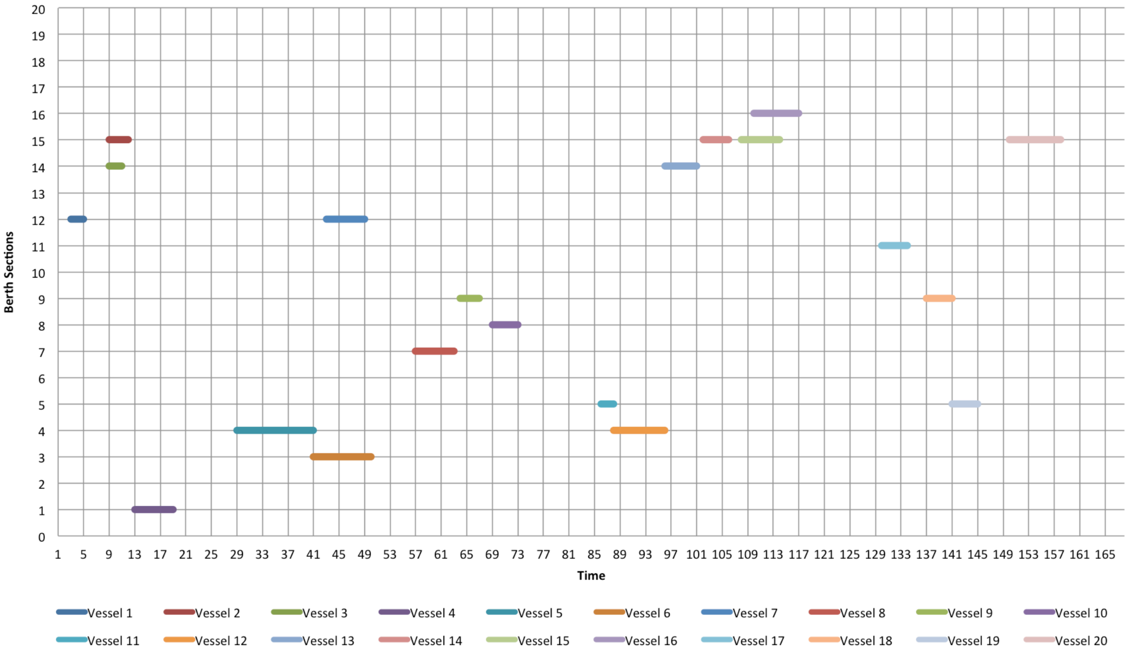


Figure 84: model M2, berth plan

Model M3

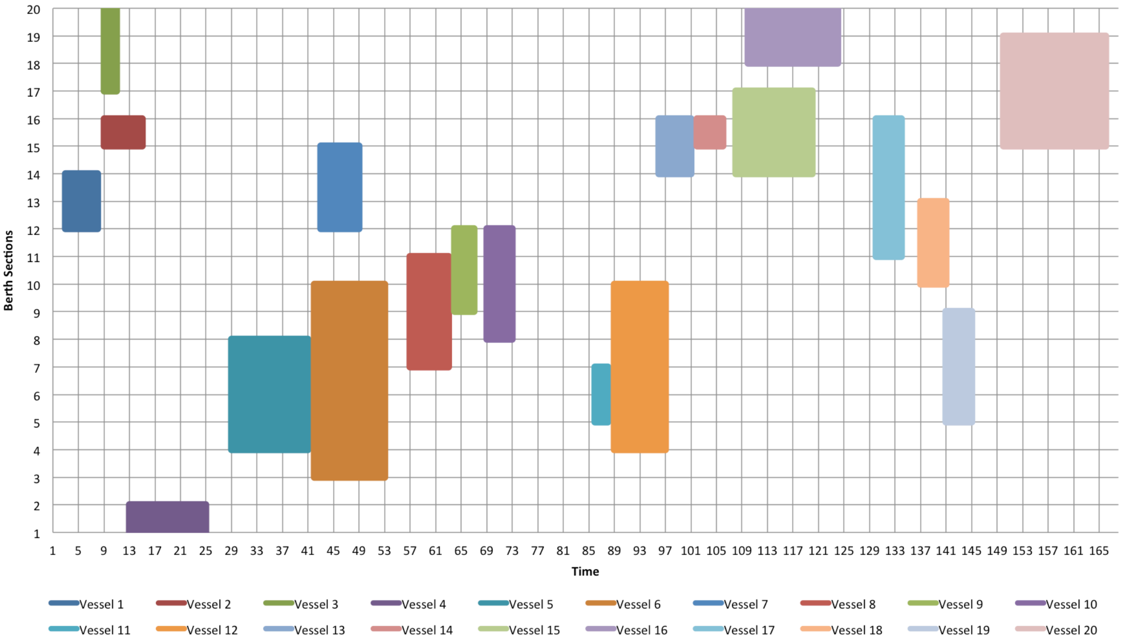


Figure 85: model M3, berth plan

Model M4

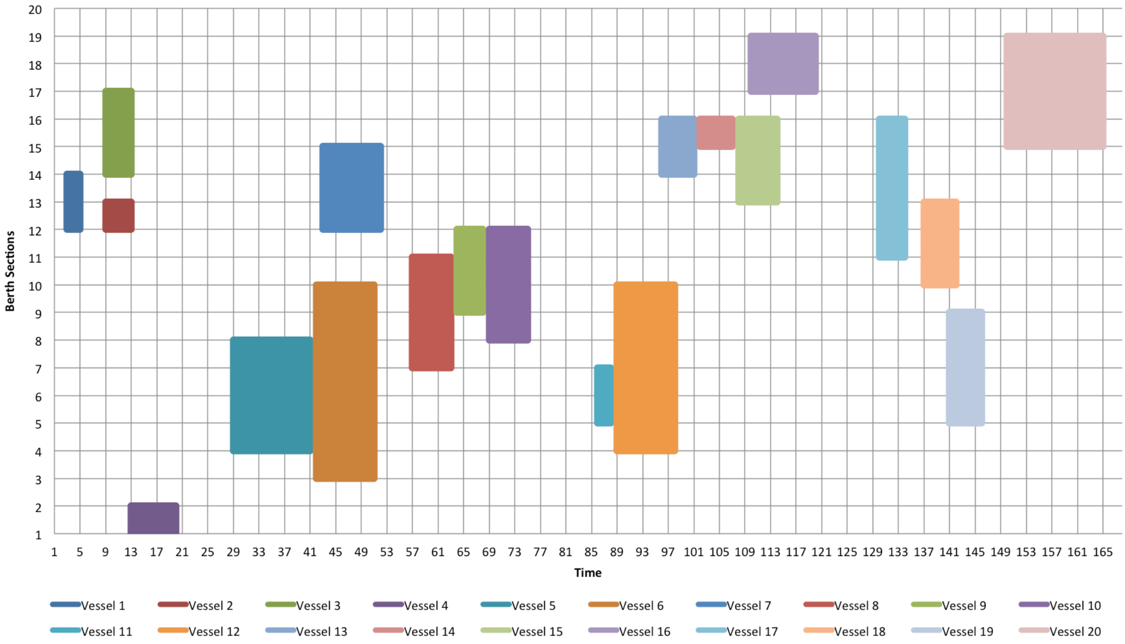


Figure 86: model M4, berth plan

Model M5

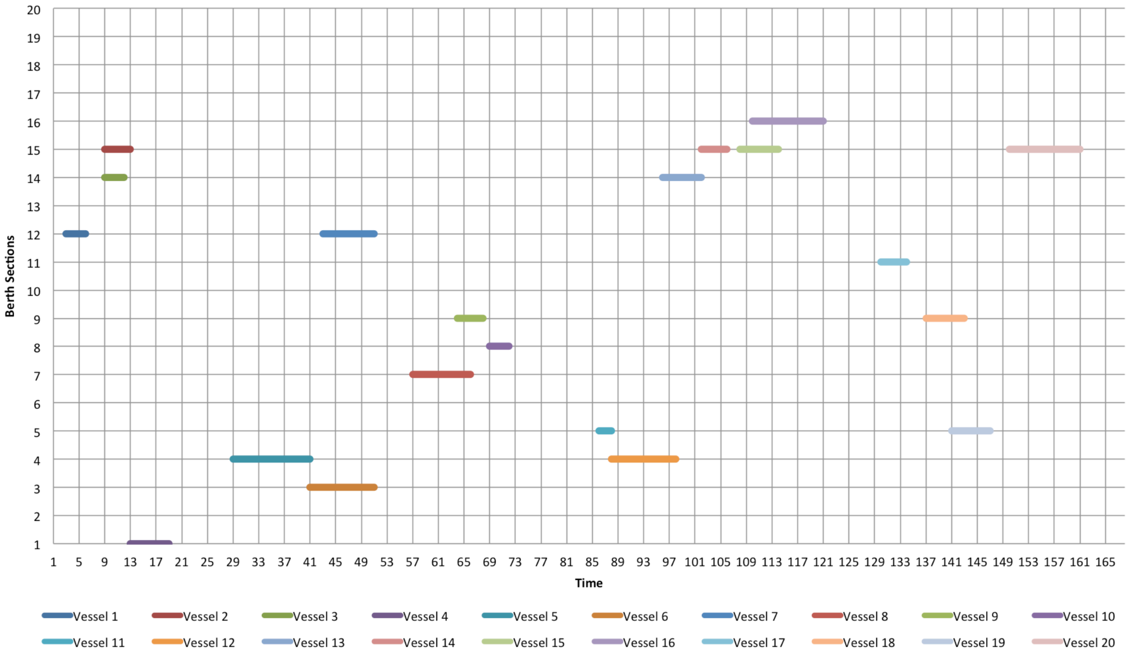


Figure 87: model M5, berth plan

Model M6

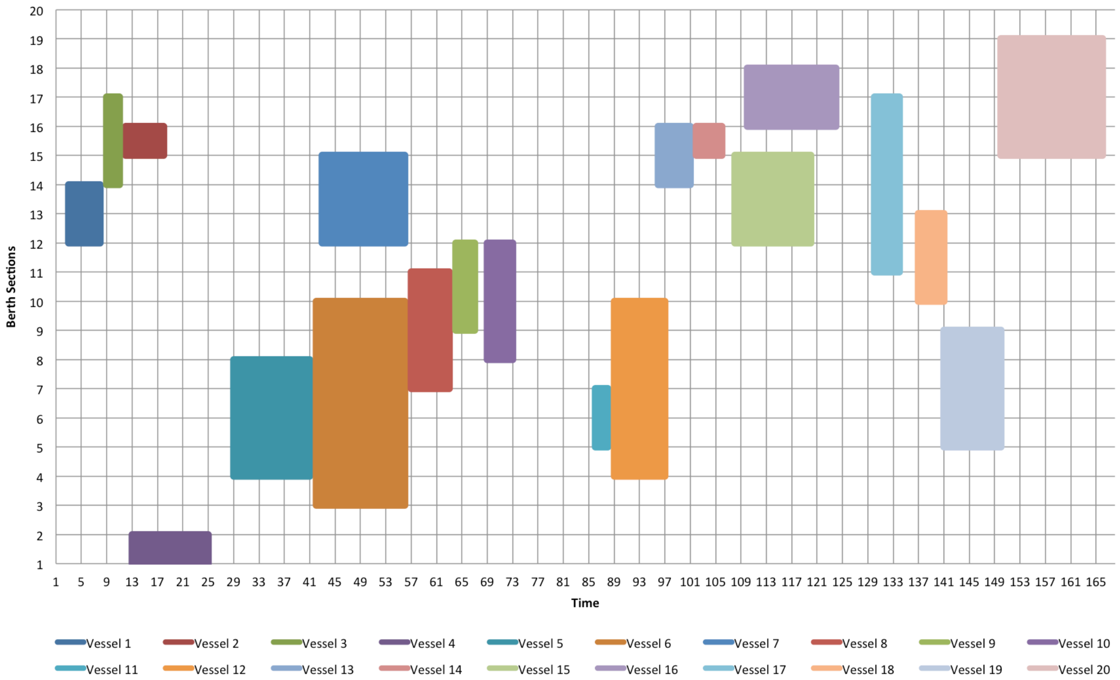


Figure 88: model M6, berth plan

4.5.3 Computational study with other instances

With the aim of examining the models' performances, we resort to 5 other set of instances where the number of vessels varies, as well as the expected arrival time, the desired berth and the minimum and maximum number of quay cranes. Other parameters distinguish each instance: the ships' length, the processing time, the quay crane requirements, the cost of deviation and the one of later berthing. The values of all the parameters are reported in the Appendix C.

The main results and information drawn from the running sessions are reported in the following Table.

	Model	Ships	Optimal Objective Value [US$]	Upper Bound [US$]	Lower Bound [US$]	GAP %	Nodes	Root Node Lower Bound [US$]	Solution Time [s]
Instance 1	M1	20	4.000	4.000	4.000	0	0	2.928,2	6,57
	M2		3.950	3.950	3.950	0	0	3.950	29,01
	M3		17.030	17.030	17.030	0	0	16.530	18,03
	M4		16.950	16.950	12.050	28,9	924.725	3.950	3.600,64
	M5		3.950	3.950	3.950	0	0	3.950	3,53
	M6		17.030	17.030	17.030	0	1.086	9.876,2	6,35

Instance 2	M1	20	5.380	5.380	5.380	0	0	3.128,8	7,57
	M2		5.330	5.330	5.330	0	3.754	4.330	25,13
	M3		36.390	36.390	36.390	0	0	33.915	25,73
	M4		-	X	22.330	-	-	4.330	3.600
	M5		5.330	5.330	5.330	0	5.881	4.330	30,47
	M6		36.390	36.390	36.390	0	3.705	3.128,8	21,14
Instance 3	M1	20	5.090	5.090	5.090	0	0	2.985,1	7,32
	M2		5.070	5.070	5.070	0	1.530	4.070	76,01
	M3		24.100	24.100	24.100	0	0	23.605	18,61
	M4		27.070	27.070	27.070	0	49.449	5.070	299,08
	M5		5.070	5.070	4.580	9,7	986.318	4.070	3.600,78
	M6		27.100	27.100	27.100	0	3.672	13.648,8	7,26
Instance 4	M1	30	6.910	6.910	6.910	0	0	4.283,2	12,51
	M2		6.780	6.780	6.780	0	191	5.780	104,1
	M3		30.040	30.040	30.040	0	0	30.033,3	24,6
	M4		-	X	9.780	-	-	6.780	3.600
	M5		6.780	6.780	6.780	0	11.330	5.780	33,41
	M6		34.040	34.040	34.040	0	4.569	5.283,2	26,2
Instance 5	M1	30	8.730	8.730	8.730	0	0	5.245,9	11,430
