MEGASHIPS AND PORT OPERATIONS: AN OPTIMIZATION-BASED FUTURE SCENARIOS ANALYSIS

CORSO DI LAUREA MAGISTRALE IN INGEGNERIA GESTIONALE (LM-31)

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Abstract

Berth Allocation Problem (BAP) is a typical optimization problem in the context of port operations. The objective is to minimize the difference between the arrival time and departure time of each ship, to make ports gain competitiveness. A variant of this problem considers constraints related to water depth and tides effects. This variant is more and more actual, because shipping companies are constantly increasing ship size and capacity in order to obtain better economies of scales, causing a lot of problems to port authorities in the management of arriving ships and in their berthing plans. The focus of this thesis is to study a BAP, but with tides constraints, to make some evaluations about future possible scenarios. In fact, megaships continue to grow in size and numbers and so, the future fleets will be different from the actual one and more and more problems could arise for port authorities, related to water depth and tides constraints. Defined this problem and solved through optimization in Python code, the thesis tries to define different configurations, created on the basis of different combinations of various factors considered. After the optimization of these different instances, an analysis on the results is provided, in order to define some possible policy advice for port authorities, taking into consideration two main performance measures: service level and service time.

The thesis is organized in four chapters: in the first one an introduction of the shipping context and trends is presented, while in the second all the details related to optimization problems and Berth Allocation problem are provided. In the third chapter the model used for the analysis is described, accompanied with all the details related to data analysis and generation. Finally, in the fourth chapter a results analysis is presented, with some policy advice and conclusions.

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Chapter 1

Shipping: context and trends

1.1 Logistics nowadays

According to the CSCMP (Council of Supply Chain Management Professionals), "Logistics management is that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customers' requirements" [1].

Since 80s more and more attention and interest in logistics have been paid, both by customers and firms. This phenomenon is primarily relatable to the huge impact that nowadays logistics has on the economy of a country. In fact, in macroeconomics terms, it is possible to understand how much considerable the logistics costs are, compared to GDP (Gross Domestic Product) in different countries [2].

Country	Logistics as a Percentage of GDP
United States	8.5
Brazil	12.0
South Africa	12.8
India	13.0
People's Republic of China	18.0
Vietnam	25.0
Indonesia	27.0

Sources: Various country reports.

Figure 1.1: Percentages of logistics costs on GDP in different countries

As Figure 1.1 shows, the percentages change among the various states, but its relevance is undeniable. Besides, it must be highlighted how big this market is. It is tough to make a precise estimate, because logistics is a world made by a lot of different functions: transportation, warehousing, procurement, inventory control, material handling, customer service, network design, etc; however, as reported in Figure 1.2 the size of the global market is impressive, especially in Asia, where the role that China gained in the last years strongly contributed to Asia huge numbers.

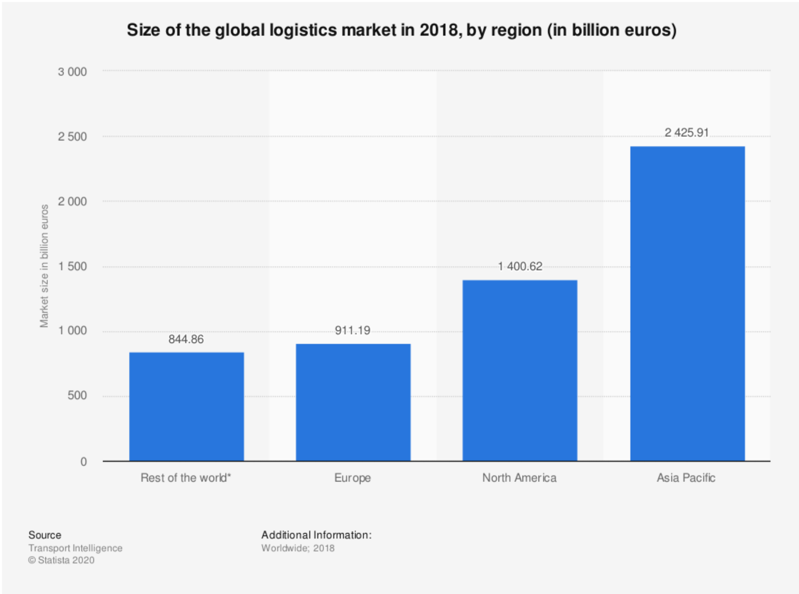


Figure 1.2: Size of the global logistics market in 2018, by region

Finally, logistics can be also a strategic driver for a company and a country. Building an efficient transportation network, with excellent facilities and infrastructures is essential for the development of a country. China is a good example, because one of the principal reason of their enormous growth of the last years are the big investments in their ports, which are their principal connections towards USA and Europe, making possible their numbers of import and exports, shown in Figure 1.3, even if other improvements are required, in order to keep sustainable their growth.

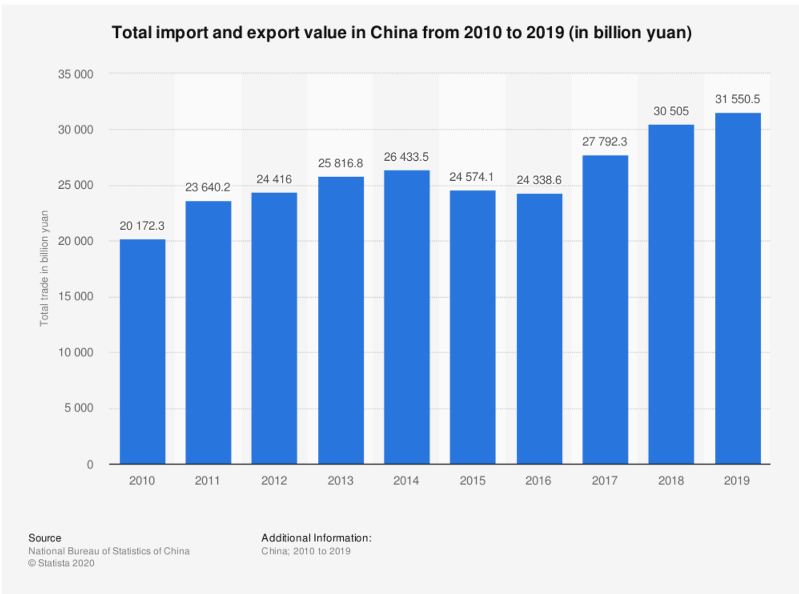


Figure 1.3: China import and export values from 2010 to 2019

At the same time companies like Amazon, Zara, Zalando and IKEA based part of their incredible success on logistics and supply chain design, creating a competitive advantage against their competitors.

Understood the great value logistics has, it is necessary to discuss which are the main reasons for the increasing recognition that logistics obtained recently. First of all, one of the key factors is the **deregulation** that characterized Europe and USA during the 1970s and 1980s [2]. In those years governments relaxed their control over carriers' rates and fares and in general on mergers and acquisition and all the market behaviour, thus leading to a more intense price competition, previously almost non-existent, because logistics managers can't completely control their most important cost components. Another consequence was the increased flexibility gained by logistics business. For example, transportation services began to define some tailored logistics solution, adjusting service level (and obviously also prices) to customer needs and, at the same time, keeping transportation costs low, leveraging large amounts of freight with a limited number of carriers.

Another relevant factor is the changes occurred in **consumer behaviour** [2]. Nowadays an increasing number of customers desires customized product, which can perfectly match their needs in a unique way. However, this means that company should have the ability to produce highly tailored products and services efficiently (mass customization). Thus, implies that logistics is become even more flexible, especially for the delivery process. It is not unusual today to be delivered some orders in the same day they are requested (same-day delivery) or the following day (one-day delivery). This is necessary because logistics performances are now part of the value perceived by clients. In fact, an item could be actually useful and convenient for the customer, only if it is delivered rapidly.

Technological improvements are also another relevant element that has characterized the rise of importance of logistics [2]. With the advent of internet in fact, a lot of companies experienced a totally new relationship with clients, thanks to the disintermediation that the online world facilitates. This means that a customer can relate directly with the producer in an online store, however causing very different settings in the producer supply chain in terms of warehouses and distribution centers or orders management. This can lead to an **omnichannel** retailing approach, with the aim of providing customers the same experience independently of the platform used to reach the company (physical retail, online store, intermediaries, etc.). Besides, also the improvements made in terms of tracking contributed to obtain consistently better logistics performances, also changing the way in which the client perceive value. Nowadays in fact, tracking a shipment is extremely important for a client, but back in 1980s that was a time-consuming and labour-intensive process, which was also often inaccurate.

Finally, **globalization** played a crucial role in this growth [2]. The stretching of supply chains, with a lot of plants relocation towards developing countries led to a situation in which the logistics became enormously important to support the network designed by these companies. In fact, having factories in Asia and not anymore in Europe or North America meant that companies needed to be able to move their product all around the world efficiently, in order to make these goods arrive in the West and be commercialized. But this is not all. Globalization is not only related to the concept of global sourcing previously described. Globalization means also a more open market, in which a company is not only focused on its national market, but it addresses all the interesting markets in the world. This is the reason for which, for example, many Italian companies attacked Asian or Arabian market in the last years, trying to exploit the big opportunities related to these places, due to their significant level of wealth. However, logistics has been not only influenced by globalization, but it has been also an essential mean to allow globalization. Without the introduction of container and the consequent growth of maritime shipping, this would not have been possible. Obviously, globalization has been facilitated also by international treaties that especially from 1990s was signed by the biggest economies in the world. So, in 1995 the World Trade Organization (WTO) was founded, becoming an international organization with the aim of reducing taxation on imports and exports. At the same time, in those years, European Union was consolidating with the Maastricht Treaty and definition of a unique European market. Understood this context, it is not surprising to notice how vigorous was the growth of exports trade worldwide especially from 1990s, showing how globalization effected today's world.

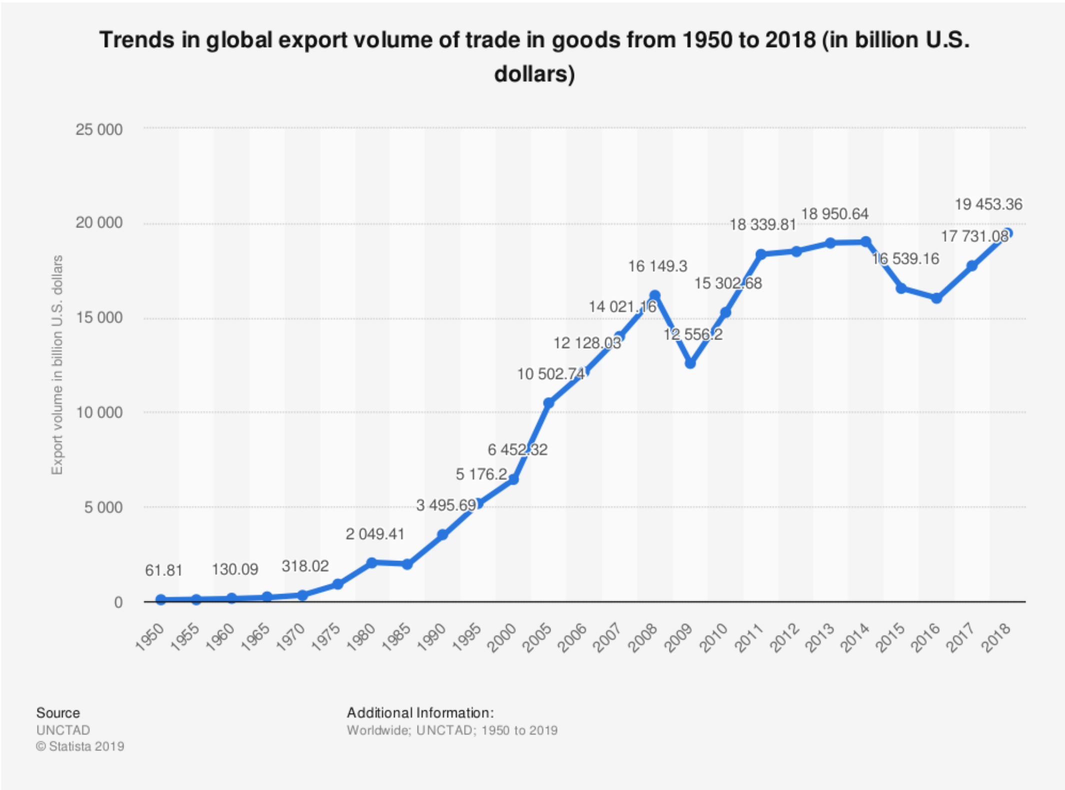


Figure 1.4: Global trend for export between 1950 to 2018

1.2 Shipping

Shipping is the transport of goods by sea, thanks to many different types of ships. This segment represents an extremely important part of logistics and transportation business. In fact, according to the Review of Maritime Transport 2019, UNCTAD, it represents more than 80% of global trade in terms of volume and more than 70% in terms of value. These figures have been reached during these decades thanks to an amazing growth, especially boosted by the globalization and the consequently stretching of supply chains, changes in the geography of supply and demand market and by the containerization. Then, it is not surprising that **container shipping** grew at the fastest rate during these decades, averaging an annual rate of growth of 8% by volume between 1980 and 2018. These phenomena are goodly described by Figure 1.5.

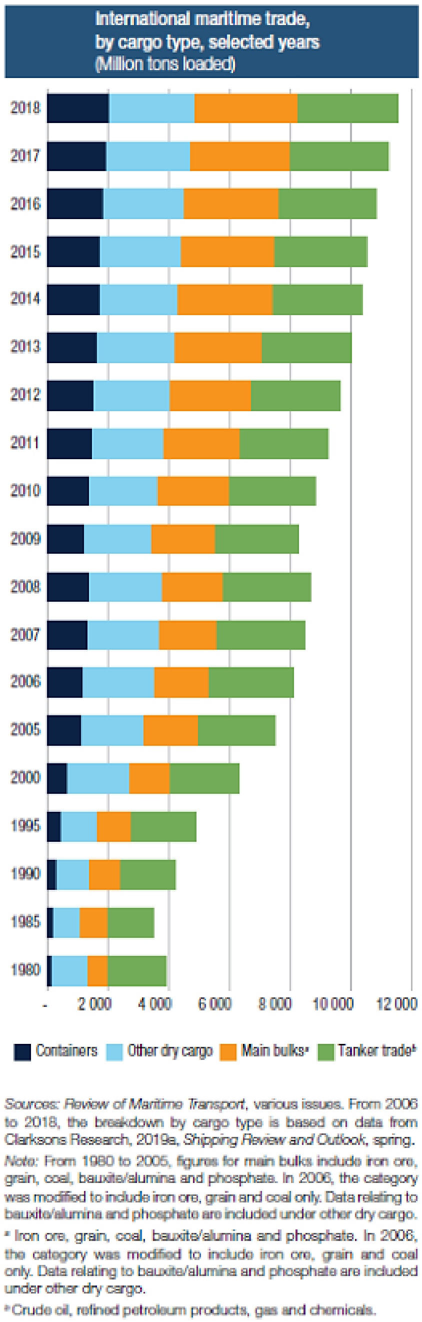


Figure 1.5: International maritime trade by cargo type (selected years)

However, it is also important to highlight how this sea global trade is organized. According to UNCTAD Report, **developing countries** play a crucial role in today's traffic. In the past they were mainly exporting countries of raw material, importing at the same time consumer goods, but since 2000 all the changes previously cited began to modify the role of these economies in the world trade. In fact, they expanded enormously their exports, reaching a percentage of 64.5% (in total tonnage) for goods unloaded, but with a little decrease in the imports [3]. These figures show how these countries are changing during the years; in fact, now, they are not only exporters of raw material utilized in Europa or America to sustain their production, but they are strong producer of finished products, sold all around the world. This led to a decrease of the weight of developed economies in these traffics over time, representing in 2018 only 34.7% of goods loaded and the same for the unloaded [3]. Figure 1.6 shows the trends described.

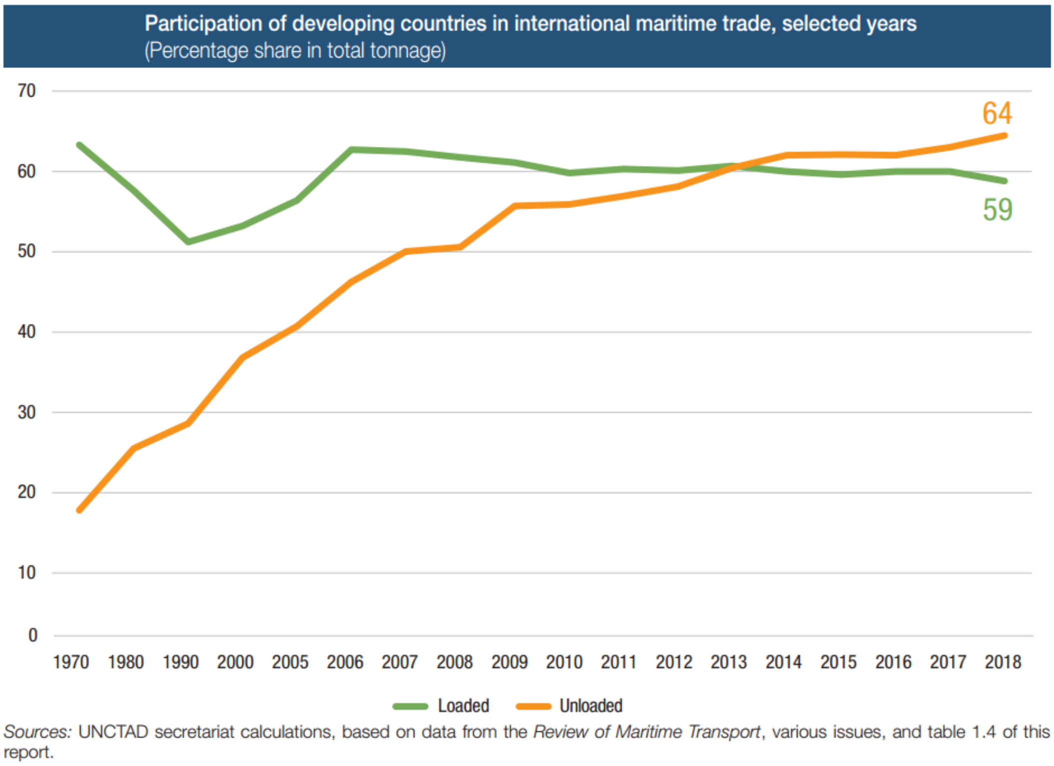


Figure 1.6: Participation of developing countries in international maritime trade

By region, **Asia** is sharply the most relevant region of the world for sea global trade, followed by Europe and Americas as represented in Figure 1.7. This is also due to the geography of the continent, which has a lot of island, as Japan or Indonesia or Taiwan, just to make some examples. However, a fundamental role is played by China, which contributes a lot to the numbers of Asia and developing countries, because it accounts for the most of their trade. In fact, looking at Figure 1.8 it is clear how the growth previously mentioned for developing countries is considerably inferior, if China is excluded [3].