	M2		17.640	17.640	8.640	51	31.261	6.640	3.616,59
	M3		59.810	59.810	59.810	0	0	58.315	26,72
	M4		-	X	29.640	-	-	10.640	3.600
	M5		-	X	6.640	-	-	6.640	3.600
	M6		64.810	64.810	64.810	0	43.187	9.076,7	281,77
Instance 6	M1	30	7.340	7.340	7.340	0	0	7.204,9	13,04
	M2		7.290	7.290	7.290	0	3.305	6.290	247,27
	M3		49.430	49.430	49.430	0	17	48.520	29
	M4		-	X	24.290	-	-	6.290	3.600
	M5		7.290	7.290	6.290	13,7	951.748	6.290	3.600,9
	M6		50.430	50.430	50.430	0	16.203	4.616,3	63,90

Table 9: overall results

Note: all the Models have been tested with a time limit of 3.600 seconds.

4.5.4 Addition of valid inequalities

With the aim to ease the models’ testing, three valid inequalities have been added to the mathematical formulations. In particular, we limit our analysis just on Model 4, 5 and 6 using Instance 1.

The three valid inequalities identified are here presented:

$$\sum_{k=LB_i}^{UB_i} y_{it}^k = 0 \qquad \forall\, i \in V, t \in T, t < e_i \tag{i}$$

$$r_{it} = 0 \qquad \forall\, i \in V, t \in T, t < e_i \tag{ii}$$

$$\sum_{k=LB_i}^{UB_i} y_{it}^k \leq 1 \qquad \forall\, i \in V, t \in T \tag{iii}$$

Observing the mathematical models we can see that the starting time of the operations for each vessel cannot be lower that the expected arrival time. Therefore, we can clearly set to 0 the value of the variable y_{it}^k for all those hours which preceed the expected time of arrival of the vessel. The same considerations can be done for the variable r_{it}.

In addition to this, the third valid inequality states that each vessel can have at most one quay crane profile (number of quay cranes) in each hour.

The following table shows the new solutions obtained after adding the valid inequalities. As expected, all the values are the same apart from the number of Nodes and the solution time, whose value decreased.

Model	Optimal Objective Value [US$]	Upper Bound [US$]	Lower Bound [US$]	GAP %	Nodes	Root Node Lower Bound [US$]	Solution Time' [s]	Solution Time [s]
M4	16.950	16.950	12.050	28,9	923.179	3.950	3.600,42	3.600,64
M5	3.950	3.950	3.950	0	0	3.950	3,12	3,53
M6	17.030	17.030	17.030	0	1.086	9.876,2	6,33	6,35

Table 10: results obtained with valid inequalities

Note: all the Models have been tested with a time limit of 3.600 seconds.

4.6 Comparison of the BACAP Models and analysis of the results

This section is dedicated to a detailed analysis of the numerical results previously reported. Firstly, taking as a reference Instance 1, we compare the six BACAP models, underlying differences and similarities in the objective function, running times, quay-crane utilization etc. Secondly, taking into account all the six Instances, we perform a sensitivity analysis in order to assess how the results change, by varying the input data and parameters.

4.6.1 Comparison and analysis with a specific instance

The six BACAP models represent different formulations for the resolution of the same problem. Our aim is to understand how diverse initial assumptions impact on the output results, given the same input data. To make the analysis more structured, we identify six areas of comparison, which are presented in the tables below. According to their characteristics, each model belongs to three of these areas.

Time-invariant assignment	Variable-in-time assignment
M1	M2
M3	M4
M6	M5

Table 11: classification according to the quay crane assignment

Length 1	Specific length
M1	M3
M2	M4
M5	M6

Table 12: classification according to the vessel's length

Arc formulation	Compact formulation
M1	M3
M2	M4
	M5
	M6

Table 13: classification according to the mathematical formulation

Focusing on the models with a time-invariant assignment, that is to say a number of quay-cranes which doesn't vary during the processing time of the vessel, we can clearly see that the objective values of model M3 and M6 are the same and equal to 17.030 US$, while the total cost obtained in model M1 is much lower and equal to

4.000 US$. Breaking up these costs into their three components (cost of berthing later from the expected time of arrival, cost of berthing far from the desired berthing position and cost of using the quay-cranes) we obtain:

	M1	M3	M6
Cost of berthing later [US$]	0	6.000	6.000
Cost of deviation [US$]	0	7.000	7.000
Quay crane cost [US$]	4.000	4.030	4.030
Total cost [US$]	4.000	17.030	17.030

Table 14: total costs in US$ for model M1, M3, M6

Model M1 results show that all the vessels berth at their expected time and at the desired berth: the only costs which is taken into account is therefore the cost associated to the use of the quay-cranes. In models M3 and M6, with respect to model M1, the vessels' specific length is considered: this is the main reason of the objective value' s change. Both in model M3 and M6, ship 6 and 12 berth later than the expected time given, this arises a cost of 6.000 US$. As regards the mooring position, in both the models, 4 vessels berth far from the desired position provided and this generates a cost of 4.030 US$.

Analysing the three models with a variable number of quay cranes, we notice that the objective value is exactly the same for model M2 and model M5 (3.950 US$) being just the cost of the quay cranes used for the operations at the harbour. Model M4 instead, has a higher objective value, which takes into account two vessels that are berthing later than expected (vessel 6 and vessel 12) as well as the cost for not berthing in the desired position, calculated for 4 vessels. As before, this is due to the fact that in model M4 the length of each vessel is specified, while in the two other formulations, the length is supposed to be 1.

	M2	M4	M5
Cost of berthing later [US$]	0	6.000	0
Cost of deviation [US$]	0	7.000	0
Quay crane cost [US$]	3.950	3.950	3.950
Total cost [US$]	3.950	16.950	3.950

Table 15: total costs in US$ for model M2, M4, M5

Considering the models with vessels' length set hypothetically to 1, the objective value obtained is very similar and equal to 4.000 US$ for model M1 and 3.950 US$ for models M2 and M5. The reason for this slight difference is due to the type of quay-crane assignment: model M1 is characterized by a time-invariant assignment while models M2 and M5 has a variable-in-time assignment which gives more flexibility to the formulation and a higher potential for minimizing the number of quay cranes used. Similar considerations can be done in the specific length scenario. In those models where the number of quay cranes is fixed through the time (M3 and M6), the total cost obtained is 17.030 US$ while the cost for model M4 with a variable-in-time assignment is lower and equal to 16.950 US$.

In general, observing the results obtained for the six BACAP formulations tested with Instance 1, we can see that all the models have been solved to optimality but model 4. The latter is indeed the most complex because it considers both vessels of specific length and a variable-in-time assignment. As concerns the solution times, the quickest model to solve is model M5 with a compact formulation, variable number of quay cranes and vessels of length 1. Models M1 and M6, both with a time-invariant assignment have a comparable time of 6 seconds approximately; model M4 instead, would have required more than 1 hour to be solved to optimality.

4.6.2 Comparison and analysis amongst all the Instances

In order to inspect the robustness of the models, we tested them with other Instances of different complexity. As we can see from the table of the results provided, models M2 and M5 provide the same optimal objective value, for all the Instances but the fifth one. The same consideration is done for Models M3 and M6 tested with Instance 1 and 2.

Model M4 presents indeed the most critical formulation: with a time limit of 1 hour, the model is solved to optimality just with Instance 3, in the starting scenario a solution is found but not necessarily the optimal one, while in all the other scenarios no solution is provided in the time window considered.

Similar considerations can be done for model M5, which is solved to optimality with just 3 of the 6 instances considered.

Instance 5 is the most critical as 3 out of 6 models are not solved to optimality and 2 of them don't get an upper bound in the time limit imposed of 3.600 seconds.

Conclusions

This Thesis provides a comprehensive study of the container shipping industry and the main planning problems that container terminals have to face.

The major logistic criticalities, which characterize the different areas of a container terminal, have been detailed and possible solutions explained. Furthermore, this work provides an outline of the major managerial decisions that container terminal managers are responsible for. Technicalities about different types of vessels, containers and handling equipment are also presented.

As regards planning problems in particular, the specific integrated problem known as Berth Allocation with Quay Crane Assignment Problem, has been analysed in details from a logistic and mathematical point of view. Six different formulations have been presented, translated into the Optimization Programming Language and tested with various instances representing realistic scenarios. All the six models aim at finding a feasible berth plan and quay crane - to - vessel assignment to all the vessels which are planned to arrive at the harbour in a time horizon of one week. This is indeed one of the most common logistic decisions that container terminal managers have to take, decision which is nowadays supported by IT systems, e.g. Container Terminal Management Systems. The common objective function aims at minimizing the sum of the following 3 costs: cost for berthing later than the expected time of arrival provided, the operational cost which arises when using the quay cranes and the cost for berthing far from the desired position. Maintaining the same logistic constraints, the six formulations differ from a mathematical point of view in terms of different decision variables. Different assumptions are also presented: some models consider vessels of hypothetical length 1, some others consider the real length of the vessels, expressed in berth sections occupied; as concerns the assignment of the quay cranes, some models assume that the same number of cranes is used during the whole processing time while some others allow this number to vary. In a realistic context, these assumptions might reflect planning and logistic decisions of terminal managers.

Having tested the models with the optimization software IBM® ILOG® CPLEX® Optimization Studio, one of the main goals was to understand how the output varies according to the input formulation.

Working with the first instance, which considers a scenario of 20 vessels, we can assert that the six models are basically equivalent since the berthing time and position is the same for almost all the ships. Observing the value of the objective functions, which represent the total costs realised, a major difference can be identified when considering vessels of length 1 or vessels with their real length. Models where a realistic length is considered, are indeed more complex, thus it becomes more difficult to accommodate shipping lines requests of desired berthing time and berthing position. In turn, this makes penalty costs rise up.

Overall, the six models offer realistic solutions to the integrated problem of Berth Allocation and Quay Crane Assignment. The main contribution to the Literature is given by the development of new formulations whose objective function is based on the minimization of penalty and operational costs, specifically combined for this work. Resorting to Operations Research methods, which support the optimization of this specific decision is fundamental.

The logistic improvement assessed is mainly related to a more efficient berth and quay cranes usage. In details, an optimal berth plan, with vessels that do not overlap neither in the space nor in the time dimension, avoids congestions at the seaside. On the other hand, the assignment of an optimal and minimum number of handling equipment to the vessels berthed, makes sure that more quay cranes are available at the terminal in the different time slots. Pertaining to the two penalty costs considered (cost for berthing later than planned and far from the desired position), other types of improvements can be identified. The mathematical models proposed aim at ensuring that all the ships berth at the desired time expressed by the shipping line: in turn, this avoids delays at the subsequent calling ports, vessel's rescheduling and congestions. In addition to this, shipping lines specifies a preferred berthing position which is usually close to the dedicated yard areas for import and export containers. The formulations proposed penalize apart berthing positions: making sure that each ship moors at the planned section, minimizes the workload of horizontal transport means.

In conclusion, the six BACAP models proposed represent a good reference for planning berthing operations and quay crane assignment at container terminals with medium container traffic. Another topic of future research may deal with the development of even more robust models, which can solve larger instances of the Berth Allocation with Quay Crane Assignment Problem.