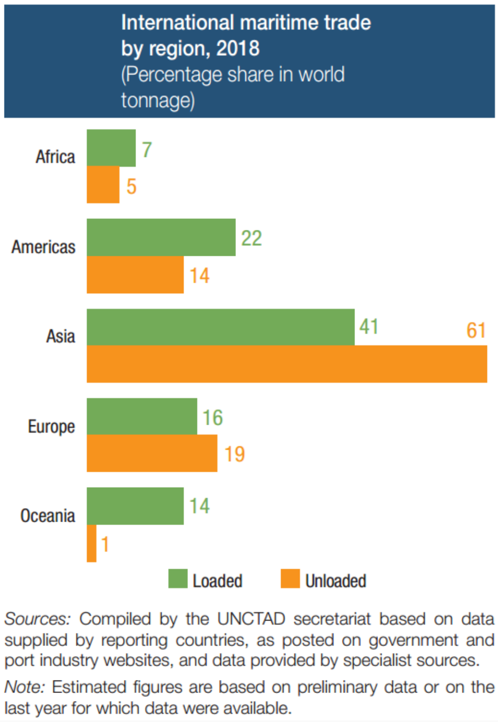


Figure 1.7: International maritime trade by region, 2018

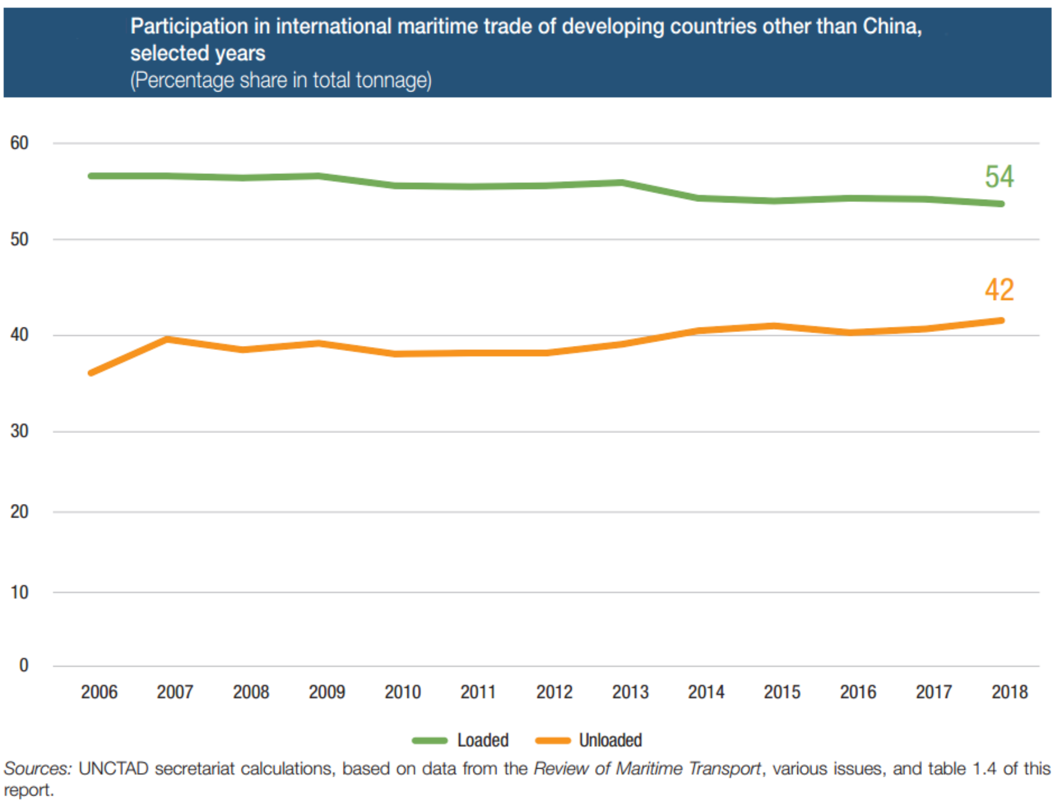


Figure 1.8: Participation of developing countries in international maritime trade, excluding China

1.3 Container

As mentioned before, containerization consistently contributed to the rise of shipping. A container is a box of different dimensions, realized between the 50s and 60s in America which literally revolutionized the world. **Malcom McLean**, an American entrepreneur operating in transportation business, is considered the inventor of this magic box called “container”, which started with Ideal-X ship, which moved from Port Newark to Houston [4]. In particular, McLean wanted to create a way in which it would have been possible to connect his coastwise shipping business with his trucking one. At that time, these two industries were totally segmented industries and so it was a big challenge. However, it is said that McLean, while waiting for the unloading of trucks and subsequent loading of ship, thought that it would have been easier to move the entire truck body, i.e. what it would become the container, than moving all the goods. This ended to be a very good idea, even if at that time it was raw. In particular, the first effect that this revolution had was a significant saving in terms of cost and time, but it required mechanized systems to move these boxes. So, McLean’s project not only consisted in the definition of a first raw container, but also in a bigger system that allowed to have an equipment of cranes, ships, ports, trucks, etc. based on this container. So, after Ideal-X voyage towards Houston, a lot of investments began to support container development, with the construction of appropriate cranes to operate adequately with containers, increasing the productivity. In fact, the first container-designed crane, built in Alameda, San Francisco Bay, was 40 times more productive than the previous system based on shipboard winches used by longshoremen [4]. After its invention, containers widespread over USA, but they remained an American affair. Meanwhile, ISO began to study container in 1961 [5]. In fact, in the first years, many different versions of container were used in the USA, avoiding a compatibility between different companies. A long process led to the definition of an **ISO standard**, that was definitely established in 1964. After the standardization, the final step for containerization was the development of an intermodal transport system, where a container can be easily moved from a ship to a truck or a train, enabling new opportunity for every shipment. However, this was a long process, that only began in 60s, but it is going on also now, trying to increase the quota of ship-train intermodal transports. This progress was possible also thanks to the increasing investment that transportation authorities and companies made during the years, sustaining it with larger ships and trains, innovated trucks and IT involvement.

The chart in Figure 1.9 (taken from *“The Humble Hero”, The Economist*, May 18) summarize the impact on trade that container have had.

Described the historical background, it is now important to highlight which are the main technical features of a container and which are its most impactful benefit and drawbacks. An intermodal container, also called **ISO Container**, in technical terms, is a metal box of standardized dimensions, used for the transportation of goods, with a parallelepiped shape. The dimensions requested for the ISO standardized version of a container are reported in ISO 668 and they are showed in Figure 1.10.

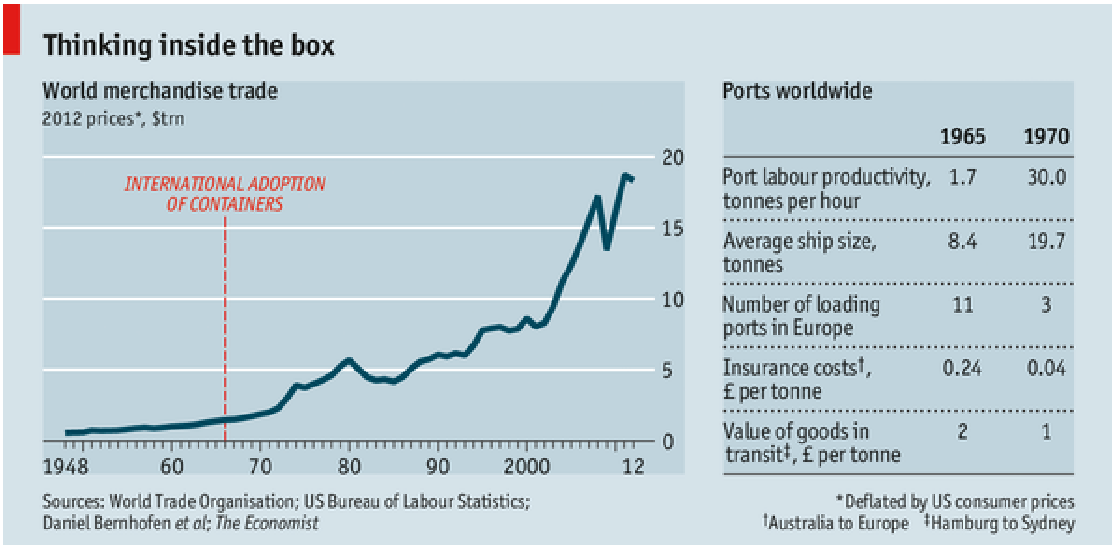


Figure 1.9: World trade trend from 1948 to 2012

		20' Container		40' Container		40' High-Cube Container		45' High-Cube Container	
		English	Metric	English	Metric	English	Metric	English	Metric
External Dimensions	Length	19' 10 ½"	6.058 m	40' 0"	12.192 m	40' 0"	12.192 m	45' 0"	13.716 m
	Width	8' 0"	2.438 m	8' 0"	2.438 m	8' 0"	2.438 m	8' 0"	2.438 m
	Height	8' 6"	2.591 m	8' 6"	2.591 m	9' 6"	2.896 m	9' 6"	2.896 m
Interior Dimensions	Length	18' 8 13/16"	5.710 m	39' 5 45/64"	12.032 m	39' 4"	12.000 m	44' 4"	13.556 m
	Width	7' 8 19/32"	2.352 m	7' 8 19/32"	2.352 m	7' 7"	2.311 m	7' 8 19/32"	2.352 m
	Height	7' 9 57/64"	2.385 m	7' 9 57/64"	2.385 m	8' 9"	2.650 m	8' 9 15/16"	2.698 m
Door Opening	Width	7' 8 ⅛"	2.343 m	7' 8 ⅛"	2.343 m	7' 6"	2.280 m	7' 8 ⅛"	2.343 m
	Height	7' 5 ¾"	2.280 m	7' 5 ¾"	2.280 m	8' 5"	2.560 m	8' 5 49/64"	2.585 m
Internal Volume		1,169 ft³	33.1 m³	2,385 ft³	67.5 m³	2,660 ft³	75.3 m³	3,040 ft³	86.1 m³
Max Gross Weight		66,139 lb	30,400 kg	66,139 lb	30,400 kg	68,008 lb	30,848 kg	66,139 lb	30,400 kg
Empty Weight		4,850 lb	2,200 kg	8,380 lb	3,800 kg	8,598 lb	3,900 kg	10,580 lb	4,800 kg
Net Load (Payload)		61,289 lb	28,200 kg	57,759 lb	26,600 kg	58,598 lb	26,580 kg	55,559 lb	25,600 kg

Figure 1.10: Standardized container dimensions, according to ISO 668

These dimensions lead to the definition of a unit of measure in order to represent how many containers a means of transport can move. There are two main alternatives:

- TEU (Twenty feet equivalent unit): it is referred to a container of 20' length
- FEU (Forty feet equivalent unit): it is referred to a container of 40' length

These two types of container dimensions are the most widespread, while 45' length version represents only a small portion. All the container with a height of 9,6' are called **high-cube**, because of their greater height.

However, there are also other classification for containers, related to their use destination and some particular features, that differentiate a version from another one.

A possible classification related to their peculiarities is presented:

- **Dry storage container**: it is suitable for any general cargo. This is the standard container and its dimensions may vary as seen in Figure 1.10.

Figure 1.11: Dry storage container

- **Hardtop Container**: this is designed to have a removable roof that can help to load and unload heavy goods by crane. This can facilitate and accelerate operations.

Figure 1.12: Hardtop container

- **Flat rack container**: it has collapsible sides, that allows to transport, on the container platform, goods of incompatible dimensions to the ISO container.

Figure 1.13: Flat rack container

- **Open top container**: in this case the container has no roof, allowing to transport goods of greater height.

Figure 1.14: Open top container

- **Tunnel container**: this container has doors on both ends of the structure, allowing to load materials from both of them.

Figure 1.15: Tunnel container

- **Open side storage container**: it is provided with doors on one side of the container. In this way there is another point from which load and unload goods.

Figure 1.16: Open side container

- **Refrigerated ISO containers**: this container is extremely important; it is a version with a refrigeration machine that is usually able to keep internal temperatures between +25 and -25 °C. This is possible because they are designed in order to be connected to ship power supply system, but also to diesel generator, that allow refrigerators to work also when they are carried on trucks. This container is used for perishable goods, as fruits, vegetables, medicines, cosmetics, etc.

Figure 1.17: Refrigerated ISO container

- **ISO Tank**: it is not an usual container, but it is characterized by a steel structure able to allocate a tank and facilitating its transportation, because the steel structure has the same dimensions features of the standard version and so it can be moved in the same easy way.

Figure 1.18: ISO tank container

Completed this overview on the different types of container, it is necessary to make a list of what are the most important advantages and drawbacks of containerization [6].

The main benefits are:

- **Standardization**: as reported before, container is a standardized unit of intermodal transportation and so it is easily usable by different actors along an entire supply chain.

- **Flexibility**: a lot of different items can be inserted in a container, also when there are some dimensional problems, thanks to the variants seen before. So, there are a wide variety of situations in which it is really useful to use a container.

- **Cost and time savings**: moving a container means moving a lot of different items with a single operation; this avoids the break bulk, which would cause a considerable decrease in productivity; then, the consequence is clear: container increases velocity and productivity and generates economies of scale (especially on ships) that, thanks to standardization too, really decrease the transportation costs.

- **Warehousing**: the container is a little warehouse itself and it protects its content efficiently. Besides, its stacking capacity causes a significant reduction in terms of utilized space in a terminal. This is really important in Southern Europe ports, characterized with limited space available.

Figure 1.19: Stacked containers

- **Security and safety**: containers can be opened only by seller, customs and buyer and in fact, they are sealed by a mechanical or, more recently, electronic seal. This decreases the possibility of theft or damages to the content of the container.

Figure 1.20: E-Sealing

The main drawbacks are:

- **Site constraints**: containerization, compared with the past and considering the growth that caused in trade, translated in the necessity for a large portion of a terminal space, that in fact has been shifted to more industrial areas, moving from the towns. Besides, the tendency, that will be analyzed in the following paragraph, to build larger containership can create some problems with the draft of the ships, that risks to be excessive respect to the port depth. This problem is one of the main focus of the work and will be detailed more in the following chapters.

- **Capital intensiveness**: as it can be noticed from the historical background, containers require a lot of very expensive superstructures (as cranes, reach stacker, etc.). So, all of these means are important capital investments, that require a large availability of money to invest. This matter is also a problem of these days, due to the increasing automation that companies and authorities are trying to bring in terminals and ports.

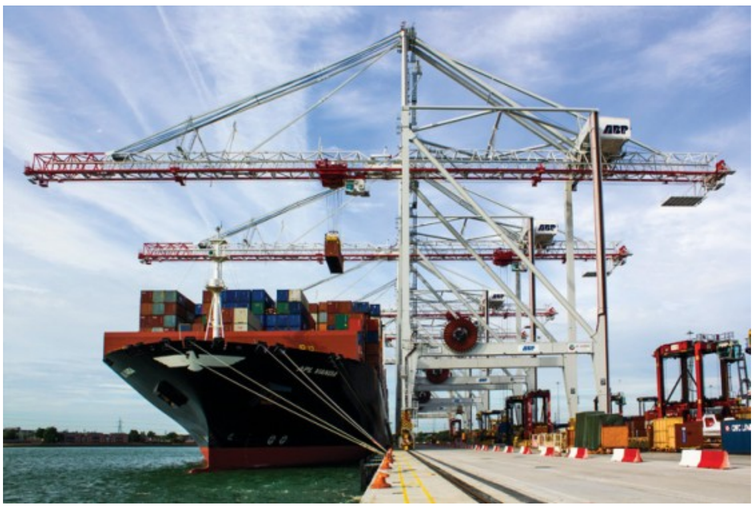


Figure 1.21: Quay Cranes

Figure 1.22: Reach Stacker

- **Stacking and repositioning**: this is a very delicate and difficult operation to perform in an efficient way. Because of its complexity, it is not unusual to move a container even if it had not to be loaded to a ship. This ends in a worse productivity and in activities even more not value added. Besides, sometimes it is necessary to move containers empty, that not only occupy the same amount of space than a full container, but also takes time to complete the movement. This is especially caused by inequalities in terms of production and consumption that can be observed all around the world. An example to understand this issue is reported in the UNCTAD Review of Maritime Trade, 2019. In this table are reported the millions of TEU moved along the most important routes of the world. It is quite evident that European and American routes with Asia are characterized by bigger numbers on the eastbound than on the westbound [3]. This explains how the presence of empty container is created and causes troubles in terminal operations.