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APPENDIX A

Abbreviations used in CTMS reports

Abbreviation	Explanation
A/C	Account Number
AGT	Vessel Agent
BAL	Balance
BTH NO	Berth Number
CAT	Container Category
COND	Container Condition
DG	Dangerous Good Container
DISC	Discharge
DTE/SHFT	Date/Shift
EQPT	Equipment
ETB	Estimated Time of Berthing
ETC	Estimated Time of Completion
GRT	Gross Registered Tonnage
HT	Height
LDG	Loading
LDG	Loading
LOA	Vessel Length Overall
OCCP	Occupied
OP	Container Operator
OPRNS	Operations
OPTR	Operator
OTH-SP-DTL	Other Special Details
PDISC	Port of Discharge
PLOAD	Port of Loading
PM	Prime Mover
PREV MAINT	Preventive Maintenance
RF	Reefer Container

ST	Container Status
STOW CAT	Stowage Category
SZ	Container Size
TA	Traffic Assistant
VSL/VOY	Vessel/Voyage
WC	Weight Class
WM FR	Wharf Mark From
WM TO	Wharf Mark To
YD BLK	Yard Block

APPENDIX B
OPL Code for the Mathematical Models

B.1 Model M1

```
/* Parameters and Sets */
int v = ...;
int s = ...;
int k = ...;
int t = ...;
int M = 10000;
int N = 10;
float temp;
range Vessels = 1..v;
range Berths = 1..s;
range AvQCs = 1..k;
range Periods = 1..t;
range Vertices = 1..v+s+s;
int ArrivalTime[Vessels] = ...;
int DesiredBerth[Vessels] = ...;
int LB[Vessels] = ...;
int UB[Vessels] = ...;
int StartingB[Berths] =. ..;
int EndingB[Berths] = ...;
int PTime[Vessels][AvQCs] = ...;
int CostDeviation[Vessels] = ...;
int CostBLater[Vessels] = ..;
float CostQC[Vessels] = ...;
tuple SchedVessels {
  int firstVessel;
  int nextVessel;
```

```
int berth;
};
{SchedVessels} ScheduleVessels = {<i,j,z> |i, j in Vertices, z in Berths};

/* Decision Variables */
dvar boolean x[ScheduleVessels][Berths];
dvar boolean y[Vessels][Periods][AvQCs];
dvar boolean z[Vessels][AvQCs];
dvar boolean w[Vessels][Berths];
dvar boolean r[Vessels][Periods];
dvar int+ a[Vessels];
dvar int+ ao[Berths];
dvar int+ ad[Berths];

execute CPLEX_PARAM
{
  var before = new Date();
  temp = before.getTime();
}

/* The Model */
minimize
        (sum(i in Vessels, k in (LB[i]..UB[i]), t in Periods) (CostQC[i]*k*y[i][t][k])+
        sum(i in Vessels, b in Berths) (CostDeviation[i]*(abs(b-DesiredBerth[i]))*w[i][b])
        + sum(i in Vessels) (CostBLater[i]*(a[i]-ArrivalTime[i])));

subject to
{
/* 1.2 */
        forall(i in Vessels)
        sum(z in Berths) w[i][z] == 1;
/* 1.3 */
        forall(z in Berths, i in Vessels)
        sum(a in ScheduleVessels: a.firstVessel == i &&
        (a.nextVessel <= v || a.nextVessel == v+s+z) && a.berth == z) x[a][z] == w[i][z]
```

```
/* 1.4 */
        forall(z in Berths)
        sum(a in ScheduleVessels: a.firstVessel == v+z &&
        (a.nextVessel <= v ll a.nextVessel == v+s+z) && a.berth == z) x[a][z] == 1;
/* 1.5 */
        forall(z in Berths)
        sum(a in ScheduleVessels: (a.firstVessel <= v ll a.firstVessel == v+z) &&
        a.nextVessel == v+s+z && a.berth == z) x[a][z] == 1;
/* 1.6 */
        forall(z in Berths, i in Vessels)
        sum(a in ScheduleVessels: (a.firstVessel <= v ll a.firstVessel == v+z) &&
        a.nextVessel == i && a.berth == z) x[a][z] ==
        sum(a in ScheduleVessels: a.firstVessel == i &&
        (a.nextVessel <= v ll a.nextVessel == v+s+z) && a.berth == z) x[a][z];
/* 1.7 */
        forall(i in Vessels)
        sum(k in (LB[i]..UB[i])) z[i][k] == 1;
/* 1.8 */
        forall(i in Vessels, t in Periods)
        sum(k in (LB[i]..UB[i])) y[i][t][k] == r[i][t];
/* 1.9 */
        forall(i in Vessels)
        sum(t in Periods) r[i][t] == sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k];
/* 1.10 */
        forall(t in Periods)
        sum(i in Vessels, k in (LB[i]..UB[i])) k*y[i][t][k] <= N;
/* 1.11 */
        forall(i in Vessels)
        sum(t in Periods, k in (LB[i]..UB[i])) (k*y[i][t][k] - k*PTime[i][k]*z[i][k]) <= 0;
/* 1.12 */
        forall(i in Vessels,t in Periods, k in (LB[i]..UB[i]))
        y[i][t][k] <= z[i][k];
/* 1.13 */
        forall(i in Vessels)
        a[i] >= ArrivalTime[i];
```

```
/* 1.14 */
        forall(i in Vessels)
        a[i] + sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k] <= T;
/* 1.15 */
        forall (i in Vessels, t in Periods)
        t*r[i][t] + T*(1-r[i][t]) >= a[i];
/* 1.16 */
        forall(i in Vessels, t in Periods) (t+1)*r[i][t] <=
        a[i]+ sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k];
/* 1.17 */
        forall(i,j in Vessels, b in Berths, r in ScheduleVessels:
        r.firstVessel == i && r.nextVessel == j  && r.berth == b)
        sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k] <= - a[i] + a[j] + (1-x[r][b])*M;
        forall(b in Berths, r in ScheduleVessels, i in Vessels:
        r.nextVessel == v+s+b && r.berth == b)
        a[i] + sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k] - ad[b] <= (1-x[r][b])*M;
/* 1.18 */
        forall(z in Berths, r in ScheduleVessels, i in Vessels:
        r.firstVessel == v+z && r.berth == z) ao[z] - a[i] <= (1-x[r][z])*M;
/* 1.19 */
        forall(z in Berths)
        StartingB[k] <= ao[z];
/* 1.20 */
        forall(z in Berths)
        ad[z] <= EndingB[z];
}

/* Execute Blocks */
execute WriteSolution
{
  writeln("Optimal Value: ", cplex.getObjValue());
  writeln("Solution Time: ", cplex.getCplexTime());
  writeln("Nodes: ", cplex.getNnodes());
  writeln("Nodes Left: ", cplex.getNnodesLeft());
  writeln("Status: ", cplex.getCplexStatus());
```

```
}
execute
{
  var c, i;
  var after = new Date();
  writeln("solving time ~= ",after.getTime()-temp);
}
execute ShowSolution
 {
   var i;
   var j;
   var k;
   for(i in Vessels)
   for(j in Berths)
   for(k in AvQCs)
   {
       if(z[i][k] > 0)
       {
         if(w[i][j]>0)
         {
           if(a[i]>0)
           {
           writeln("Ship ", i, " berths in section ", j,
           " at time ", a[i], " and is processed by ", k,
           " quay cranes. The ship has a processing time of ", PTime[i][k], " hours." );
       }
    }
 }
}
}
```