Containerized trade on major East–West trade routes, 2014–2018
(Million 20-foot equivalent units and annual percentage change)

	Trans-Pacific			Asia–Europe			Transatlantic		
	Eastbound	Westbound		Eastbound	Westbound		Eastbound	Westbound	
	East Asia–North America	North America–East Asia	Trans-Pacific	Northern Europe and Mediterranean to East Asia	East Asia to Northern Europe and Mediterranean	Asia–Europe	North America to Northern Europe and Mediterranean	Northern Europe and Mediterranean to North America	Transatlantic
2014	16.2	7.0	**23.2**	6.3	15.4	**21.8**	2.8	3.9	**6.7**
2015	17.5	6.9	**24.4**	6.4	15.0	**21.5**	2.7	4.1	**6.9**
2016	18.3	7.3	**25.6**	6.8	15.4	**22.2**	2.7	4.2	**7.0**
2017	19.5	7.3	**26.8**	7.1	16.5	**23.6**	3.0	4.6	**7.6**
2018	20.9	7.4	**28.2**	7.0	17.4	**24.4**	3.1	4.9	**8.0**
Annual percentage change									
2014–2015	7.9	-2.0	**4.9**	1.4	-2.6	**-1.4**	-2.4	5.6	**2.2**
2015–2016	4.4	6.6	**5.1**	6.3	2.5	**3.6**	0.4	2.9	**1.9**
2016–2017	6.7	-0.5	**4.7**	4.1	6.9	**6.0**	7.9	8.3	**8.1**
2017–2018	7.0	0.9	**5.4**	-1.3	5.7	**3.6**	5.8	6.8	**6.4**

Source: UNCTAD secretariat calculations, based on data from MDS Transmodal, World Cargo Database, May 2019.

Figure 1.23: Disequilibrium on major East-West trade routes

- **Theft and losses**: even if containers are sealed, they can be forcefully opened by criminals. Besides, every year, it is estimated that 1500 containers are lost at sea.

Figure 1.24: Shipwrecked ship

- **Criminal traffics**: unfortunately, containers are also used by criminal organization to move goods, drugs, weapons and even people for immigration finalities.

1.4 Naval gigantism

Container diffusion throughout the years generated a constant increase in ship dimensions. The main reason for this behaviour can be found in the concept of **economies of scale**. Having larger ships means having the opportunity to carry on board more and more containers, leading to lower costs per TEU with ships with greater capacity. At the same time, it allows to save money in fuel and crews and limit GHG (Greenhouse-gas) per container [7]. It is also coherent with the increasing hub and spoke networks, in which the biggest ships move from hub to hub, represented by transhipment ports (i.e ports in which containers are moved from a ship to another and not inland), while smaller ships are in charge of move containers from hub to smaller ports, in order to cover the market.

The biggest containership in the world in 2020 is **HMM Algeciras**, with a capacity of 23 964 TEU [8]. The ship has been completed in April 2020 in Daewoo Shipping Marine Engineering's Okpo shipyard, commissioned by HMM (Hyundai Merchant Marine, one of ten most important container shipping line of the world). It is about 400m long and 61m wide, while its draft is about 15m.

Figure 1.25: HMM Algeciras in Port of Rotterdam

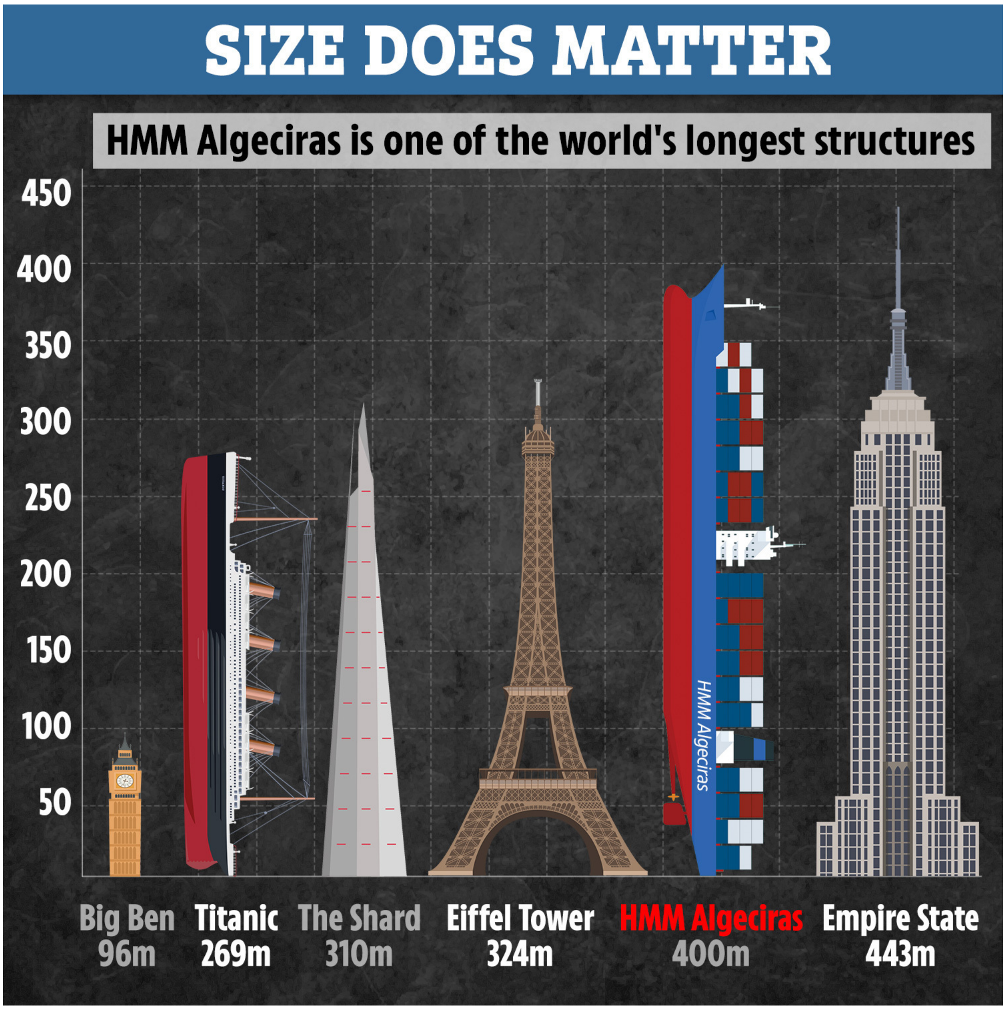


Figure 1.26: HMM Algeciras size comparison with other infrastructures

This is one of the so-called megaships. However, the definition of megaship changes trough the time, because different eras succeed each other. The last generation of megaship is started with the Triple E-ships of Maersk in 2013 [9]. These ships have very similar dimensions to the ones cited for HMM Algeciras. So, it is clear that this is not a series of isolated cases, but this is a real tendency that is characterizing this industry from decades. However, although the continuous search for always better economies of scale, to force the price competition, according to the *Report of International Transport Forum "The impact of Mega Ships"*, commissioned by OECD in 2015, this is not a smart industry behaviour. In fact, the growing demand for bigger ships has a higher pace than the grow in the demand for transportation, leading to a situation in which the entire industry fares must be decreased, due to **overcapacity**. In fact, as stated in the report, it took 30 years to arrive to a capacity of 1 500 TEU, but only 10 years to double this capacity, reaching 3 000 TEU, showing how rapidly this growth is. These trends are well represented in Figure 1.27, taken from the OECD Report on megahips.

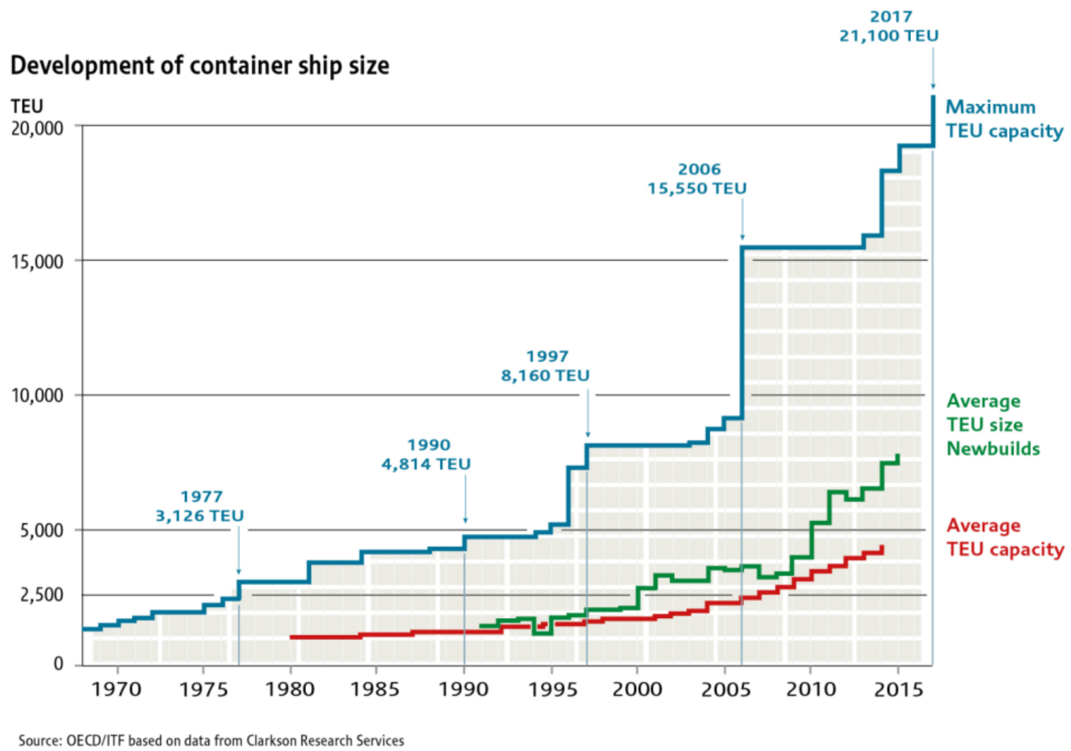
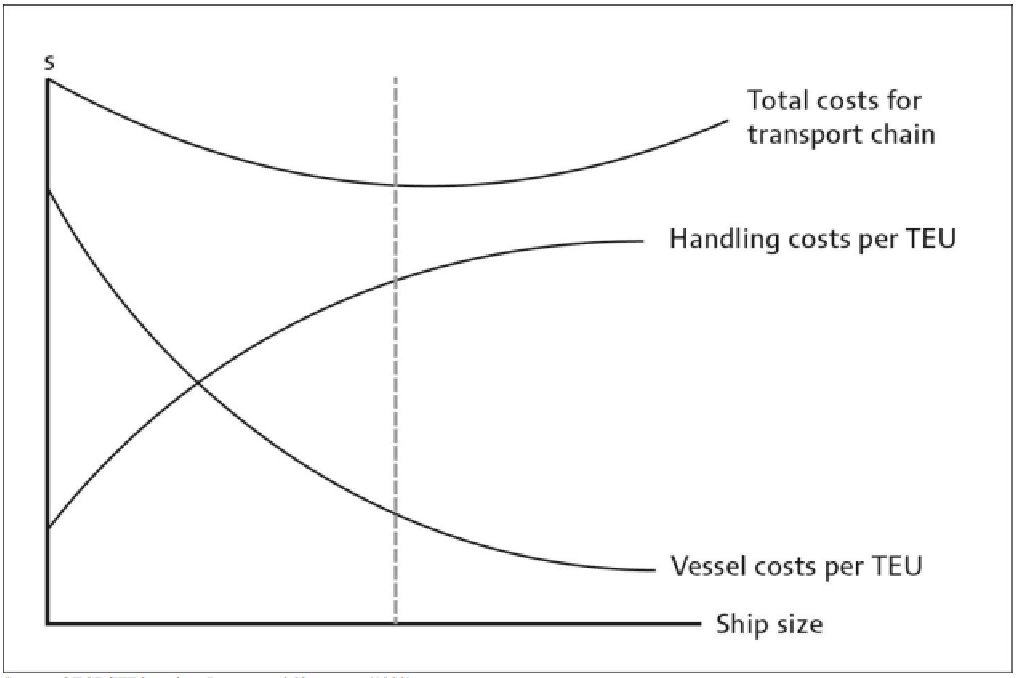


Figure 1.27: Development of container ship size

But is this growth sustainable? To try to give an answer, it must be understood how these costs can vary relatively to the ship size. It is undeniable, as stated previously, that with bigger ships, transportation costs per TEU decreases, but what about handling costs in the rest of supply chain? According to OECD Report on Megaships, these costs tend to increase with a bigger size of ships [9]. So, looking at Figure 1.28, the problem is to understand in which point of the Total costs for transport chain curve container shipping industry is right now. But it is important to highlight that there is a limit on ship size; over this limit this growth becomes anti-economical.



Source: OECD/ITF based on Jansson and Shneerson (1982)

Figure 1.28: Relationship between ship size and transport costs

Knowing how far this limit is can be really difficult and it has been the goal of a McKinseyCompany Report called *"Container shipping: The next 50 years"*, published in 2017. As stated in McKinsey Report, today's capacity is probably not the natural limit for container ships, but it may be possible that this limit is really far. McKinsey in fact, suggests the idea that in the future 50 years containerships capacity could arrive to the huge number of **50 000 TEU** [7]. Nevertheless, a lot of variables can play a fundamental role in the definition of this future scenario. First of all, capacity growth must be sustained by a **demand growth**. As it can be seen from Figure 1.29, these two trends are running at different paces and surely, supply growth will slow in the next years if demands will continue to be lower [7]. However, if an equilibrium between supply and demand will be found, according to McKinsey, "the logic of scale will once again drive orders for bigger and bigger ships". Another factor will surely be the **fuel price**. One of the biggest advantages of megaships consists in the possibility to save money for fuel, because more goods can be moved at the same time. So, if fuel prices would increase in the following years, stronger investments in bigger ships should be expected [7]. **Physical constraints** are another variable that will influence this growth. In particular, strategical points in the world routes, as for example the Strait of Malacca for the water depth, have some physical limitations, that will be described in the following paragraph, that can create an obstacle for the passage of megaships [7]. This problem also affects port infrastructures, increasing its severity.

However, according to OECD Report, most of the cost saving of the newest megaship are not caused by their size, but they are related to their **new way of navigation** [9]. Nowadays in fact, ships tend to go slower to consume less fuel, an interesting goal both for sustainability and savings. So, the new megaships are designed to navigate at a slower speed and so they are more efficient than the previous genera-

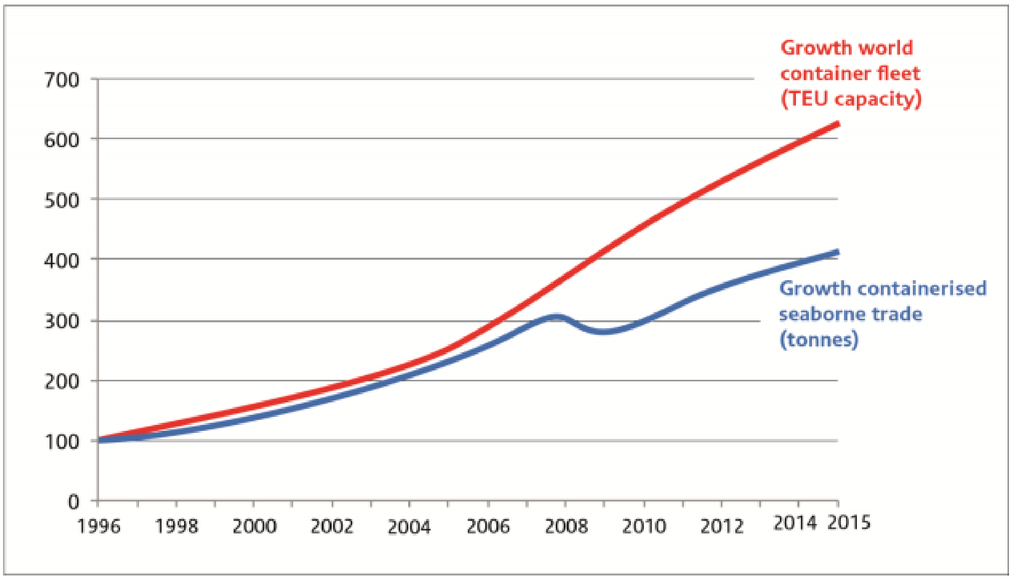


Figure 1.29: Growth trends for container fleet and containerized seaborn trade

tions, designed for higher speeds. This has an important consequence. It is shown in fact that "cost savings are decreasing as ships become bigger" [9]. In the past, naval gigantism has been promoted especially for the savings generated from the economies of scales, but this effect seems to be decreasing, as shown in Figure 1.30.