B.2 Model M2

```
/* Parameters and Sets */
int v = ...;
```

```
int s = ...;
int k = ...;
int t = ...;
int M = 10000;
int N = 10;
int T = 168;
float temp;
range Vessels = 1..v;
range Berths = 1..s;
range AvQCs = 1..k;
range Periods = 1..t;
range Vertices = 1..v+s+s;
int ArrivalTime[Vessels] = ...;
int DesiredBerth[Vessels] = ...;
int StartingB[Berths] = ...;
int EndingB[Berths] = ...;
int LB[Vessels] = ...;
int UB[Vessels] = ...;
int CostDeviation[Vessels] = ...;
int CostBLater[Vessels] = ...;
float CostQC[Vessels] = ...;
int QCHours[Vessels] = ...;
tuple SchedVessels {
  int firstVessel;
  int nextVessel;
  int berth;
};
{SchedVessels} ScheduleVessels = {<i,j,k> | i,j in Vertices,k in Berths: (i!=j) &&
<i,j>!=<j,i>};

/* Decision Variables */
dvar boolean x[ScheduleVessels][Berths];
dvar boolean y[Vessels][Periods][AvQCs];
dvar boolean w[Vessels][Berths];
dvar boolean r[Vessels][Periods];
```

```
dvar int+ a[Vessels];
dvar int+ d[Vessels];
dvar int+ ao[Berths];
dvar int+ ad[Berths];

execute CPLEX_PARAM
{
  var before = new Date();
  temp = before.getTime();
}

/* The Model */
minimize
        (sum(i in Vessels, k in (LB[i]..UB[i]),t in Periods) (CostQC[i]*k*y[i][t][k])
        +sum(i in Vessels, z in Berths) (CostDeviation[i]*(abs(z-DesiredBerth[i]))*w[i][z])
        + sum(i in Vessels) (CostBLater[i]*(a[i]-ArrivalTime[i])));

subject to
{
/* 2.2 */
        forall(i in Vessels)
        sum( z in Berths) w[i][z] == 1;
/* 2.3 */
        forall(z in Berths, i in Vessels)
        sum(a in ScheduleVessels: a.firstVessel == i &&
        (a.nextVessel <= v || a.nextVessel == v+s+z) && a.berth == z) x[a][z] == w[i][z];
/* 2.4 */
        forall(z in Berths)
        sum(a in ScheduleVessels: a.firstVessel == v+z &&
        (a.nextVessel <= v || a.nextVessel == v+s+z) && a.berth == z) x[a][z] == 1;
/* 2.5 */
        forall(z in Berths)
        sum(a in ScheduleVessels: (a.firstVessel <= v || a.firstVessel == v+z) &&
        a.nextVessel == v+s+z && a.berth == z) x[a][z] == 1;
/* 2.6 */
```

```
        forall(z in Berths, i in Vessels)
        sum(a in ScheduleVessels: (a.firstVessel <= v || a.firstVessel == v+z) &&
        a.nextVessel == i && a.berth == z) x[a][z] ==
        sum(a in ScheduleVessels: a.firstVessel == i &&
        (a.nextVessel <= v || a.nextVessel == v+s+z) && a.berth == z) x[a][z];
/* 2.7 */
        forall(i in Vessels, t in Periods)
        sum(k in (LB[i]..UB[i])) y[i][t][k] == r[i][t];
/* 2.8 */
        forall(i in Vessels)
        sum(t in Periods) r[i][t] == d[i]-a[i];
/* 2.9 */
        forall(t in Periods)
        sum(i in Vessels, k in (LB[i]..UB[i])) k*y[i][t][k] <= N;
/* 2.10 */
        forall(i in Vessels)
        sum(k in (LB[i]..UB[i]), t in Periods) k*y[i][t][k] >= QCHours[i];
/* 2.11 */
        forall(i in Vessels)
        a[i] >= ArrivalTime[i];
/* 2.12 */
        forall(i in Vessels)
        a[i] + sum(t in Periods,k in (LB[i]..UB[i])) y[i][t][k] <= T;
/* 2.13 */
        forall(i in Vessels, t in Periods)
        t*r[i][t] + T*(1-r[i][t]) >= a[i];
/* 2.14 */
        forall(t in Periods, i in Vessels)
        (t+1)*r[i][t] <= d[i];

/* 2.15 */
        forall(i,j in Vessels, z in Berths, r in ScheduleVessels:
        r.firstVessel == i && r.nextVessel == j  && r.berth == z)
        sum(t in Periods,k in (LB[i]..UB[i])) y[i][t][k] <= - a[i] + a[j] + (1-x[r][z])*M;
        forall(z in Berths, r in ScheduleVessels, i in Vessels:
```

```
            r.nextVessel == v+s+z && r.berth == z)
            a[i] + sum(t in Periods,k in (LB[i]..UB[i])) y[i][t][k] - ad[z]  <= (1-x[r][z])*M;
/* 2.16 */
            forall(z in Berths, r in ScheduleVessels, i in Vessels:
            r.firstVessel == v+z && r.berth == z) ao[z] - a[i] <= (1-x[r][z])*M;
/* 2.17 */
            forall(z in Berths)
            StartingB[k] <= ao[z];
/* 2.18 */
            forall(z in Berths)
            ad[z] <= EndingB[z];
}

/* Execute Blocks */
execute WriteSolution
{
  writeln("Optimal Value: ", cplex.getObjValue());
  writeln("Solution Time: ", cplex.getCplexTime());
  writeln("Nodes: ", cplex.getNnodes());
  writeln("Nodes Left: ", cplex.getNnodesLeft());
  writeln("Status: ", cplex.getCplexStatus());
}
execute
{
  var c, i;
  var after = new Date();
  writeln("solving time ~= ",after.getTime()-temp);
}
execute ShowSolution
 {
   var i;
   var j;
   for(i in Vessels)
   for(j in Berths)
   {
```

```
      if(w[i][j] > 0)
      {
        if(a[i]>0)
        {
          if(d[i]>0)
          {
          writeln("Ship ", i, " berths in section ", j,
          " at time ", a[i], ". The ship has a processing time of ",
          (d[i]-a[i]), " hours." );
      }
    }
  }
}
}
```

B.3 Model M3

```
/* Parameters and Sets */
int v = ...;
int s = ...;
int k = ...;
int t = ...;
int N = 10;
int S = 20;
int T = 168;
float temp;
range Vessels = 1..v;
range Sections = 1..s;
range AvQCs = 1..k;
range Periods = 1..t;
int ArrivalTime [Vessels] = ...;
int LB[Vessels] = ...;
int UB[Vessels] = ...;
int Length[Vessels] = ...;
int PTime[Vessels][AvQCs] = ...;
```

```
int DesiredBerth[Vessels] = ...;
int CostDeviation[Vessels] = ...;
int CostBLater[Vessels] = ...;
float CostQC[Vessels] = ...;

/* Decision Variable */
dvar boolean x[Vessels][Sections][Periods][AvQCs];

execute CPLEX_PARAM
{
  var before = new Date();
  temp = before.getTime();
}

/* The Model */
minimize
          (sum(i in Vessels,k in (LB[i]..UB[i]),j in (1..(S-Length[i]+1)),
          t in (ArrivalTime[i]..(T-PTime[i][k]+1)))
          ((CostDeviation[i]*(abs(j-DesiredBerth[i]))+ CostBLater[i]*(t-ArrivalTime[i])+
          CostQC[i]*k*PTime[i][k])*x[i][j][t][k]));

subject to
{
          forall(i in Vessels, j in Sections, t in Periods, k in AvQCs: j>(S-Length[i]+1) ||
          t > (T - PTime[i][k] +1) || t < ArrivalTime[i] || k < LB[i] || k > UB[i]) x[i][j][t][k] == 0;
/* 3.2 */
          forall(i in Vessels)
          sum(j in (1..(S-Length[i]+1)), k in (LB[i]..UB[i]),
          t in (ArrivalTime[i]..(T-PTime[i][k]+1))) x[i][j][t][k] == 1;
/* 3.3 */
          forall(a in Sections, b in Periods)
          sum(i in Vessels, j in ((maxl(1,a-Length[i]+1))..(minl(S-Length[i]+1,a))),
          k in (LB[i]..UB[i]),
          t in ((maxl(ArrivalTime[i],b-PTime[i][k]+1))..(minl(T-PTime[i][k]+1,b))))
          x[i][j][t][k] <= 1;
```

```
/* 3.4 */
            forall(b in Periods)
            sum(i in Vessels,j in (1..(S-Length[i]+1)),k in (LB[i]..UB[i]),
            t in ((maxl(ArrivalTime[i],b-PTime[i][k]+1))..(minl(T-PTime[i][k]+1,b))))
            k*x[i][j][t][k] <= N;
}

/* Execute Block */
execute WriteSolution
{
  writeln("Optimal Value: ", cplex.getObjValue());
  writeln("Solution Time: ", cplex.getCplexTime());
  writeln("Nodes: ", cplex.getNnodes());
  writeln("Nodes Left: ", cplex.getNnodesLeft());
  writeln("Status: ", cplex.getCplexStatus());
}
execute
{
  var c, i;
  var after = new Date();
  writeln("solving time ~= ",after.getTime()-temp);
}
execute ShowSolution
 {
   var i;
   var j;
   var k;
   var t;
   for(i in Vessels)
   for(j in Sections)
   for(t in Periods)
   for(k in AvQCs)
   {
       if(x[i][j][t][k] > 0)
       {
```

```
      writeln("Ship ", i, " berths in section ", j, " at time ", t,
      " and is processed by ", k," quay cranes. The ship has a processing time of "
      PTime[i][k], " hours");
     }
   }
 }
```

B.4 Model M4 and Model M5

```
/* Parameters and Sets */
int v = ...;
int s = ...;
int k = ...;
int t = ...;
int M = 10000;
int N = 10;
int S = 20;
int T = 168;
float temp;
range Vessels = 1..v;
range AvQCs = 1..k;
range Periods = 1..t;
range Berths = 1..s;
int ArrivalTime [Vessels] = ...;
int Length[Vessels] = ...;
int LB[Vessels] = ...;
int UB[Vessels] = ...;
int QCHours[Vessels] = ...;
int DesiredBerth[Vessels] = ...;
int CostDeviation[Vessels] = ...;
int CostBLater[Vessels] = ...;
float CostQC[Vessels] = ...;

/* Decision Variables */
dvar boolean y[Vessels][Periods][AvQCs];
```

```
dvar int+ b[Vessels];
dvar boolean r[Vessels][Periods];
dvar int+ z[Vessels];
dvar int+ w[Vessels];
dvar boolean f[Vessels][Vessels];
dvar boolean c[Vessels][Vessels];

execute CPLEX_PARAM
{
  var before = new Date();
  temp = before.getTime();
}

/* The Model */
minimize
        (sum(i in Vessels,k in (LB[i]..UB[i]),t in Periods) (CostQC[i]*k*y[i][t][k])
        +sum(i in Vessels) (CostDeviation[i]*abs(b[i]-DesiredBerth[i]))
        +sum(i in Vessels) (CostBLater[i]*(z[i]-ArrivalTime[i])));

subject to
{
/* 4.2 */
        forall(t in Periods)
        sum(i in Vessels,k in (LB[i]..UB[i])) k*y[i][t][k] <= N;
/* 4.3 */
        forall(i in Vessels)
        sum(k in (LB[i]..UB[i]), t in Periods) k*y[i][t][k] >= QCHours[i];
/* 4.4 */
        forall(i in Vessels, t in Periods)
        sum(k in (LB[i]..UB[i])) y[i][t][k] == r[i][t];
/* 4.5 */
        forall(i in Vessels)
        sum(t in Periods) r[i][t] == w[i]-z[i];
/* 4.6 */
        forall(i in Vessels)
```

```
            z[i] >= ArrivalTime[i];
/* 4.7 */
            forall(i in Vessels)
            z[i] + sum(t in Periods,k in (LB[i]..UB[i])) y[i][t][k] <= T;
/* 4.8 */
            forall(i in Vessels, t in Periods)
            t*r[i][t] + T*(1-r[i][t]) >= z[i];
/* 4.9 */
            forall(t in Periods, i in Vessels)
            (t+1)*r[i][t] <= w[i];
/* 4.10 */
            forall(i in Vessels, p in Vessels: i !=p)
            b[p] + M*(1-f[i][p]) >= b[i] + Length[i];
/* 4.11 */
            forall(i in Vessels, p in Vessels: i !=p)
            z[p] + M*(1-c[i][p]) >= w[i];
/* 4.12 */
            forall(i in Vessels, p in Vessels: i !=p)
            f[i][p] + f[p][i] + c[i][p] + c[p][i] >= 1;
/* 4.14 */
            forall(i in Vessels)
            b[i] <= S-Length[i];
 }

/* Execute Blocks */
execute WriteSolution
{
  writeln("Optimal Value: ", cplex.getObjValue());
  writeln("Solution Time: ", cplex.getCplexTime());
  writeln("Nodes: ", cplex.getNnodes());
  writeln("Nodes Left: ", cplex.getNnodesLeft());
  writeln("Status: ", cplex.getCplexStatus());
}
execute
{
```

```
  var c, i;
  var after = new Date();
  writeln("solving time ~= ",after.getTime()-temp);
}
execute ShowSolution
 {
   var i;
   for(i in Vessels)
   {
       if(b[i] > 0)
       {
         if(w[i]>0)
         {
           if(z[i]>0)
           {
           writeln("Ship ", i, " berths in section ", b[i],
           " at time ", z[i], ". The ship has a processing time of ",
           (w[i]-z[i]), " hours." );
       }
    }
 }
}
}
```

B.5 Model M6

```
/* Parameters and Sets */
int v = ...;
int s = ...;
int k = ...;
int t = ...;
int M = 10000;
int N = 10;
int S = 20;
int T = 168;
```

```
float temp;
range Vessels = 1..v;
range AvQCs = 1..k;
range Periods = 1..t;
int ArrivalTime [Vessels]=...;
int Length[Vessels]=...;
int PTime[Vessels][AvQCs]=...;
int LB[Vessels]=...;
int UB[Vessels]=...;
int DesiredBerth[Vessels]=...;
int CostDeviation[Vessels]=...;
int CostBLater[Vessels]=...;
float CostQC[Vessels]=...;

/* Decision Variables */
dvar boolean y[Vessels][Periods][AvQCs];
dvar boolean z[Vessels][AvQCs];
dvar int+ b[Vessels];
dvar boolean r[Vessels][Periods];
dvar int+ aTime[Vessels];
dvar boolean f[Vessels][Vessels];
dvar boolean c[Vessels][Vessels];

execute CPLEX_PARAM
{
  var before = new Date();
  temp = before.getTime();
}

/* The Model */
minimize
        (sum(i in Vessels) (CostDeviation[i]*(abs(b[i]-DesiredBerth[i])))
        +sum(i in Vessels) (CostBLater[i]*(aTime[i]-ArrivalTime[i]))
        +sum(i in Vessels, k in (LB[i]..UB[i]), t in Periods) (CostQC[i]*k*y[i][t][k]));
```

```
subject to
{
/* 6.2 */
        forall(i in Vessels)
        sum(k in (LB[i]..UB[i])) z[i][k] == 1;
/* 6.3 */
        forall(i in Vessels, t in Periods)
        sum(k in (LB[i]..UB[i])) y[i][t][k] == r[i][t];
/* 6.4 */
        forall(i in Vessels)
        sum(t in Periods) r[i][t] == sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k];
/* 6.5 */
        forall(t in Periods)
        sum(i in Vessels, k in (LB[i]..UB[i])) k*y[i][t][k] <= N;
/* 6.6 */
        forall(i in Vessels)
        sum(t in Periods, k in (LB[i]..UB[i])) (k*y[i][t][k] - k*PTime[i][k]*z[i][k]) <= 0;
/* 6.7 */
        forall(i in Vessels,t in Periods, k in (LB[i]..UB[i]))
        y[i][t][k] <= z[i][k];
/* 6.8 */
        forall(i in Vessels)
        aTime[i] >= ArrivalTime[i];
/* 6.9 */
        forall(i in Vessels)
        aTime[i] + sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k] <= T;

/* 6.10 */
        forall (i in Vessels, t in Periods)
        t*r[i][t] + T*(1-r[i][t]) >= aTime[i];
/* 6.11 */
        forall(i in Vessels, t in Periods)
        (t+1)*r[i][t] <= aTime[i] + sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k];
/* 6.12 */
        forall(i in Vessels, p in Vessels: i !=p)
```

```
            b[p] + M*(1-f[i][p]) >= b[i] + Length[i];
/* 6.13 */
            forall(i in Vessels, p in Vessels: i !=p)
            aTime[p] + M*(1-c[i][p]) >= aTime[i] + sum(k in (LB[i]..UB[i])) PTime[i][k]*z[i][k];
/* 6.14 */
            forall(i in Vessels, p in Vessels: i !=p)
            f[i][p] + f[p][i] + c[i][p] + c[p][i] >= 1;
/* 6.17 */
            forall(i in Vessels)
            b[i] <= S-Length[i];
}

/* Execute Blocks */
execute
{
  var c, i;
  var after = new Date();
  writeln("solving time ~= ",after.getTime()-temp);
}
execute ShowSolution
 {
   var i;
   var k;
   for(i in Vessels)
   for(k in AvQCs)
   {
       if(b[i] > 0)
       {
         if(z[i][k]>0)
         {
           if(aTime[i]>0)
           {
           writeln("Ship ", i, " berths in section ", b[i],
           " at time ", aTime[i], " and is processed by ", k,
           " quay cranes. The ship has a processing time of ",
```

```
            PTime[i][k], " hours." );
        }
    }
 }
}
}
```

APPENDIX C
Instances

C1. Instance 1

v = 20;

s = 20;

k = 10;

t = 168;

StartingB = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0];

EndingB = [168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168];

```
PTime =  [[37  19  13  10  8   7   6   5   5   4]
          [12  6   4   3   3   2   2   2   2   2]
          [11  6   4   3   3   2   2   2   2   2]
          [48  24  16  12  10  8   7   6   6   5]
          [54  27  18  14  11  9   8   7   6   6]
          [14  7   5   4   3   3   2   2   2   2]
          [13  7   5   4   3   3   2   2   2   2]
          [14  7   5   4   3   3   2   2   2   2]
          [33  17  11  9   7   6   5   5   4   4]
          [7   4   3   2   2   2   1   1   1   1]
          [11  6   4   3   3   2   2   2   2   2]
          [17  9   6   5   4   3   3   3   2   2]
          [10  5   4   3   2   2   2   2   2   1]
          [11  6   4   3   3   2   2   2   2   2]
          [48  24  16  12  10  8   7   6   6   5]
          [13  7   5   4   3   3   2   2   2   2]
          [47  24  16  12  10  8   7   6   6   5]
          [59  30  20  15  12  10  9   8   7   6]
          [12  6   4   3   3   2   2   2   2   2]
          [11  6   4   3   3   2   2   2   2   2]];
```