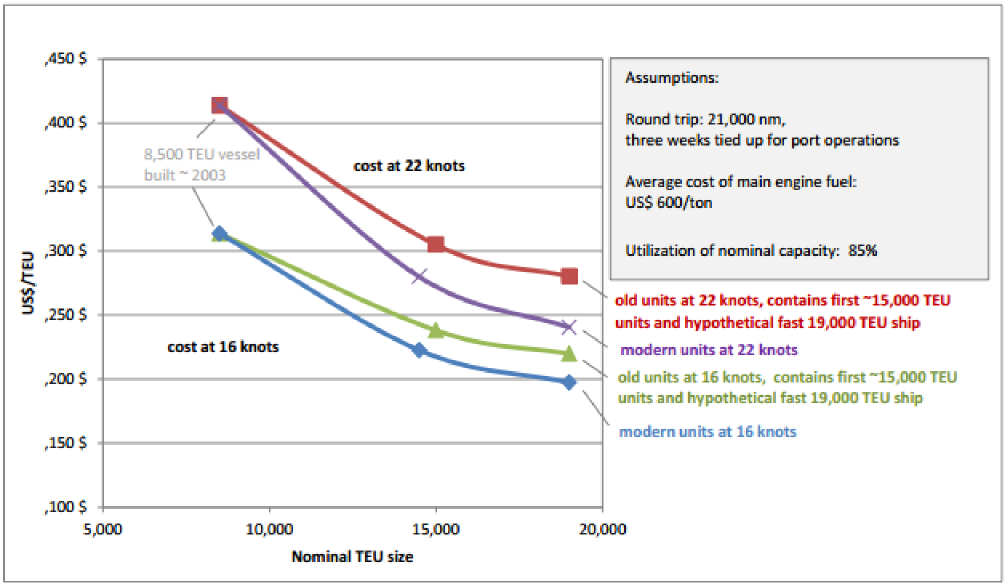


Figure 1.30: Decreasing cost savings with increasing size

This is not the only negative effect that megaships are experiencing. Another problem is related to their continuous growth. In fact, more and more megaships are under construction, as it can be noticed from Alphaliner 2020 report in Figure 1.31, in which it is presented the following orderbook of ships.

A lot of ships in the range 18 000 – 24 000 TEU are under construction. This

Cellular Orderbook Fleet Breakdown						
Size Range	All cellular ships		Of which chartered			Orderbook/
TEU	Units	TEU	Units	TEU	% Chrt	Existing %
18,000-24,000	37	860,900	1	23,756	2.8%	37.2%
15,200-17,999	0	0	0	0	0.0%	0.0%
* 12,500-15,199 NPX	47	689,374	29	419,374	60.8%	19.9%
10,000-12,499	34	402,350	26	306,350	76.1%	22.8%
7,500-9,999	0	0	0	0	0.0%	0.0%
5,100-7,499	2	10,590	2	10,590	0.0%	0.4%
4,000-5,099	1	4,011	0	0	0.0%	0.1%
3,000-3,999	13	39,788	1	3,100	7.8%	4.5%
2,000-2,999	106	260,933	35	86,866	33.3%	15.1%
1,500-1,999	57	102,841	44	79,136	76.9%	9.9%
1,000-1,499	41	47,366	9	11,340	23.9%	5.8%
500-999	9	5,824	0	0	0.0%	1.0%
100-499	2	420	0	0	0.0%	0.7%
TOTAL	349	2,424,397	147	940,512	38.8%	10.4%

Figure 1.31: Alphaliner 2020 Ships Orderbook

means that ships that had been realized in order to serve a specific route, for example the Far East-North Europe trade lane, could be shifted to another route, for example the Transpacific, due to the introduction of a bigger ships on that specific route. The natural consequence of this possible shift is the reduction of the distance travelled, with a less consistent saving on fuel. So, some **diseconomies effects** can arise from this cascading effect [9].

Another issue, not be underestimated, is the difficulties that a liner shipping company could face to **fill the entire ship** [9]. Obviously, the load factor of a ship is expected to be as high as possible, in order to exploit the economies of scale previously described. However, as it can be easily understood, it is more complicated to fill a ship of 24 000 TEU than a 18 000 TEU one. A possible solution to this problem has been found in the **Alliances**. In fact, more than 80% of the world's cargo holds is distributed on three alliances, which are:

- 2M Alliance
- Ocean Alliance
- The Alliance

In these three alliances are reunited the companies indicated in Figure 1.32.

One of the goals of these alliances is to share the space on board of ships between the members of the alliance, according to the proportions defined in the agreements stipulated between these companies (**vessel sharing agreements**). In this way they can partially solve the problem of increasing the utilization of their ships and at the same time, they can be present on multiple routes, but limiting the investments. Alliances allow also shipping companies to increase their negotiation power, a possible solution for the freight decrease caused by the disconnected growth of world container fleet and containerized seaborne trade, previously described.

Finally, another factor must be taken into consideration. The **risks** associated

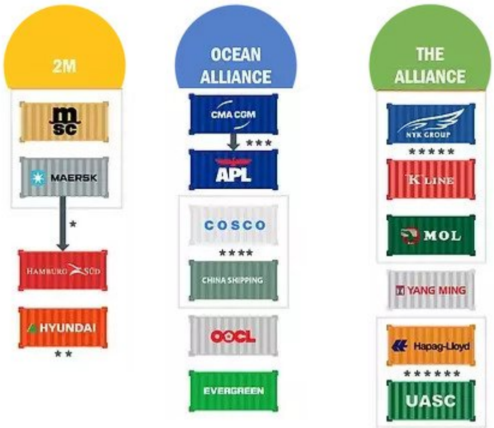


Figure 1.32: The three alliances

with these megaships are enormously bigger than the ones related to smaller ships. As stated in the OECD Report, "exposure to risk for shippers increases in a linear way with the capacity of ships" [9]. This is one of the actual problems that shipping companies are facing with the insurance companies.

1.5 Impact on port and terminal container

Only a limited number of ports in the world are able to serve these megaships. This, coherently with the developed hub-and-spoke network, means that the container port system for megaships is really concentrated. Looking at North Europe and Asia, approximately 80% of calls from respectively Asia and North Europe, is concentrated only in six main ports [9]. Figure 1.33 and 1.34 provide an example on how these systems are organized, especially in terms of market share, on Far East – North Europe trade lane.

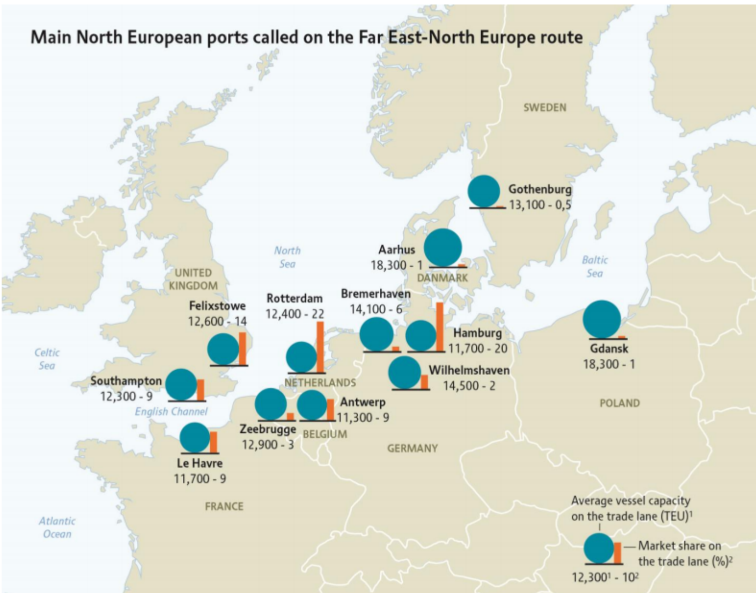


Figure 1.33: North Europe main ports

Figure 1.34: Far East main ports

This is not casual, but it is the consequence of all the limiting factors that make difficult, in certain cases, for megaships to access ports. The main physical barriers are [9]:

- **Depth**

  Estuary ports (as Hamburg in Europe or Shanghai in Asia), i.e. ports situated in the estuary of a river, have calls from megaships, due to their importance. However, this means that they are not deep-sea ports and so the increasing draft of megaships can create a serious problem. This has been challenged by ports authorities with big investment in dredging the river or access channels, but this operation is enormously expensive in some cases and besides, it affects the river and/or sea ecosystems and biodiversity, causing also possible oppositions from other authorities or citizens. So, this solution is not always practicable. But this is not all. The problem can be complicated by some tidal effects and load factor of ships. It is clear in fact, that a full ship has a deeper draft than an empty one and so also this factor must be taken into account. Instead, tides can be helpful, in the period of high tide, but they can also expose the ports to a certain level of variability that can complicate the entire operations management, causing the necessity for advanced IT systems to manage the situation.

- **Locks**

  For river ports, also locks can be a bottleneck for megaships. An inadequate and obsolete locks system can deny an efficient port access and so, they should be replaced.

- **Bridges**

  Bigger ships mean greater heights in some cases. In fact, this is another way to expand capacity, increasing stacking potential, but limiting the enlargement of length and beam. However, the presence of bridges in some parts of ports makes them inaccessible for megaships. A possible solution can be a partial relocation of the port, at least for megaships, providing an area without any bridge in the way, that can allow an easy access for them. However, in many cases, ports are rebuilding their bridges, to avoid this problem, but also to improve port traffic.

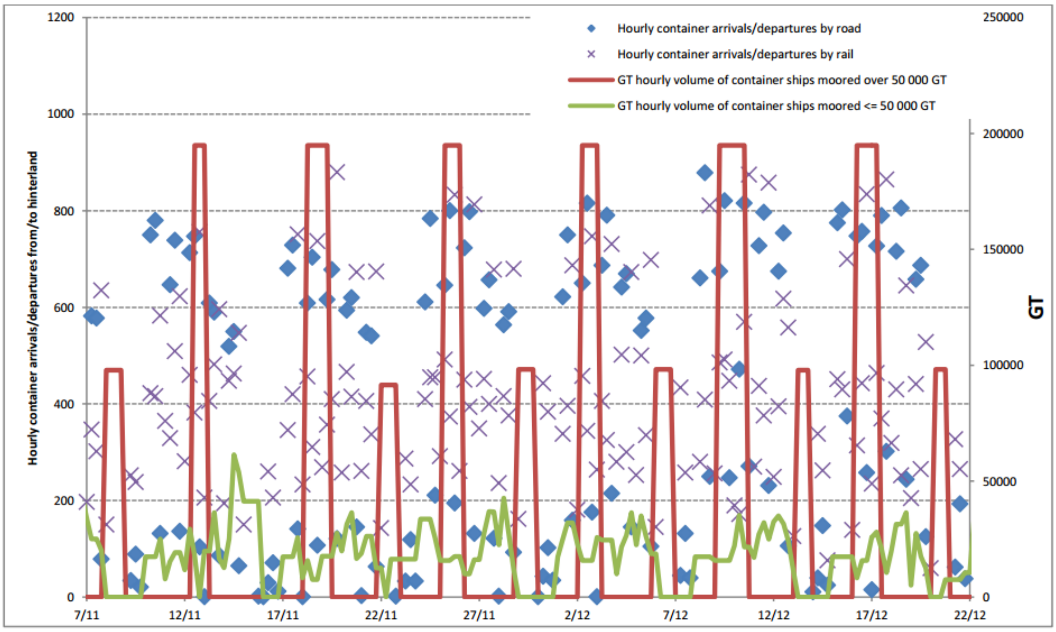
- **Quays**

  Some investments for terminal are necessary also in terms of strengthen and increasing the height and length of quays. In fact, megaships exercise bigger forces on quay walls when berthed and moored and so this is a mandatory adaptation, specially for safety reason. However, this is a capital-intensive investment; an example for port of Rotterdam estimates that adapting quay walls for megaships could cost between 23.545€/m and 44.400€/m. Bigger costs are expected for entirely new quay walls.

- **Cranes**

  According to OECD Report, the newest megaships require crane able to handle 23 containers rows. However, this is not a critical issue, because it is expected that 380 cranes, able to handle from 23 to 25 container rows, will be present in North Europe terminals within 2024. Nevertheless, other investments will be required to gradually increase the productivity of these terminals in serving these megaships.

Physical constraints are not the only one drawback of naval gigantism for terminals. Operational problems are in fact another big change for ports, both seaside than in the yard and in the hinterland. The arrival of a megaship in fact creates a **peak** in all the operations that need to be performed [9]. If this peak is repeated several times to serve multiple megaships the entire demand curve for operations will change, becoming more variable, as it can be seen from Figure 1.35, taken from OECD Report.



Source: OECD/ITF elaboration based on data provided by port authority and terminal operator

Figure 1.35: Peaks caused by arrival distribution of megaships

The consequences of these peaks are extremely impactful and they can be summarized as follows [9]:

- **Increased turnaround time**

  Megaships usually stay 20% more in ports than the other ships, due to the longer time they require to be served, but also for berthing policies of the ports. Some ports give priority to small feeder ships, increasing waiting time for megaships to enter in the port. Some possible solutions to solve the problem can be found in crane density or crane productivity. However, there is a limit of cranes that can serve a megaship and also the distribution of them to the various ships should be studied carefully, as it will be seen in the following chapter. Nevertheless, this problem could be avoided serving a ship from both side of a berth, as shown in Figure 1.36. Instead, crane productivity is a serious problem, because generally megaships reduce their values. However, researches showed that investments in faster cranes (instead that in bigger cranes) could solve the problem.

- **Port hinterland congestion**

  A megaship arrival with containers to unload tends to occupy a lot of space in the yard. This is a big problem, but bigger is the issue related to the trucks that arrive in a port to take these containers. The peaks create a situation in which a concentration of trucks occurs in a limited amount of time. This can easily create congestion if the hinterland connections to the port are not adequate to support those levels of traffic. A possible solution can be the development of integrated systems able to coordinate hinterland arrivals to megaship arrivals, but there are not yet cases of similar implementations. Another possible solution could be the opening of terminals 24h per day, but it would require a lot of management changes. The last solution can be a modal

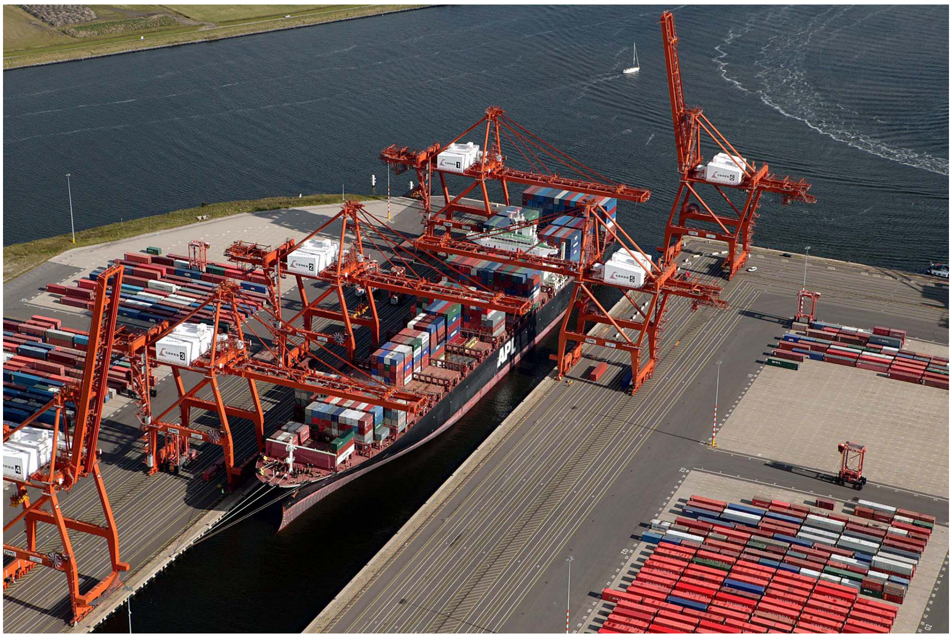


Figure 1.36: Ship served by cranes on two sides of the berth in Port of Amsterdam

shift towards rail intermodality, creating better railways connection between ports and hinterland.

1.6 Arrival operations

For the aim of this thesis, it is important to present what are the most important operations that happens in a port when an arriving ship is approaching. This description will be presented describing the role and activities performed by different actors.

- **Vessel**

  It is important for each ship to enter in the port as smoothly as possible and to have the cargo loaded and discharged in the fastest possible way. Every hour at the port is valuable and a delay could be really expensive for it. Every ship communicates the expected arrival time to the port and when it is approaching it adjusts the speed, to decrease the environmental impact and to better execute the necessary maneuvers.

- **Ship agent**

  A ship agent represents the ship during the call at the port. He has a contact with all the parts involved in the operations and handles a lot of information about the ship and its cargo, also helping the ship clearance and pilot dispatches ordering bunkers and ordering other services the ship may need. He needs information in order to forward it promptly and arrange the ship's call at the port to the best possible effect. He keeps contact with the port authority, sharing all the useful information, in order to forward them to the right recipients. This allows the port to handle the cargo in the fastest and most efficient way.

- **Pilot**

  Many ships need a pilot for arrival at and departure from the port. For larger vessels two pilots are sometimes necessary. Before the pilot comes on board of a ship, he must have access to as much information as possible about the incoming ship. It is particularly important to have an accurate berthing plan informing which berth has been previously reserved for that ship, considering all the constraints that could have been present in the area. He has the responsibility to guide the ship into the port seas, which is much more difficult than the high seas navigation.

- **Tugs**

  They are requested by the agent or the commander well in advance before the ship arrival. The number of tugs is regulated depending on the ship size, terminal of destination and the current weather conditions. They are in charge of dragging the ship towards the berth, because when a ship arrives into the port seas it has to shut down the engines.

Figure 1.37: Tugboat

- **Boatmen**

  When a ship is arriving at or departing from a terminal it is necessary for the mooring staff to handle some robust cables, that allows to moor the ship, sometimes with the help of one or more boats. The tasks they perform are important for safe berthing as well as a safe departure.

- **Terminal operators**

  Each terminal has usually its own proceedings for loading and discharging cargo. It plays a crucial role in creating an efficient service during a ship's call. They need to share information with the port authority in order to allow a complete visibility for all the main actors.

Chapter 2

Optimization Problems

2.1 Operations Research

Operations Research can be defined as “the use of quantitative methods to assist analysts and decison-makers in designing, analysing, and improving the performance or operation of systems” (*Carter, Michael, Price, Camille, and Rabadi,Ghaith, “Operations Research: A Practical Introduction”, CRC Press, 2018*). The systems can be an engineering system or a financial, industrial, scientific one. The most important thing is that all these systems are characterized by the possibility to be treated and solved thanks to a scientific approach that justifies the use of Operations Research. Many different disciplines can be incorporated in Operations Research because it tends to use from them various analytical tools. However, this science tends to report some results that must be supervised and critically studied by decision-maker and analysts in order to take a decision that allows to achieve the best performance desired for the system [10]. This means that the analytical tools used by Operations Research are only able to provide information and results data, but all the connections that could arise from the analysis are a different job, even if also part of Operations Research.

Historically, the dawn of Operations Research dates back to World War II, when the British Army created some teams, in charge of support the operational activities with quantitative based analysis [10]. In particular, the first created team helped the British to win the battle against the German submarines. This success created a spirit of emulation among the different armies in Britain, but also among the Allies, that tended to use more this quantitative approach to improve their decision processes. So, these teams ended to be extremely useful for the war, helping the British and the Allies to win the conflict. After World War II, the British Association for the Advancement of Science began to acknowledge the value of Operations Research as a real science in a symposium organized in Dundee in 1947. From that moment, the use of Operations Research always grew through the time, thanks to the increased interest on civil and industrial application and most of all, with all the development of simplex algorithm for linear programming and of computers ability and speediness to make calculations. For this reason, also computer science is strictly related to the world of Operations Research, in order to improve the ability of computer to solve difficult problems and so, to assess more difficult instances.

The main sectors in which Operations Research are now utilized are:

- Financial engineering
- Manufacturing
- Public Services
- Supply Chain
- Policy modeling
- Transportation

Operations Research involves a significant range of methods that can be used to solve the problems faced, as simulation, mathematical optimization, queueing theory, neural networks, analytic hierarchy process, etc. A possible classification among the various group of tools can be related to the different approaches available:

- **Optimization approach** (what-is-best): in this way the problem is solved in order to obtain an optimal or sub-optimal solution, after the definition of a model.
- **Simulation** (what-if): it is used to analyse the same problem but with different configurations. It requires a lot of statistics or game theory tools in order to obtain good parameters.
- **Stochastic processes**: this is the branch in which all the models are probabilistic, in order to determine the behaviour of the system. They are strictly related to Financial Engineering.

In the following paragraph, optimization is introduced.

2.2 Optimization and Linear Programming

An optimization problem is defined as the search for the **optimum**, a minimum or a maximum as appropriate, of a function. A lot of circumstances lead the engineers to use an optimization approach, because it could be a client's request or a needing due to the performance required for the systems under analysis. However, all the systems are characterized by some constraints, that must be considered in an optimization process. Obviously, it is extremely rare to be able to completely represent the system in all of its features, constraints and peculiarities, because if an optimization approach is necessary, then the problem is very complex and so the solution provided must be considered as an approximation. Nevertheless, optimization is always a good tool of conceptualization and analysis and it allows engineers to comprehend how the systems behave in the different situation analysed [11]. In order to practically optimize a problem, it must be defined a **mathematical model**, via mathematical programming. This means that all the relevant features of the problem should be represented by means of mathematical abstraction. Differently from other instruments like regression or artificial neural networks, where the relationships between input and output are not clear or explicit and must be understood, in this case, the problem has relatively a specific and definite structure, that permits to design the model required to solve the issue [12]. The description made suggests the idea that this model is composed by a function, with some decision variables and parameters, which had to be optimized respecting some constraints. Then, the most important elements of an optimization model are [13]:

- **Objective Function $\boldsymbol{f}$**
  It is the function that needed to be optimized. It can also be called the cost function or optimization criterion.

- **Decision variables $\vec{x}$**
  It is a vector of variables x, whose assumed values allow to perform the search for the optimum of the objective function.

- **Constraints**
  They are the limits in which the search for the optimum has to move. In fact, they describe the search space.

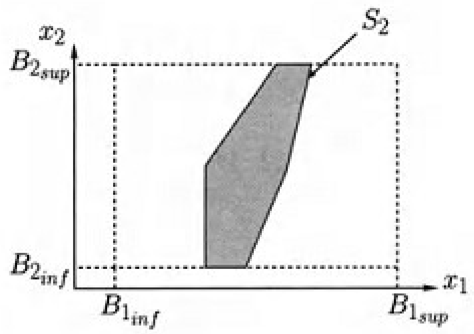


Figure 2.1: Search Space

Although the objective function and the constraints are specific for the problem to be treated, they can be schematized as follows [13]:

$$\begin{array}{ll} \boldsymbol{minimize} & f\ (\vec{x}) \\ with & \vec{g}(\vec{x}) <= 0 \\ and & \vec{h}(\vec{x}) = 0 \end{array}$$

where $\vec{x} \in \mathrm{I\!R}^{\mathrm{n}}$, $f\ (\vec{x}) \in \mathrm{I\!R}$, $\vec{g}(\vec{x}) \in \mathrm{I\!R}^{\mathrm{m}}$, $\vec{h}(\vec{x}) \in \mathrm{I\!R}^{\mathrm{p}}$.

At this point, it must be highlighted that different types of mathematical programming exist. The simplest is surely the **Linear Programming (LP)**. In this case the function cited before is linear in the unknowns and also the equalities and inequalities defined by the constraints are linear [11]. However, if there are some integer variables (for example binaries ones), then a **MILP (Mixed Integer Linear Programming)** is required. This type of problem is a variation to integer linear programming (ILP) where all the variables can be defined in a continuous or integer set, as appropriate [12]. Nevertheless, even if MILP allows to deal with many more problems than LP, the solution methods require a significant increased computational effort. Fortunately, nowadays, cutting-plane and branch-and-bound techniques are well implemented in the most common solver available on the market (CPLEX, Gurobi, etc.). These two methods are considered the most efficient way to lead a MILP problem to the optimality [12], even if for large size instances they could be insufficient, making necessary the development of heuristics, metaheuristics, genetic algorithms or, more in general, other different ways to obtain an optimal solution. For LP problems, the simplex method can be used to obtain the solution. Nonetheless, not always the resolution of a problem can lead to optimality, but it is possible that the problem is **infeasible**. This means that there is no combination of the value assignable to the variables, respecting all the constraints, that allows to obtain a feasible solution [11]. Instead, a different situation appears when there is an **unbounded solution**, i.e. a solution where the variables can assume values as high (or as little) as possible, without a physical limit [11]. Apart from these situations, in general a MILP or LP should provide at least one optimal solution, in order to take some conclusions about the results. It is also possible to have **multiple optimal solution**, where different combinations of the variables lead to the same value of the objective function [11].

An interesting way of using optimization in linear programming is to investigate the behaviour of the optimal solution with respect to changes in the input parameters of original optimization problem. This is the so-called "**sensitivity analysis**" or post-optimality analysis and sometimes it is even more important than the optimization itself, just because in real life the parameters to work with are not definite or maybe are forecasted and consequently they could be affected by various form of errors. To be more precise, this analysis tends to study how the optimal solution varies if any variations in the input data occurred. This approach could be really useful to evaluate different scenarios, augmenting the power of linear programming and allowing to increase the perspective of the conclusions that could be obtained from the model realized [14].

2.3 Optimization problems in ports and terminal containers

A terminal container in a port can be interested by different types of optimization problems. However, it is important to highlight that in that context of logistic and transport systems (as in the planning of any other system), these problems can be classified on a precise hierarchical structure, according to the subsystem interested [15]:

- **Strategic level**: all the problems concerning the design and the long-term planning of a terminal container, with a time horizon in order of magnitude of years. These problems are enormously important for a terminal container because they define the system structure and resources and they lead to high expenses in order to be performed, when the choice is made. These strategic level problems are usually faced by top management, for their importance. In terms of planning effort, they are usually simple problems, because they work with aggregated data and they are not so specific, but the main issue is to estimate the data on which they are based, because there is a lot of uncertainty. Some typical examples of these problems are the design of the layout of the terminal or all the choices concerning the equipment to provide.

- **Tactical level**: it is an intermediate level, with a medium-term planning (usually not more than one year, not less than one month). In general, in terms of structure these decisions are more complicated, but they work with less aggregated data, but easier to estimate and so less affected by error and uncertainty. They are usually faced by high level of the management and some examples can be the allocation of the workforce or the vehicles in the different areas of the terminal, etc.

- **Operational level**: all the problems focused on the day by day operations are included in this class. They require short term decision, with a time basis of hours or days. They are usually the most difficult problem to face because they need to be solved in a short time, but a high detail level is required, because all the possible constraints must be taken into account. However, this often means that the data are easily available and usable. They are usually faced by the local level of management. Some problems classifiable in this category are the scheduling of the operations to be performed, the resource allocation or routing problems.

- **On-line level**: this decision-making level is a sort of branch of the operational level and it concerns all the activities of supervision and control, in order to comprehend if some distortions are occurring from what has been planned. These problems could be really difficult to face, because they require immediate actions.

For the aim of this thesis, it is relevant to give more details about the operational and on-line level problems. As said before, they are the most difficult in terms of structure and for the way the solution needs to be found. However, they are also extremely important because they can work on crucial factor for a terminal, marking the difference between two competitors and so allowing the best to obtain a competitive advantage. This explain why from 2000 these problems became more widespread in literature, with a constantly increasing interest, also due to the parallel growth of the intermodal and containerized transport [16]. The two levels differ mainly for the way in which the optimization is processed. In fact, the operational level tends to work with all the data available before the beginning of the process, while an on-line level process works directly with the data arriving in real time [16]. This "live" approach is better for some reason, because it allows to work with more precise data and not only on forecasts or planned data, but that could change for a lot of reasons. However, the quality of the solution provided by this approach can't be comparable to the one related to the offline optimization and in fact it is said that this approach provides sub-optimal solutions. At the same time, while an offline optimization, with all the data available, could lead to better results, it can provide also unrealistic solutions, because the data could be not true anymore when the process starts. In a terminal container this situation is not uncommon, because, for example, the terminal cannot control ships or trucks or trains arrival, and all these data would be only planned, but not "real" until a truck, a ship or a train arrives. Concluded this premise, it must be said that this does not mean that offline optimization is not used. On the contrary, this is really widespread in literature, because it allows to do several types of analysis, but it must be comprehended that in a port environment, the system must take into account also an on-line planning, especially for some specific problems.

Now, a focus on the most common operational optimization problems in a port terminal is presented, according to the scheme reported in the paper by *Bierwirth, Christian, and Frank Meisel "A survey of berth allocation and quay crane scheduling problems in container terminals"* [17]. As can be seen in Figure 2.2, the problems are organized by area of the terminal in which they are located, dividing the terminal in seaside, yard and landside. This work is focused on the operations concerning the ships arrival in the port, so landside and yard are not taken into account in the following descriptions.

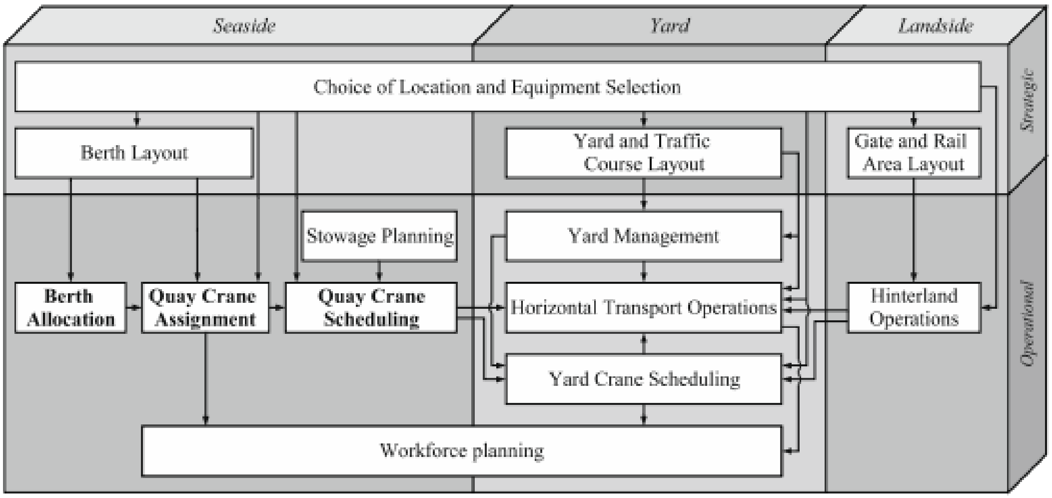


Figure 2.2: Terminal containers optimization problems by area

- **Stowage planning**: on a ship, the position of each container is identified by a triad of three coordinates, which are bay, row and tier, as it can be seen in Figure 2.3. In this case the optimization is used in order to determinate the space allocation of each container on board, aiming to put each of them in the best triad possible, considering various factors like the weight of a container, the destination and origin port, the content, etc. with the final goal of minimizing the total loading or unloading (or both of them) time. To be more precise, the objective is usually to minimize the number of movements necessary to catch a container which is behind or below other ones [16]. Many different constraints can be present in a similar optimization problem, like, for example, a limited number of electrical sockets to connect reefer container to, or simply physical limits due to the stability of the ship.

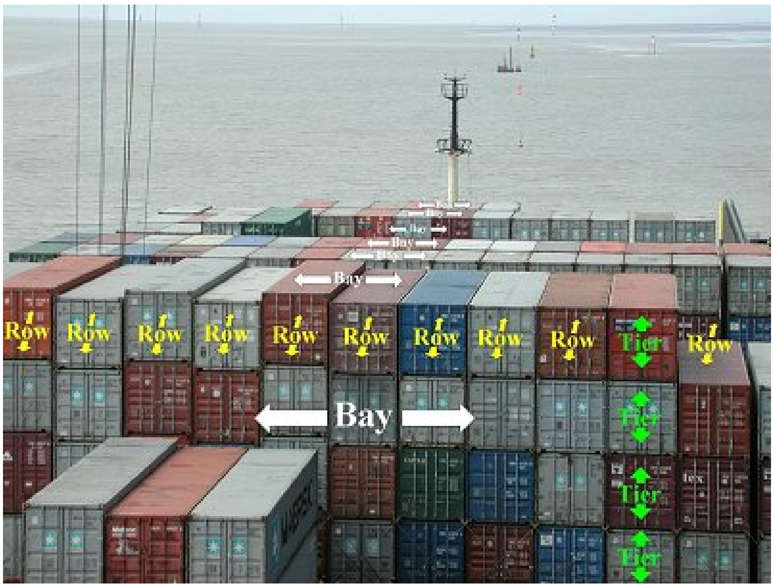


Figure 2.3: Container coordinates on a ship

- **Berth Allocation Problem (BAP)**: the number of ships arriving in a port terminal every day is incredibly high and so it must be well organized, in order to exploit in the best possible way the quay available for the port. In general, the typical objective function of these problems is to minimize the total berthing time, but the setting of the problem can vary a lot, according to the desired detail level of the problem and to which aspects emphasize or not [16]. A more detailed description will follow in the next paragraph.

- **Quay crane scheduling and assignment problem (QSCAP)**: once defined the arrival berth for each ship, it must be determined a resource allocation about the quay cranes that should serve the ships. The problem can be declined in several forms, but in general the objective is to identify the optimal number of quay cranes that should serve a ship and which quay crane should be assigned to each bay of the ship. In this case the final goal is to minimize the makespan for that ship, in order to increase the productivity of the port and make it more competitive [16]. However, a lot of constraints arise in this case and they can obviously vary among different variants of the same problem. Nevertheless, common constraints are caused by the agreement concluded between the shipping line and the port authority, that can limit the number of cranes assignable to a specific shipping company; another example can be related to the structure of these quay cranes, that are usually moved on rails, thus meaning that the cranes operating on a ship cannot overlap each other. These are only simple examples, but, as said before, the setting of the problem can be changed in relationship to the aim of the problem that is been facing. For example, it can be allowed that a bay could be served by multiple quay cranes at the same time, so changing the constraints of the problems; instead, objective function may vary too, concentrating not on the makespan but on the utilization of quay cranes, pursuing its maximization [17].

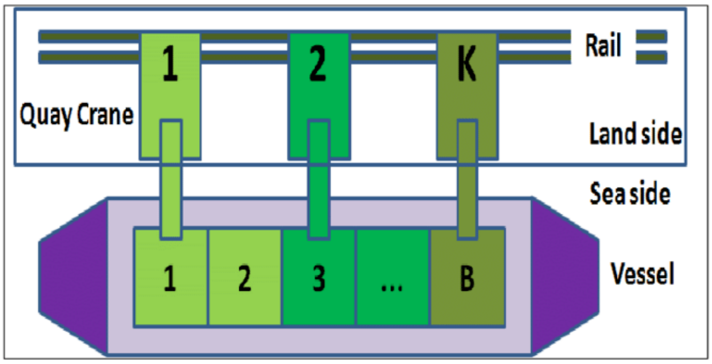


Figure 2.4: Quay Crane Assignment representation

It is important to highlight that recent studies have tried to implement BAP and QCSAP together. Actually, the two problems are strongly interconnected and so this approach makes sense, but the complexity of the problem considerably increases [17].

2.4 BAP: Berth Allocation Problem

Berth Allocation Problem "is the assignment of quay space and service time to vessels that have to be unloaded and loaded at a terminal" (*Bierwirth, Christian, and Frank Meisel. "A survey of berth allocation and quay crane scheduling problems in container terminals." European Journal of Operational Research 202.3 (2010): 615-627*). In a similar problem the layout of a terminal container is given, with a certain number of vessels arriving in the port at a given time; these vessels must be served in a specific time horizon. This is only the basis of the problem, but more details could be considered, as the vessels dimensions or the quay, the handling or mooring times, etc. From a structural point of view this is an optimization problem in which a given objective function must be optimized, assigning to a ship a berthing position during a certain amount of time, considering that the vessels cannot occupy the same berthing position simultaneously [17]. A space-time representation of this problem is showed in Figure 2.5.