LB = [2, 1, 1, 2, 4, 1, 1, 1, 2, 1, 1, 2, 1, 1, 2, 1, 2, 4, 1, 1];

UB = [4, 2, 2, 4, 6, 2, 2, 2, 4, 2, 2, 4, 2, 2, 4, 2, 4, 6, 2, 2];

ArrivalTime = [3, 9, 9, 13, 29, 41, 43, 57, 64, 69, 86, 88, 96, 102, 108, 110, 130, 137, 141, 150];

```
DesiredBerth = [12, 15, 14, 1, 4, 3, 12, 7, 9, 8, 5, 4, 14, 15, 15, 16, 11, 9, 5, 15];
QCHours = [37, 12, 11, 48, 54, 14, 13, 14, 33, 7, 11, 17, 10, 11, 48, 13, 47, 59, 12, 11];
Length = [3, 2, 4, 2, 5, 8, 4, 5, 4, 5, 3, 7, 3, 2, 4, 3, 6, 4, 5,  5];
CostDeviation = [2, 1, 1, 2, 3, 1, 1, 1, 2, 1, 1, 2, 1, 1, 2, 1, 2, 3, 1, 1];
CostBLater = [2, 1, 1, 2, 3, 1, 1, 1, 2, 1, 1, 2, 1, 1, 2, 1, 2, 3, 1, 1];
CostQC = [0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01,
0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01];
```

C2. Instance 2

```
v = 20;
s = 20;
k = 10;
t = 168;
StartingB = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0];
EndingB = [168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168,
168, 168, 168, 168, 168];
PTime =   [[6     3    2    2    2    1    1    1    1 1]
           [7     4    3    2    2    2    1    1    1 1]
           [6     3    2    2    2    1    1    1    1 1]
           [13    7    5    4    3    3    2    2    2 2]
           [50   25   17   13   10    9    8    7    6 5]
           [57   29   19   15   12   10    9    8    7 6]
           [14    7    5    4    3    3    2    2    2 2]
           [28   14   10    7    6    5    4    4    4 3]
           [8     4    3    2    2    2    2    1    1 1]
           [15    8    5    4    3    3    3    2    2 2]
           [5     3    2    2    1    1    1    1    1 1]
           [53   27   18   14   11    9    8    7    6 6]
           [12    6    4    3    3    2    2    2    2 2]
           [9     5    3    3    2    2    2    2    1 1]
           [13    7    5    4    3    3    2    2    2 2]
           [15    8    5    4    3    3    3    2    2 2]
           [20   10    7    5    4    4    3    3    3 2]
           [10    5    4    3    2    2    2    2    2 1]
           [20   10    7    5    4    4    3    3    3 2]
           [34   17   12    9    7    6    5    5    4 4]];
LB = [1, 1, 1, 1, 2, 4, 1, 2, 1, 2  1  4, 1, 1, 1, 1, 2, 1, 2, 2];
UB = [2, 2, 2, 2, 4, 6, 2, 4, 2, 4, 2, 6, 2, 2, 2, 2, 4, 2, 4, 4];
```

ArrivalTime = [2, 5, 18, 25, 29, 33, 77, 86, 86, 87, 97, 99, 104, 107, 110, 113, 116, 120, 144, 147];

DesiredBerth = [5, 18, 13, 6, 3, 15, 6, 3, 2, 15, 14, 7, 3, 6, 10, 4, 9, 11, 5, 12];

Length = [5, 3, 2, 5, 7, 3, 3, 3, 6, 4, 5, 6, 4, 3, 6, 4, 6, 8, 3, 3];

QCHours = [6, 7, 6, 13, 50, 57, 14, 28, 8, 15, 5, 53, 12, 9, 13, 15, 20, 10, 20, 34];

CostDeviation = [1, 1, 1, 1, 2, 3, 1, 2, 1, 2, 1, 3, 1, 1, 1, 1, 2, 1, 2, 2];

CostBLater = [1, 1, 1, 1, 2, 3, 1, 2, 1, 2, 1, 3, 1, 1, 1, 1, 2, 1, 2, 2];

CostQC = [0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01];

C.3 Instance 3

v = 20;

s = 20;

k = 10;

t = 168;

StartingB = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0];

EndingB = [168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168];

```
PTime =   [[26   13    9    7    6    5    4    4    3 3]
           [11    6    4    3    3    2    2    2    2 2]
           [6     3    2    2    2    1    1    1    1 1]
           [49   25   17   13   10    9    7    7    6 5]
           [30   15   10    8    6    5    5    4    4 3]
           [55   28   19   14   11   10    8    7    7 6]
           [15    8    5    4    3    3    3    2    2 2]
           [11    6    4    3    3    2    2    2    2 2]
           [39   20   13   10    8    7    6    5    5 4]
           [9     5    3    3    2    2    2    2    1 1]
           [27   14    9    7    6    5    4    4    3 3]
           [7     4    3    2    2    2    1    1    1 1]
           [8     4    3    2    2    2    2    1    1 1]
           [40   20   14   10    8    7    6    5    5 4]
           [6     3    2    2    2    1    1    1    1 1]
           [14    7    5    4    3    3    2    2    2 2]
           [5     3    2    2    1    1    1    1    1 1]
           [15    8    5    4    3    3    3    2    2 2]
           [52   26   18   13   11    9    8    7    6 6]
           [8     4    3    2    2    2    2    1    1 1]];
```

LB = [2, 1, 1, 2, 2, 4, 1, 1, 2, 1, 2, 1, 1, 2, 1, 1, 1, 1, 4, 1];

UB = [4, 2, 2, 4, 4, 6, 2, 2, 4, 2, 4, 2, 2, 4, 2, 2, 2, 2, 6, 2];

ArrivalTime = [7, 8, 15, 22, 30, 30, 36, 38, 44, 47, 68, 72, 72, 76, 80, 80, 83, 118, 148, 153];

DesiredBerth = [5, 12, 5, 2, 12, 3, 14, 3, 13, 7, 3, 15, 11, 15, 13, 5, 16, 16, 7, 11];

Length = [5, 2, 3, 6, 6, 8, 2, 3, 5, 3, 5, 2, 3, 5, 3, 2, 3, 3, 8, 2];

QCHours = [26, 11, 6, 49, 30, 55, 15, 11, 39, 9, 27, 7, 8, 40, 6, 14, 5, 15, 52, 8];

CostDeviation = [2, 1, 1, 2, 2, 3, 1, 1, 2, 1, 2, 1, 1, 2, 1, 1, 1, 1, 3, 1];

CostBLater = [2, 1, 1, 2, 2, 3, 1, 1, 2, 1, 2, 1, 1, 2, 1, 1, 1, 1, 3, 1];

CostQC = [0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01];

C.4 Instance 4

v = 20;

s = 20;

k = 10;

t = 168;

StartingB = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0];

EndingB = [168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168];

DesiredBerth = [2, 12, 7, 5, 1, 14, 8, 5, 13, 17, 17, 18, 3, 9, 16, 2, 7, 1, 5, 15];

ArrivalTime = [2, 9, 11, 12, 20, 27, 57, 69, 71, 73, 75, 79, 86, 89, 95, 100, 117, 137, 141, 150];

LB = [1, 2, 1, 4, 2, 2, 1, 1, 2, 1, 1, 1, 1, 4, 1, 1, 1, 1, 2, 2];

UB = [2, 4, 2, 6, 4, 4, 2, 2, 4, 2, 2, 2, 2, 6, 2, 2, 2, 2, 4, 4];

Length = [2, 5, 4, 6, 6, 5, 2, 2, 6, 4, 3, 2, 3, 8, 3, 4, 2, 4, 5, 5];

QCHours = [12, 38, 7, 54, 19, 24, 11, 6, 43,10, 9, 9, 14, 55, 6, 14, 10, 12, 20, 34];

CostDeviation = [1, 2, 1, 3, 2, 2, 1, 1, 2, 1, 1, 1, 1, 3, 1, 1, 1, 1, 2, 2];

CostBLater = [1, 2, 1, 3, 2, 2, 1, 1, 2, 1, 1, 1, 1, 3, 1, 1, 1, 1, 2, 2];