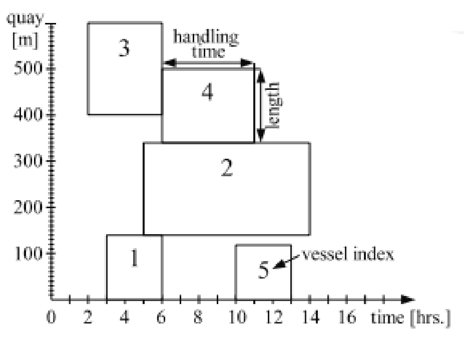


Figure 2.5: Chart representation of BAP

Understood the basis of the problem, it is important to highlight that there are several different BAP formulations, according to the way in which various features are defined. Then, here a presentation on how these features can be considered is [17]:

- **Spatial constraints**: this is referred to the way in which the berths are modeled. There are three main cases:

  – Discrete layout: the quay is divided into berths, which are the stations in which the vessel can moor when they arrive. One berth can host only one vessel at a time.

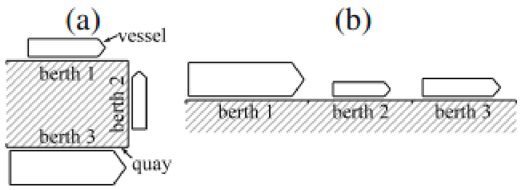


Figure 2.6: Discrete layout

  – Continuous layout: the quay is not partitioned, and a vessel can berth in every possible way along the quay, respecting its physical boundaries. In this case the problem is more complicated than the discrete one, but it allows to obtain a better utilization of the space.

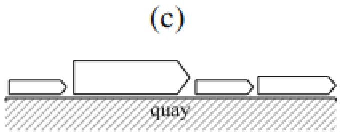


Figure 2.7: Continuous layout

  – Hybrid layout: the quay is divided in berth, but one of them can be shared by different vessels, while a big vessel can use more than one berth at the same time. For example, this configuration allows to represent the situation in which a ship berths in a way that allows to load/unload from both sides, as shown in Figure 2.8(f) and 1.36.

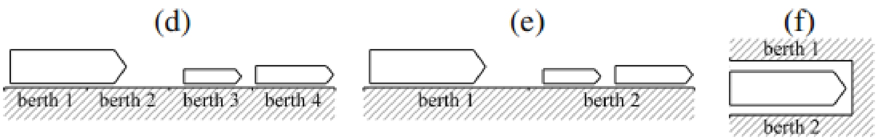


Figure 2.8: Hybrid layout

- **Draft constraints**: vessels are allowed to berth along the quay only if a sufficient water depth is available. This a real problem for a lot of ports characterized by tidal effects.

- **Re-positioning**: vessels usually do not change their position during the service time, but it can be considered a re-positioning during these operations, allowing the vessel to re-position, but increasing the total handling time.
- **Arrivals**: vessels arrivals can be organized in two different ways:
  - Static arrivals: the vessel are all ready and wait to be served outside the port; it is like there is no arrival of the ships and so there are no constraints related to the start of their processing.
  - Dynamic arrivals: each vessel arrives in a precise moment in the time and so it cannot be served before that moment.
- **Due date**: sometimes a ship must depart from a port within a specific date, so it must be processed before that time, in order to correctly serve that "client".
- **Handling times**: they can be considered in many different ways:
  - Deterministic handling times
  - Depending on berthing positions
  - Depending on the number of cranes serving the vessel
  - Depending on work schedule and on the assignment of the cranes during the time
  - Depending on all the factors mentioned above

  However, quite always the handling times are considered deterministic in literature.

In terms of objective function, in most of the literature papers about this matter, the **total completion time** tends to be minimized. This is obtained when the goal is to minimize the sum of waiting time and service time for each ship, thus reducing the total port stay time. However, it is possible also to focus on only one of these two aspects, i.e. waiting or handling time. Other objective functions can be the speedup of a vessel or the tardiness, in order to limit the difference between the departure time of a ship and its due date; also the minimization of the rejected vessels can be an interesting performance measure to investigate, as the resource utilization "generated" by each vessel or the distance, referring to the position, between the desired berth and the assigned one. Finally, using a multiobjective approach, more than one objective function can be analysed at the same time. A summary list of the possible features that characterize this kind of problem is presented in Figure 2.9.

2.5 BAP with tides constraints

As mentioned in the previous chapter, a physical limit that could be taken into consideration, realizing a mathematical model for the BAP problem, is the draft of the ships, especially considering the growth that ships are experiencing in these years. In fact, nowadays, with the **naval gigantism**, these drafts have become bigger and bigger, causing more and more problems to the management of port

A classification scheme for BAP formulations.

Value	Description
1. Spatial attribute	
disc	The quay is partitioned in *dis*crete berths
cont	The quay is assumed to be a *cont*inuous line
hybr	The *hybr*id quay mixes up properties of discrete and continuous berths
draft	Vessels with a draft exceeding a minimum water depth cannot be berthed arbitrarily
2. Temporal attribute	
stat	In *stat*ic problems there are no restrictions on the berthing times
dyn	In *dyn*amic problems arrival times restrict the earliest berthing times
due	*Due* dates restrict the latest allowed departure times of vessels
3. Handling time attribute	
fix	The handling time of a vessel is considered *fix*ed
pos	The handling time of a vessel depends on its berthing *pos*ition
QCAP	The handling time of a vessel depends on the assignment of QCs
QCSP	The handling time of a vessel depends on a QC operation schedule
4. Performance measure	
wait	*Wait*ing time of a vessel
hand	*Hand*ling time of a vessel
compl	*Compl*etion time of a vessel
speed	*Speed*up of a vessel to reach the terminal before the expected arrival time
tard	*Tard*iness of a vessel against the given due date
order	Deviation between the arrival *order* of vessels and the service order
rej	*Rej*ection of a vessel
res	*Res*ource utilization effected by the service of a vessel
pos	Berthing of a vessel apart from its desired berthing *pos*ition
misc	*Misc*ellaneous

Figure 2.9: BAP Classification scheme

authority around the world. Among them, a lot of river port are struggling in their operations, because of the effects of tides on the water level and consequently they have to adapt their systems to allow the entrance of a ship in the port, because of an excessive draft [18]. This situation caused an increasing interest in research, in order to face this problem. The first work that considered this particular issue is *"Berth allocation with time-dependent physical limitations on vessels", Xu, Dongsheng, Chung-Lun Li, and Joseph Y-T. Leung. European Journal of Operational Research 216.1 (2012): 47-56.* In that pioneering work the authors tried to highlight how big was the impact of **tidal effects** on the Pearl River Delta ports of China. In fact, the companies operating in that area were suffering the presence of deep-draft vessel, because of tide effects on river ports, losing millions of yuan and with a consistent damage to their competitiveness. This was caused by the fact that the BAP they considered did not take into account the tidal effects and so it provided infeasible solution in the real world. The paper of Xu et al. so proposed a BAP with water depth changing trough the time (thanks to the tidal effects), showing that their solution allowed to help terminal operators to make better decision when assigning vessels to berths [19]. However, in this paper the tidal effect was modeled partitioning the level of the sea into two subgroups: high tide and low tide; moreover, they considered only a time horizon of 24 hours, not enough to solve more complicated instances. Then, the evolution trough the time of the water level is missed and only a cyclical change is modelled. Nevertheless, after that work, interest in the problem arises, also because many different ports in the world had the same issue, like Shanghai, Shahid Rajaee and Hamburg. So, other papers have been published on that matter, distinguished by the resolution method, by the case study, by the way in which the tide is modelled or the arrival considered, etc. varying features according to the classification made in the previous paragraph. To completely understand how impactful are these tides constraints an example is presented, taken by *Song, Yujian, et al. "The berth allocation optimisation with the consideration of time-varying water depths." International Journal of Production Research 57.2 (2019): 488-516.* In this work, the tide is modelled not as in Xu et al., but a specific pattern is described, as shown in Figure 2.10.

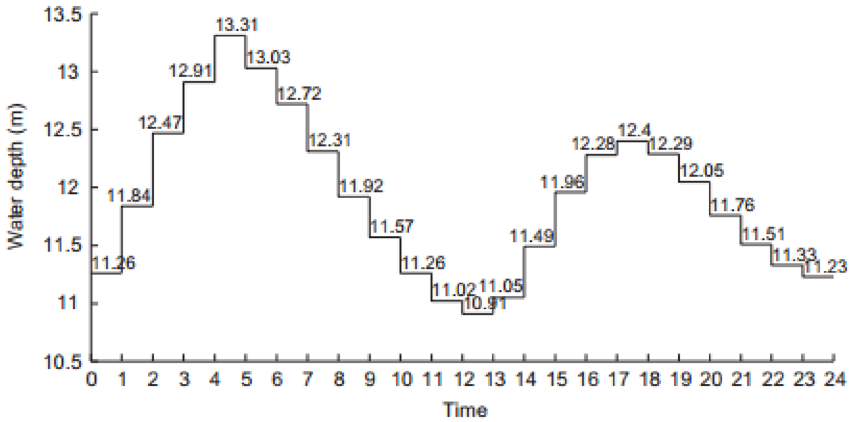


Figure 2.10: Water depth changing due to tides effect

With the model presented in the paper, an illustrative instance is optimized with and without the tide constraints. The resulted diagram is shown in Figure 2.11, where on the y-axis are represented the two berths considered, while the x-axis is a temporal axis (the model of the paper considered a BAP and QCSAP integrated problem and so the grey rectangles represent the number of quay cranes assigned to each vessel) and the blue vertical lines are used to show the time in which the vessel leaves the port [18]. The objective function indicated in the paper wanted to minimize the weighted sum of the difference between departure and arrival of each vessel. As reported in the paper and comprehensible from Figure 2.11, the problem considering the tides constraints provides a worse solution (15.8), higher than the case in which this constraint is not considered (13.5). However, as it is imaginable, the 13.5 solution is not feasible in the real world, because it generates a situation in which a ship should leave the port without having a sufficient water level for its draft [18].

In the next chapter a Berth allocation problem with tides constraints will be defined and used to evaluate different scenarios.

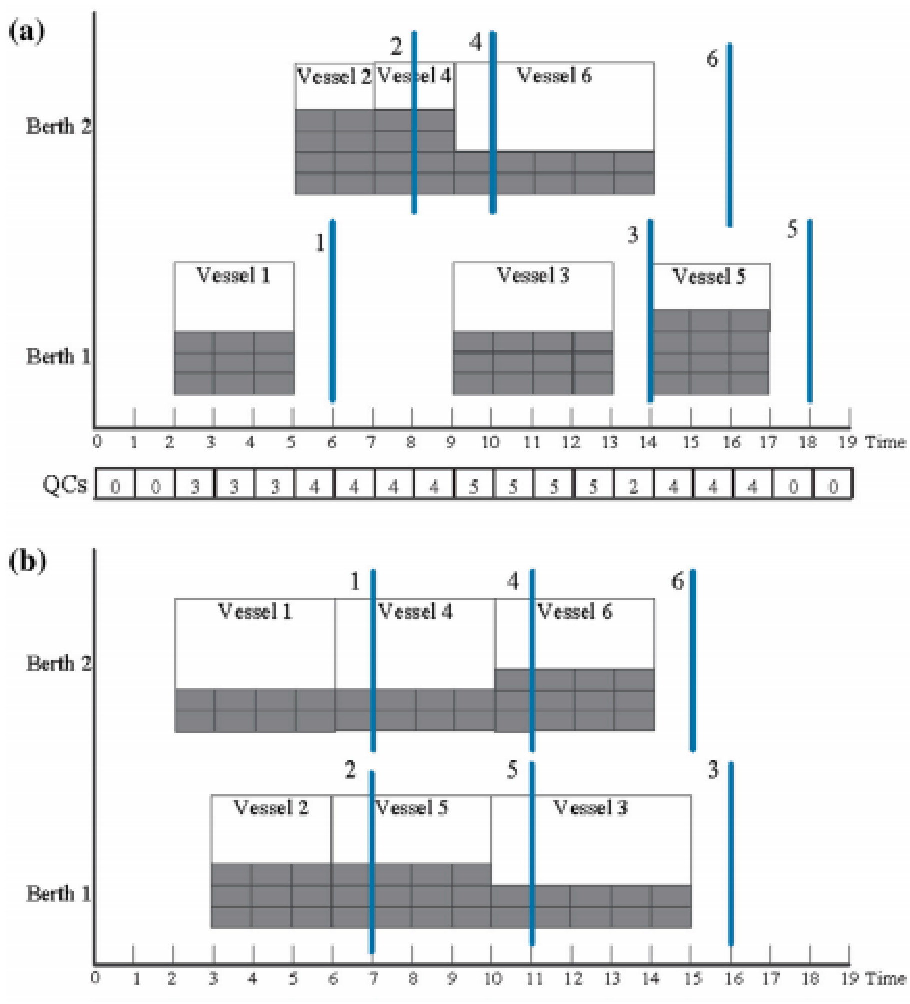


Figure 2.11: BAP leads to different results considering tides constraints

Chapter 3

Data and Model

3.1 Optimization Model

Focus of the thesis is to optimize a specific Berth Allocation Problem with different data input, in order to evaluate some performance measures in different scenarios.

In order to do that, a problem must be defined and with it an optimization model. The problem identified is a BAP with tides constraints, but considering not as in Xu et al. [19] only a division of the time horizon in high tide and low tide window, but defining a time-varying water depth, according to the behaviour of tides. The problem can be defined according to the BAP classification presented in Figure 2.9 in Chapter 2.

- **Spatial attribute**: the layout considered in this problem is discrete, so the quay is divided into a specific number of berths in which the ships can be moored.
- **Draft constraints**: obviously, these constraints are present. In particular, the problem requires an adequate level of water depth during the berthing time.
- **Repositioning**: not allowed.
- **Due date**: not considered.
- **Handling times**: they are considered deterministic, but different levels are present, as it will be seen in the next paragraphs.
- **Arrivals**: dynamic arrivals are considered. So, every ship has a specific arrival time and cannot be processed before that time.
- **Objective function**: completion time is the function to be minimized, in order to reduce as much as possible the difference between arrival and departure time of each ship. However, in further analysis, also service level is considered, trying to understand how many ships will not be served.

The problem analysed is derived by *Qin, Tianbao, Yuquan Du, and Mei Sha. "Evaluating the solution performance of IP and CP for berth allocation with time-varying water depth"*[20].

In order to present their model a description of all the indexes, variables and parameters used in it, is necessary.

- Indexes

Index	**Description**
i	It is related to the ships. It varies from 1 to n, where n represents the number of ships arriving in the port
k	It is related to the berths. It varies from 1 to m, where m is the number of berths available in the defined quay layout
t	It is related to the time unit. It varies from 0 to T, which is the time horizon. Time granularity considered is 1h. So, between t and t+1 there is one hour of difference.
s	It is also related to the time unit, but it varies in different intervals than t.

Table 3.1: Indexes

- Variables

Variable	**Description**
C_i	The time in which a ship has been completely served and can depart from the port. It is defined in an integer set, composed by numbers from 0 to T, as it will be seen in the model
x_{kit}	It indicates when (t) a ship i starts its stevedoring at berth k. They are binaries variables
x_{kis}	It is the same of x_{kit}, but it refers to s index

Table 3.2: Variables

- Parameters

Parameters	**Description**
T	Time horizon in which the problem is solved and executed. It is defined as: $T = 5 \cdot 12 \cdot n/m$.
p_i	Processing time for the ship i
a_i	Arrival time of ship i
d_i	Draft of ship i
r_{kt}	Water depth level of berth k at time t
w_i	Weight of ship i for calculation of objective function

Table 3.3: Parameters

The most important **assumptions** behind the definition of the model are [20]:

- Each berth is considered to be longer than the longest arriving ship. This means that every ship can be berthed to every berth.
- Berths are homogeneous, i.e. they have the same productivity and handling times do not depend on berths.
- The draft value d_i of each ship already includes the additional water depth requirement for under knee clearance, defined by the considered terminal operator.
- Water depth level is constant in the time unit. In fact, time is discretized in intervals; so, between t and t+1 water depth level does not change. As a consequence, water depth levels appear having a similar pattern.

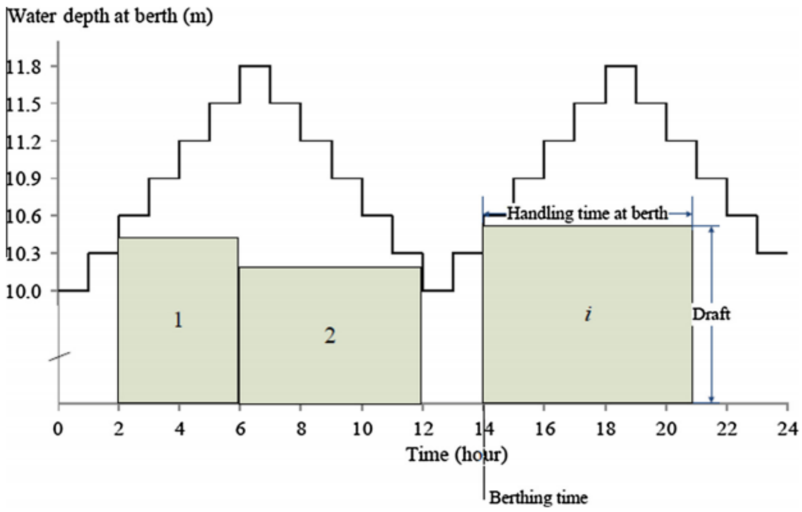


Figure 3.1: Time varying water depth pattern

After these premises, the **model** can be presented [20]:

$$\textbf{min}\ \ f = \sum_{i=1}^{n} w_i(C_i - a_i) \tag{3.1}$$

s.t.:

$$x_{kit} = 0 \qquad k = 1, ..., m,\ \ t = 0, ..., a_i - 1,\ \ i = 1, ..., n \tag{3.2}$$

$$\sum_{k=1}^{m} \sum_{t=0}^{T-p_i} x_{kit} = 1 \qquad i = 1, ..., n \tag{3.3}$$

$$\sum_{i=1}^{n} \sum_{s=max\{0,t+1-p_i\}}^{t} x_{kis} \leq 1 \qquad k = 1, ..., m,\ \ t = 0, ..., T - 1 \tag{3.4}$$

$$\sum_{s=max\{0,t+1-p_i\}}^{t} d_i \cdot x_{kis} \leq r_{kt} \qquad k = 1,...,m, \;\; i = 1,...,n, \;\; t = 0,...,T-1 \tag{3.5}$$

$$x_{kit} = 0 \qquad k = 1,...,m, \;\; i = 1,...,n, \;\; t = T - p_i + 1,...,T-1 \tag{3.6}$$

$$\sum_{k=1}^{m} \sum_{t=0}^{T-p_i} (t + p_i) x_{kit} = C_i \qquad i = 1,...,n \tag{3.7}$$

$$x_{kit} \in \{0, 1\} \qquad k = 1,...,m, \;\; i = 1,...,n, \;\; t = 0,...,T-1 \tag{3.8}$$

$$C_i \geq 0 \qquad i = 1,...,n \tag{3.9}$$

Now, it is necessary to explain the model just defined. First of all, the **objective function** in **3.1** explains that the final goal is to minimize the weighted sum of the differences between completion time C_i, i.e. the time in which ship i has been completely served and departs from the port, and a_i, i.e. the time in which ship i arrives in the port. It is extremely important to highlight that the time in which a ship arrives in the port is not necessarily the time in which terminal operators start to serve it. There could be in fact, a waiting time, due to total occupation of available berths or, especially in this configuration of BAP, a problem related to water levels, because of tides, that impede ships to enter in the port when they arrive. **Constraint 3.2** is related to the dynamic arrivals defined for this model: it makes impossible to serve ships before their arrivals. **Constraint 3.3** specifies that each ship must be assigned exactly one berth and one start time of stevedoring. **Constraint 3.4** requires that not more than one ship at the time can be moored in the same berth. **Constraint 3.5** requires that during all the time in which ship i is moored at berth k an adequate level of water depth must be available, in order to allow that ship to be moored there. Instead, **constraint 3.6** specifies that all the operations to perform for the ships must be completed within the time horizon. **Constraint 3.7** is necessary to define and assign a value to the auxiliary variable C_i, that is used in the objective function. Finally, **constraints 3.8** and **3.9** define variables domains.

Now, the main **differences** and variations introduced in the derived model of this thesis must be explained.

- Water depth level has been considered the same for every berth. So, the parameter r_{kt} became r_t, because it does not vary from berth to berth.

- The model described did not allow not to serve some ships. Considering that this thesis wants to use a similar model to analyse how big would be the impact of future fleets, with bigger drafts and more megaships, it is considered **possible not to serve some ships**. In order to do that the model has been changed. In particular, to the m berths physically present in the quays, b **fictional berths** have been added. Then, the model has been modified in this way:

$$\mathbf{min}\ \ f = \sum_{i=1}^{n} w_i(C_i - a_i) \tag{3.10}$$

s.t.:

$$x_{kit} = 0 \qquad k = 1, ..., m+b,\ \ t = 0, ..., a_i - 1,\ \ i = 1, ..., n \tag{3.11}$$

$$\sum_{k=1}^{m+b} \sum_{t=0}^{T-p_i} x_{kit} = 1 \qquad i = 1, ..., n \tag{3.12}$$

$$\sum_{i=1}^{n} \sum_{s=max\{0,t+1-p_i\}}^{t} x_{kis} \leq 1 \qquad k = 1, ..., m+b,\ \ t = 0, ..., T-1 \tag{3.13}$$

$$\sum_{s=max\{0,t+1-p_i\}}^{t} d_i \cdot x_{kis} \leq r_{kt} \quad k = 1, ..., m,\ \ i = 1, ..., n,\ \ t = 0, ..., T-1 \tag{3.14}$$

$$x_{kit} = 0 \qquad k = 1, ..., m+b,\ \ i = 1, ..., n,\ \ t = T - p_i + 1, ..., T-1 \tag{3.15}$$

$$\sum_{k=1}^{m} \sum_{t=0}^{T-p_i} (t+p_i)x_{kit} + \sum_{k=m+1}^{m+b} \sum_{t=0}^{T-p_i} (t+p_i)x_{kit} \cdot 1000 = C_i \quad i = 1, ..., n \tag{3.16}$$

$$x_{kit} \in \{0,1\} \qquad k = 1, ..., m+b,\ \ i = 1, ..., n,\ \ t = 0, ..., T-1 \tag{3.17}$$

$$C_i \geq 0 \qquad i = 1, ..., n \tag{3.18}$$

The model is formally quite the same, but its meaning changes a lot. As it can be seen from **constraints 3.11, 3.13, 3.15** and **3.17** now the berths are not m, but $m + b$, in all the indexes, parameters and variables. However, b of them are not real, but they are necessary to host all that ships that the model fails to serve, due to draft constraints. In fact, for these b berths, **constraint 3.14** is not applied, meaning that all the ships that cannot be served for draft constraints are planned to "berth" in these fictional berths, but practically they are not served. However, in order to make the solver assign these ships to these berths only in extreme cases, in which alternatively it would have provided an unfeasible solution, a **penalty** is applied for these berths, as can be seen in **constraint 3.16**. This constraint explains that all the ships berthed in the fictional berths have a penalty consisting of a x1000 factor on the value of C_i. This penalty discourages the solver to assign these ships to fictional berths, except if it is essential for the feasibility of the problem. Although this trick allows to create the possibility of avoiding serving all the ships, it creates some distortions on the objective function. In fact, if a ship is assigned to a fictional berth, it should not be counted in the objective function. So, it is necessary to develop a derived objective function, that from now on, will be named "**corrected objective function**". It is the same function, but considering only the served ships, thus avoiding any distortions. The corrected objective function has been defined as:

$$corrected\_of = \sum_{i \in Y} w_i (C_i - a_i)$$

where Y is the set of all the served ship.

Finally, it is important to also define another quantity, essential for the other phases of the work. All the ships that results to be moored on fictional berths must be counted, in order to define the "**not served ships**":

$$not\_served\_ships = \sum_{i=1}^{n} \sum_{k=m+1}^{m+b} \sum_{t=0}^{T} x_{kit}$$

In this way, optimizing the model, it is possible to have from its resolution two quantities that will be extremely important for the definition of performance measures and at the same time it makes for the solver not mandatory to serve all the ships, even if in this case there is a penalty.

3.2 Data generation

To use the model just described, it is necessary to generate some input data. The appropriate way to do this it is presented in the next two paragraphs, in which are explained the two main processes generate data input.

3.2.1 Random variate generation

All the data that needed to be generate are derived from a given distribution. So, a random variate is a realization of a random variable from that distribution. In order to obtain these data various methods can be used, but all of them require random numbers R_i uniformly distributed on [0,1], which generation will be described in the next paragraph, and a complete specification of all distribution parameters [21].

When deciding for a method for random variate generation (from now on called "**RVG: Random Variate Generator**"), different features must be taken into consideration [21]:

- **Exactness**: a RVG must provide variates following exactly the distribution desired.
- **Efficiency**: it should not require a big amount of time and memory space to generate these variates.
- **Complexity**: a RVG should not be too complex in terms of conceptualization and implementation of the generation algorithm.
- **Robustness**: a RVG must work efficiently regardless of distribution parameters.
- **Synchronization**: it is related to the ability of an RVG to bond random numbers R_i with the value of the random variate (for example, to a high value of R_i in [0,1] corresponds a high value of the random variate in its own distribution).

The most common generation methods are [21]:

- **Inverse-transform**:
  As it will be seen in the next paragraph, a random number R_i is generated with a value in the interval [0,1]. This means that R_i can be used also to represent the value assumed by a cumulative distribution function (cdf) $F(x)$, which is continuous and strictly increasing between 0 and 1. In this case X is a continuous random variable, which realizations x need to be generated. Let F^{-1} denote the inverse of F.

  So, the generation algorithm is the following:

  1. Generate $R_i \sim U[0,1]$
  2. Return $x = F^{-1}(R)$

  This algorithm is based on the following relationship between x and R:

  $$P(X \leq a) = F(a) = P(F^{-1}(R) \leq a) = P(R \leq F(x))$$

  This method is the simplest, but it cannot be always used. In fact, F^{-1} must be expressed in a closed form to allow to use inverse-transform. Alternatively, an exact solution cannot be found. However, this method is also the one which obtains the strongest correlation between the random number generated and their respective variates.

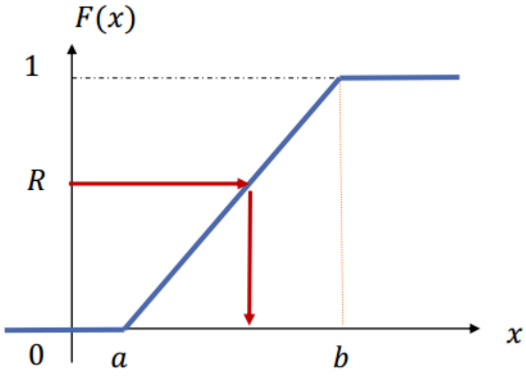


Figure 3.2: Relationship between x and R in a uniform cdf

- **Convolution**:
  This method is really useful when the random variable X can be easily expressed by the sum of other random variables, easier and faster to generate individually than variable X. So:

  $$X = Y_1 + Y_2 + ...Y_m$$

  If F is the cdf of X and G is the cdf of Y_i, convolution can be used with the following algorithm:

  1. Generate all the y_i, starting from G cdf.
  2. Return $x = y_1 + y_2 + ... + y_m$

  To generate y_i other methods can be used, inverse-transform too.

- **Acceptance-rejection**:
  This is a more complex method. It does not refer directly to the distribution of the random variate under analysis. However, this method defines a majorizing function $t(x)$, such that:

  $$t(x) \geq f(x) \qquad \forall x$$

  where $f(x)$ is the probability distribution function (pdf) of variable X.

  However, $t(x)$ is not a density, because:

  $$c = \int_{-\infty}^{+\infty} t(x)dx \geq \int_{-\infty}^{+\infty} f(x)dx = 1$$

  So, a density function $r(x)$ derived by $t(x)$ must be defined:

  $$r(x) = t(x)/c$$

  This can also be easily understood from Figure 3.3 [22].

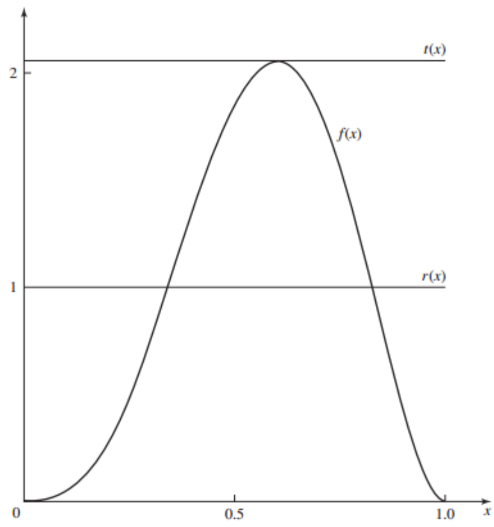


Figure 3.3: $t(x)$, $r(x)$ and $f(x)$ functions

At this point, it is clear that generating variates from $r(x)$ is simpler than from $f(x)$ and so, the following algorithm can be applied:

1. Define $t(x)$ as specified previously and calculate c.
2. Generate x from $r(x)$
3. Calculate values for $f(x)$ and $t(x)$
4. Generate a random number R and verify if $R \cdot c \cdot h(x) \leq f(x)$
5. If TRUE accept x generated. If FALSE reject x generated and come back to step 2.

Practically, this method is trying to fill the space under $f(x)$ with all the x accepted, trying to outline the same distribution, as shown in Figure 3.4

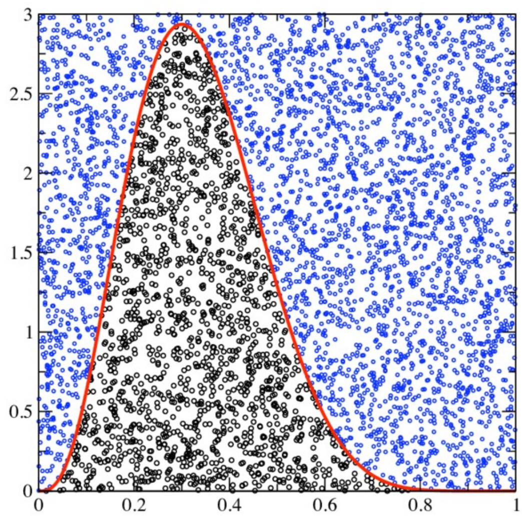


Figure 3.4: Blue points are the ones rejected, while only black ones are accepted

The problem related to this method is that it could be inefficient computationally if $t(x)$ is not well defined. In fact, it impacts a lot algorithm efficiency and so it should be carefully defined. For example, it is a good practice to define $t(x)$ as the maximum of $f(x)$ and not over, in order to reduce as much as possible rejection area (i.e. what is above $f(x)$).

- **Special properties**:
  It is a class of techniques used for specific distribution F, exploiting some special properties they are characterized by. An example can be the Box-Muller method for Normal distribution [22].

3.2.2 Random number generation

As seen in the previous paragraph, to generate variates, random numbers are necessary. These are essential elements for many different types of operations research projects. To be random, a sequence of number R_1,R_2, ... must be characterized by two properties: independence and uniformity [23].

- **Independence**: between a number R_i and any other number R_j of a sequence of numbers, there must not be any type of correlation.
- **Uniformity**: every number R_i of the sequence must be generated from a continuous uniform distribution between 0 and 1.

These properties have two main consequences. The first one is that the probability of having a number in a specific subinterval does not depend from the numbers previously generated [23]. The second is that if the interval [0,1] is divided in n equal subintervals and N numbers are generated, each subinterval is expected to contain N/n observations on average [23].

However, every random number generator (RNG) has a critical issue. In fact, it does not exist a real random RNG, but it is said that they are only "**pseudo-random**". The problem in fact is that there is always an algorithm that explains how to find a number R_i and so the sequence of numbers can be repeated. This clarifies why RNG are only pseudo-random. Therefore, they cannot have properties of uniformity and independence, but, dependently on how good they are designed, they could pass statistical tests used to check these properties for a random number generator. This means that they can seem to be actually random, getting closer to have these two properties [23]. The **statistical**, or empirical, **tests** used to verify the two properties mentioned before for RNG are:

- Frequency tests: Chi-square test and Kolmogorov-Smirnov test; they are used to verify uniformity.
- Autocorrelation tests: they are used to analyse the independence.

These statistical tests use to deal with the sequence of number generated, while another class of test, named **theoretical tests** or lattice tests, studies the structure of RNG, analysing its parameters and without working with a generated sequence of numbers [23].

In general, RNG starts with a sequence of integers X_1, X_2, ... and then they use these integers to define the sequence of R_1, R_2,... in this way:

$$R_i = X_i/m \qquad i = 0, 1, 2, ...$$

where m is the modulus.

There are several types of RNG. A possible classification is [23]:

- **Linear congruential generators (LCG)**:

  $$X_{i+1} = (aX_i + c) mod\ m \qquad i = 0, 1, 2, ...$$

  where X_0 is the seed, i.e. the initial value, a is the multiplier, c is the increment.

  In this case the generator defines the next element of the sequence of X based on the linear equation previously expressed.

- **General congruential generators (GCG)**:

  $$X = g(X_{i-1}, X_{i-2}, ...) mod\ m$$

  In this class of RNG the equation is different compared to LCGs, because it is not mandatorily based on a linear relationship, but it depends on the way in which $g(X_{i-1}, X_{i-2}, ...)$ is defined. For example, it can be a quadratic relationship:

  $$g(X_{i-1}, X_{i-2}, ...) = aX_{i-1}^2 + bX_{i-1} + c$$

  where b is another multiplier.

- **Composite Generators**: they are obtained mixing two or more generators together.

In order to evaluate the quality of a RNG it is necessary to analyse their **period** and **modulus**. The concept of period is related to the problem initially described of the possibility that the sequence can be repeated. In fact, due to the RNG's nature, when the same number are inserted in the equation, obviously the numbers resulting from the algorithm would be the same. So, for example, thinking about a LCG, if $X_{i+1} = (aX_i + c) mod\ m$ provides a value equal to X_0, the seed, the sequence will be entirely repeated. So, a period of a RNG can be defined as the length of the sequence of numbers before they start repeating. Obviously, it is better to have a RNG with a very long period. It is strongly related with all the parameters, especially with the modulus m. For example, for LCG the maximum period cannot be more than m, while for GCG it can be a power of m.

Instead, the modulus, also used in the equations of generators seen before, is very important to define the density of numbers R_i. In fact, R_i is defined dividing X_i, regardless of the type of RNG used, by m. So, the discretization of the interval [0,1] depends on how big is m. Bigger m allows to discretize more the space, increasing the similarity with a continuous interval. But, for example, if $m = 10$, it is possible to obtain only numbers like 0.1, 0.2, etc. This means that all the numbers between

0.1 and 0.2 cannot be generated. This is a problem, because it limits a lot the uniformity property required by RNG.

So, all the parameters of the generator must be chosen carefully in order to have the maximum period available and remembering that m should be big enough to grant a sufficient density. In general, m values are in the order of magnitude of about 2^{48}, to facilitate representation of this number on computers. Composite generators generally obtain a bigger period, if well defined. So, it is not a fortuity that the most widespread generator is the **Mersenne Twister**, with a period of $2^{19937} - 1$. This is the generator used in Python to generate random numbers and in fact it is also the one used for the aim of this thesis. In particular, `random` library has been used to generate random numbers with the command `random.uniform`.