CostQC = [0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01];

```
PTime =  [[12    6    4    3    3    2    2    2    2  2]
          [38   19   13   10    8    7    6    5    5  4]
          [7     4    3    2    2    2    1    1    1  1]
          [54   27   18   14   11    9    8    7    6  6]
          [19   10    7    5    4    4    3    3    3  2]
          [24   12    8    6    5    4    4    3    3  3]
          [11    6    4    3    3    2    2    2    2  2]
          [6     3    2    2    2    1    1    1    1  1]
          [43   22   15   11    9    8    7    6    5  5]
          [10    5    4    3    2    2    2    2    2  1]
          [9     5    3    3    2    2    2    2    1  1]
          [9     5    3    3    2    2    2    2    1  1]
          [14    7    5    4    3    3    2    2    2  2]
          [55   28   19   14   11   10    8    7    7  6]
          [6     3    2    2    2    1    1    1    1  1]
          [14    7    5    4    3    3    2    2    2  2]
          [10    5    4    3    2    2    2    2    2  1]
          [12    6    4    3    3    2    2    2    2  2]
          [20   10    7    5    4    4    3    3    3  2]
          [34   17   12    9    7    6    5    5    4  4]];
```

C.5 Instance 5

v = 30;

s = 20;

k = 10;

t = 168;

StartingB = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0];

EndingB = [168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168];

LB = [1, 2, 2, 2, 2, 1, 1, 1, 1, 2, 1, 2, 1, 1, 4, 2, 2, 1, 1, 1, 1, 4, 1, 1, 4, 2, 1, 1, 1, 1];

UB = [2, 4, 4, 4, 4, 2, 2, 2, 2, 4, 2, 4, 2, 2, 6, 4, 4, 2, 2, 2, 2, 6, 2, 2, 6, 4, 2, 2, 2, 2];

ArrivalTime = [3, 5, 7, 8, 31, 33, 36, 38, 39, 46, 52, 58, 69, 73, 75, 88, 94, 97, 98,107, 110, 112, 114, 114, 122, 124, 128, 129, 135, 143];

DesiredBerth = [12, 12, 5, 7, 8, 16, 14, 3, 11, 11, 13, 5, 5, 17, 5, 3, 2, 14, 11, 11, 16, 10, 1, 12, 10, 1, 8, 11, 6, 9];

Length = [3, 5, 5, 6, 5, 2, 2, 3, 2, 5, 3, 5, 2, 4, 6, 5, 6, 5, 3, 4, 4, 7, 3, 2, 7, 5, 4, 4, 4, 2];

QCHours = [6, 15, 26, 27, 37, 5, 15, 11, 10, 21, 14, 29, 6, 10, 61, 23, 22, 11, 14, 8, 9, 55, 8, 8, 62, 15, 15, 11, 9, 15];

CostDeviation = [1, 2, 2, 2, 2, 1, 1, 1, 1, 2, 1, 2, 1, 1, 3, 2, 2, 1, 1, 1, 1, 3, 1, 1, 3, 2, 1,

```
1, 1, 1];
CostBLater = [1, 2, 2, 2, 2, 1, 1, 1, 1, 2, 1, 2, 1, 1, 3, 2, 2, 1, 1, 1, 1, 3, 1, 1, 3, 2, 1, 1, 1,
1];
CostQC = [0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01,
0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01,
0.01, 0.01];
PTime =   [[6     3    2    2    2    1    1    1    1 1]
           [15    8    5    4    3    3    3    2    2 2]
           [26   13    9    7    6    5    4    4    3 3]
           [27   14    9    7    6    5    4    4    3 3]
           [37   19   13   10    8    7    6    5    5 4]
           [5     3    2    2    1    1    1    1    1 1]
           [15    8    5    4    3    3    3    2    2 2]
           [11    6    4    3    3    2    2    2    2 2]
           [10    5    4    3    2    2    2    2    2 1]
           [21   11    7    6    5    4    3    3    3 3]
           [14    7    5    4    3    3    2    2    2 2]
           [29   15   10    8    6    5    5    4    4 3]
           [6     3    2    2    2    1    1    1    1 1]
           [10    5    4    3    2    2    2    2    2 1]
           [61   31   21   16   13   11    9    8    7 7]
           [23   12    8    6    5    4    4    3    3 3]
           [22   11    8    6    5    4    4    3    3 3]
           [11    6    4    3    3    2    2    2    2 2]
           [14    7    5    4    3    3    2    2    2 2]
           [8     4    3    2    2    2    2    1    1 1]
           [9     5    3    3    2    2    2    2    1 1]
           [55   28   19   14   11   10    8    7    7 6]
           [8     4    3    2    2    2    2    1    1 1]
           [8     4    3    2    2    2    2    1    1 1]
           [62   31   21   16   13   11    9    8    7 7]
           [15    8    5    4    3    3    3    2    2 2]
           [15    8    5    4    3    3    3    2    2 2]
           [11    6    4    3    3    2    2    2    2 2]
           [9     5    3    3    2    2    2    2    1 1]
           [15    8    5    4    3    3    3    2    2 2]];
```

C.6 Instance 6

```
v = 30;
s = 20;
k = 10;
t = 168;
```

```
StartingB = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0];
EndingB = [168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168, 168,
168, 168, 168, 168, 168];
ArrivalTime = [ 2, 3, 6, 7, 9, 23, 31, 36, 38, 39, 39, 45, 75, 76, 79, 80, 89, 90, 93, 106,
110, 116, 122, 125, 143, 146, 147, 155, 161, 164];
DesiredBerth = [2, 1, 2, 8, 14, 16, 8,14, 9, 17, 6, 7, 12, 15, 18, 13, 3, 10, 9, 7, 10, 8,
16, 5, 9, 13, 6, 4, 16, 16];
LB = [1, 1, 2, 1, 1, 1, 2, 1, 1, 1, 4, 1, 2, 2, 1, 1, 2, 1, 1, 1, 2, 1, 2, 4, 1, 1, 4, 2, 2, 1];
UB = [2, 2, 4, 2, 2, 2, 4, 2, 2, 2, 6, 2, 4, 4, 2, 2, 4, 2, 2, 2, 4, 2, 4, 6, 2, 2, 6, 4, 4, 2];
Length = [2, 3, 6, 3, 4, 4, 5, 2, 3, 2, 6, 3, 5, 5, 2, 3, 5, 4, 3, 4, 6, 4, 5, 8, 2, 2, 8, 6, 5, 3];
QCHours = [12, 7, 30, 8, 6, 13, 37, 15, 10, 14, 53, 9, 35, 40, 9, 6, 33, 12, 5, 14, 48, 13,
47, 53, 15, 9, 55, 35, 16, 5];
PTime =   [[12    6    4    3    3    2    2    2    2 2]
           [7     4    3    2    2    2    1    1    1 1]
           [30   15   10    8    6    5    5    4    4 3]
           [8     4    3    2    2    2    2    1    1 1]
           [6     3    2    2    2    1    1    1    1 1]
           [13    7    5    4    3    3    2    2    2 2]
           [37   19   13   10    8    7    6    5    5 4]
           [15    8    5    4    3    3    3    2    2 2]
           [10    5    4    3    2    2    2    2    2 1]
           [14    7    5    4    3    3    2    2    2 2]
           [53   27   18   14   11    9    8    7    6 6]
           [9     5    3    3    2    2    2    2    1 1]
           [35   18   12    9    7    6    5    5    4 4]
           [40   20   14   10    8    7    6    5    5 4]
           [9     5    3    3    2    2    2    2    1 1]
           [6     3    2    2    2    1    1    1    1 1]
           [33   17   11    9    7    6    5    5    4 4]
           [12    6    4    3    3    2    2    2    2 2]
           [5     3    2    2    1    1    1    1    1 1]
           [14    7    5    4    3    3    2    2    2 2]
           [48   24   16   12   10    8    7    6    6 5]
           [13    7    5    4    3    3    2    2    2 2]
           [47   24   16   12   10    8    7    6    6 5]
           [53   27   18   14   11    9    8    7    6 6]
           [15    8    5    4    3    3    3    2    2 2]
           [9     5    3    3    2    2    2    2    1 1]
           [55   28   19   14   11   10    8    7    7 6]
           [35   18   12    9    7    6    5    5    4 4]
           [16    8    6    4    4    3    3    2    2 2]
           [5     3    2    2    1    1    1    1    1 1]];
```

```
CostDeviation =  [1, 1, 2, 1, 1, 1, 2, 1, 1, 1, 3, 1, 2, 2, 1, 1, 2, 1, 1, 1, 2, 1, 2, 3, 1, 1, 3,
2, 2, 1];
CostBLater = [1, 1, 2, 1, 1, 1, 2, 1, 1, 1, 3, 1, 2, 2, 1, 1, 2, 1, 1, 1, 2, 1, 2, 3, 1, 1, 3, 2, 2,
1];
CostQC = [0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01,
0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01,
0.01, 0.01];
```

List of Tables

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