3.3 Data Analysis

To provide data for the model described in paragraph 3.1 it is necessary to define how these input data have been estimated, in order to generate adequate variates, as described in paragraph 3.2. In the following, a detailed description of how these data have been gathered is presented:

- **Fleet mix**:
  Ships have been classified in three main categories, according to their capacity. They can be:
  - **Feeder**: small vessels, destined to take part of the container loaded on bigger ships and to distribute them towards small ports. This category includes ships with a capacity from 0 to 3 000 TEU.
  - **Deepsea vessel**: these are ships of medium size. They are mainly ships used in the past to serve bigger ports and the main routes and that have been progressively downgraded in terms of importance. This category includes ships with a capacity from 3 000 to 12 500 TEU.
  - **Megaship**: these are the biggest and newest ships, as described in Chapter 1. This category includes ships with a capacity from 12 500 to 25 000 TEU.

  Fleet mix is analysed under three scenarios, according to the forecasts presented in *Meng, Qiang, Jinxian Weng, and L. Suyi. "Impact analysis of mega vessels on container terminal operations." Transportation Research Procedia 25 (2017): 187-204.* In particular:
  - **First scenario**: it is defined on actual data based on record compiled in the work, related to Hong Kong port, one of biggest in the world [24]. The mix of this scenario is reported in Table 3.4

Ship category	Percentage
Feeder	49.14%
Deepsea vessel	50%
Megaship	0.86%

Table 3.4: Fleet mix 1, actual scenario

- **Second scenario**: it is a forecasted scenario for the short-term, related to Hong Kong port. It has been estimated from data reported in MAN Diesel (2008) [25], "based on the difference between the existing fleet mix of world container vessles in 2008 and the fleet mix under construction in 2008" [24]. The mix of this scenario is reported in Table 3.5

Ship category	**Percentage**
Feeder	41%
Deepsea vessel	54%
Megaship	5%

Table 3.5: Fleet mix 2, short-term forecast

- **Third scenario**: it is a forecasted scenario for the long-term, related to Hong Kong port. The authors define this estimation as "somehow subjective"[24]. So, it has been considered as an expert's forecast. The mix of this scenario is reported in Table 3.6

Ship category	**Percentage**
Feeder	10%
Deepsea vessel	70%
Megaship	20%

Table 3.6: Fleet mix 3, long-term forecast

- **Arrival times**:
The problem, as the one treated in the original work *Qin, Tianbao, Yuquan Du, and Mei Sha. "Evaluating the solution performance of IP and CP for berth allocation with time-varying water depth." Transportation Research Part E: Logistics and Transportation Review 87 (2016): 167-185*, is organized to study all the ships that arrives in a port during a week. So, as in the paper, arrivals are distributed in this way:

$$a_i \sim U[0, 168]$$

with hours [h] as time unit.

- **Ships draft**:
The draft of each ships varies relatively to each category and relatively to each scenario, considering the increasing draft predicted with the development of megaships [26]. They are presented in the following tables:

  - First scenario:

Ship category	**Draft value distribution [m]**
Feeder	U[5-10]
Deepsea vessel	U[10-14.5]
Megaship	U[14.5-15.5]

Table 3.7: Fleet mix 1 drafts

– Second scenario:

Ship category	Draft value distribution [m]
Feeder	U[5-10]
Deepsea vessel	U[10-14.5]
Megaship	U[14.5-16.5]

Table 3.8: Fleet mix 2 drafts

– Third scenario:

Ship category	Draft value distribution [m]
Feeder	U[5-10]
Deepsea vessel	U[10-14.5]
Megaship	U[14.5-17.5]

Table 3.9: Fleet mix 3 drafts

The actual values are taken from the classification reported in Figure 3.5 [27].

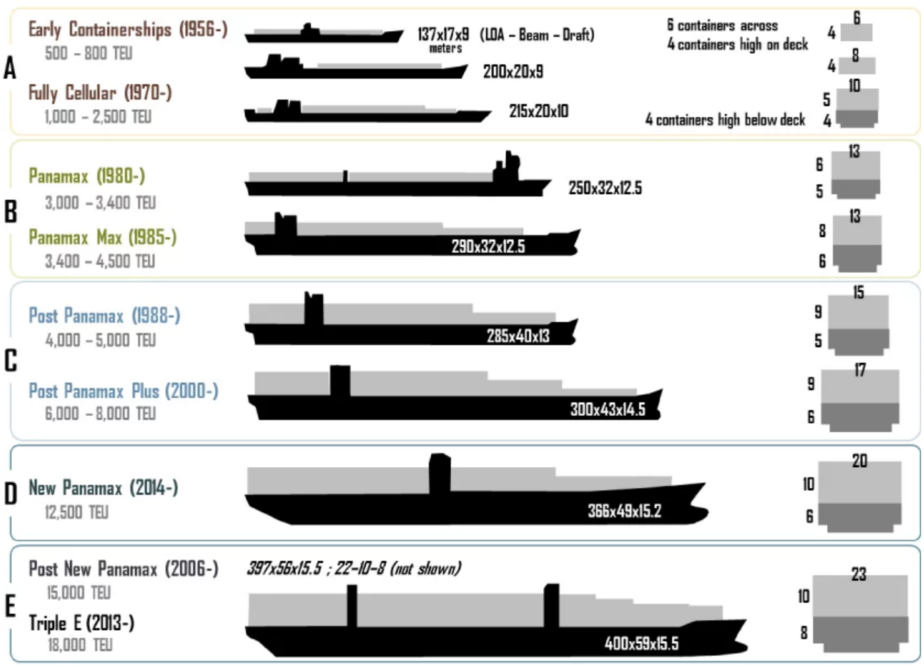


Figure 3.5: Containership sizes

Instead, the values from the forecasted scenarios are taken from the forecasts about ship dimensions reported in *Park, Nam Kyu, and Sang Cheol Suh. "Tendency toward mega containerships and the constraints of container terminals." Journal of Marine Science and Engineering 7.5 (2019): 131* [26].

- **Processing time**:
  Three levels of processing time are considered for each ship class. These three levels have been considered in order to take into account different productivity levels. In this way it is possible to evaluate some possible action that the terminals can take to improve their service time, also considering the future evolution of fleets [26]. So, in the next tables the three levels for each class are presented:

Productivity Level	**Processing time distribution [h]**
High Productivity	U[6-8]
Intermediate Productivity	U[8-10]
Low Productivity	U[10-12]

Table 3.10: Feeder processing times

Productivity Level	**Processing time distribution [h]**
High Productivity	U[12-14]
Intermediate Productivity	U[14-16]
Low Productivity	U[16-18]

Table 3.11: Deepsea vessel processing times

Productivity Level	**Processing time distribution [h]**
High Productivity	U[18-20]
Intermediate Productivity	U[20-22]
Low Productivity	U[22-24]

Table 3.12: Feeder processing times

- **Weights**:
  They can be defined relatively in a subjective way. The choice, in this case, is to give priority to bigger ships, in order to try to serve the maximum possible percentage and in the minimum possible time. They are related to the different ship classes and they are shown in Table 3.13.

Ship category	**Weight distribution**
Feeder	U[0-0.4]
Deepsea vessel	U[0.4-0.8]
Megaship	U[0.8-1]

Table 3.13: Weight distribution for each class

- **Water depth level**:
  To define these data two possibilities have been considered.

  – The first one is related to the actual situation of **Port of Antwerp**. In particular, this is a river port, crossed by Scheldt river. In September

Figure 3.6: Port of Antwerp

2011 this port has been characterized by some dredging operations, that have deepened the Scheldt, allowing megaships with deeper draft to berth in the port. In particular, this action increased water depth from an initial value of 11.8m to an actual value of 13.1m, regardless of tides [28]. However, tides effects can bring this value to a maximum of 15.5m of water depth [29]. The pattern to describe tides has been realized considering a change of 0.4m per hour, in order to reach the highest level of 15.5m, from 13.1m, in 6 hours. Then, after other 6 hours the water depth come back to 13.1m, as shown in Figure 3.7 that represents the described pattern of water depth.

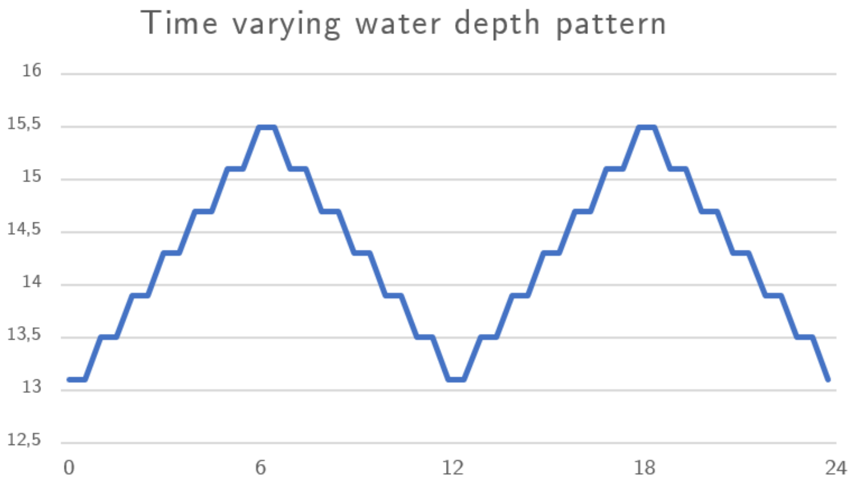


Figure 3.7: Actual water depth pattern

– The second possibility is a **hypothetical configuration** of port water depth, assuming a dredging operation similar to the one of 2011. In this case it is imagined that water depth is increased from 13.1m to 14.6m, regardless of tides, with a maximum level of 17m, reachable thanks to tides. The pattern to describe tides has been realized considering a change of 0.4m per hour in this case too, in order to reach the highest level of 17m, from 14.6m, in 6 hours, as described in Figure3.8

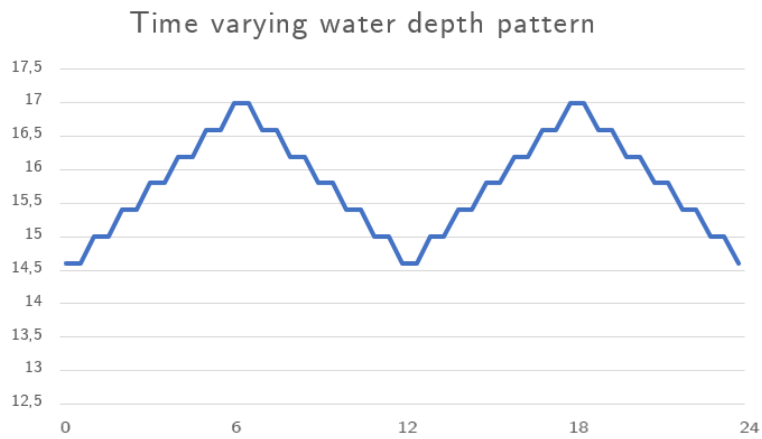


Figure 3.8: Hypothetical water depth pattern

These are all the data necessary to optimize the model described in this chapter. However, different configurations can be designed to test the model and the various scenarios described. In the following chapter all the details about the test performed will be presented.

Chapter 4

Numerical experiments

4.1 Instances and working method

Described the mathematical model representing the problem under analysis it is necessary to define the way in which it is solved and all the configurations of the problem that have been tested.

First of all, the mathematical model presented in Chapter 3 has been coded in **Python**, working with PyCharm 2020.1 environment, using `pythonmip` library. In particular, this library allows to solve MILP models, combining with a commercial solver. The solver used in this thesis is **Gurobi 9.1**, with an academic license, processed on a 2.50GHz Intel(R) Core(TM) i7-4710HQ CPU processor and with 8GB ram installed on the laptop utilized. The code realized is organized in a first part in which all the information from which generate data for the model are inserted. They are reported in lists, from which using different indexes, it is possible to extract the values necessary for the generation. In the following, all the instances are generated, using the methods described in the previous chapter. In order to sort correctly the data, the list related to the arrival of the ships is sorted in ascending order and all the other lists related to other data are sorted according to arrival list, using the `zip` function. Now, a clarification must be expressed. In fact, the total time to solve all the instances provided would have been too big to be performed in a single run. So, multiple run have been made, but in order to do this, a file with all the indexes to which the processing is arrived is realized and then, when a new run starts, these indexes are read from the file and so the new run can continue from the point in which the previous run stopped. Finally, the MILP model is written with `pythonmip` and $corrected\_of$ and not_served_ships are calculated.

The configurations on which the model has been tested are realized considering different values for the numbers of ships and berths, to represent different sizes of the terminal and different volumes of incoming ships. The number of ships and berths considered is reported in Table 4.1 and 4.2 and they represent realistic sizes of a terminal at a river port [20]. Therefore, combining these alternatives with the 3 fleet mix, 2 port configurations, 3 productivity levels for each of the 3 ship classes, a total of **1458 combinations** is studied.

$$\#Combinations = 3 \cdot 3 \cdot 3 \cdot 2 \cdot 3^3 = 1458$$

Ships
40
60
80

Table 4.1: Number of ships considered

Berths
5
7
9

Table 4.2: Number of berths considered

However, 5 instances for each combination are generated, for a total of 7290 analysed instances. So, the experimental results that will be reported consider averages over the five instances per combination.

At this point, it is necessary to highlight what this work wants to focus on. The model and its solutions are used to analyse how the performance measures, that will be defined in the following, change according to the various combinations. In particular, some of them are aggregated to outline how a possible change to the terminal configuration can impact the performances in different scenarios of incoming vessels and fleet mix, trying to isolate the effect due to that change from the ones derived from the others. In particular, three main aspects are analysed:

- **Dredging**: it is related to the possibility to deepen water depth level, as hypothesized in the previous chapter.
- **Number of berths**: it is related to the possibility to increase the number of berths, in order to have more flexibility for the incoming vessels.
- **Productivity improvement**: it is related to the possibility to increase productivity, reducing the time in which a vessel can be served.

Finally, the performance measures of interest must be defined, to obtain a good comprehension of the service quality that the hypothesized port is able to provide. Starting from the quantities *corrected objective function* and *not served ships*, the following performance measures are defined:

- **Average service time (AST)**:

  $$AST = corrected\_of/\#Ships$$

  This performance measure aims to calculate the average time necessary for each ship in the port to be served, regardless of the ship category. It is a way to evaluate how fast the incoming ships can be served in this port.

- **Average service level (ASL)**:

  $$ASL = (\#Ships - not\_served\_ships)/\#Ships$$

  This performance measure aims to calculate the average percentage of ships that are effectively served by terminal. It is a way to evaluate how good is the port to satisfy demand of incoming ships.

4.2 Dredging

Dredging operations are a series of activities necessary to increase water depth, favouring the passage of deeper ships. A dredging consists of an underwater excavation, performed by a dredge and realized in four steps: loosening the material, collecting materials on the surface, transportation and disposal. However, this can be a very expensive operation and a lot of environmental consequences can arise: impact on marine fauna and flora, toxic substances release, creation of "spoil islands", increase in water turbidity, etc. So, it is not a simple intervention and it can be performed only if well supervised and authorized.

Figure 4.1: Dredging operations in a port

In the case analysed this activity consists of increasing the depth from 13.1m to 14.6m, regardless of tides, reaching a maximum of 17m in the high-tide window, switching from the pattern shown in Figure 3.7 to the one represented in Figure 3.8. To comprehend how big is the impact of this intervention on port structure, a difference between the service level (ΔASL) and service time (ΔAST) before and after the dredging is studied. In the following, the results are presented according to the different number of ships considered. It must be noticed that the three fleet mix presented in the previous chapter are here defined as 0 for the first scenario, 1 for the second one and 2 for the third one. Moreover, it must be underlined that all the data provided in tables and graphs represent averages on the selected combinations.

- **40 Ships**

#Berths	**Fleet type**	ΔASL	ΔAST [h]
5	0	14,43%	0,73
5	1	17,46%	0,85
5	2	19,93%	0,65
7	0	14,52%	0,42
7	1	14,24%	0,45
7	2	23,50%	0,48
9	0	15,52%	0,56
9	1	16,41%	0,63
9	2	20,56%	0,38

Table 4.3: 40 Ships cases results

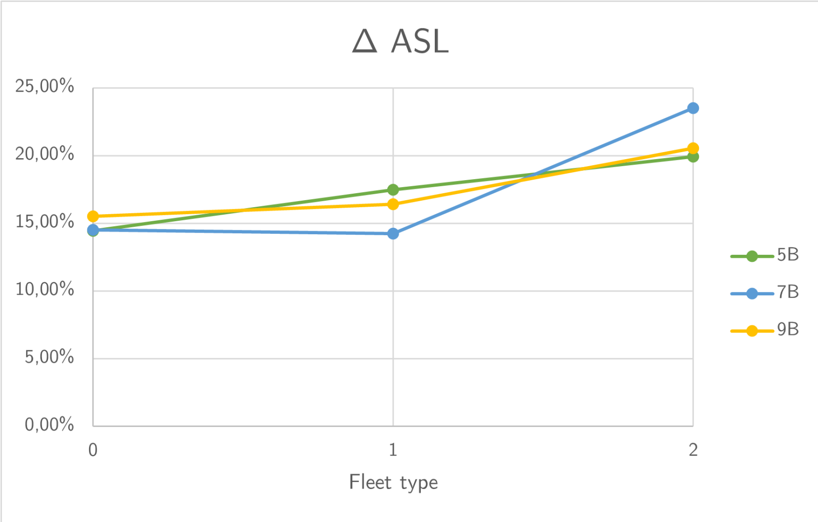


Figure 4.2: Dredging impact on ΔASL for 40 ships

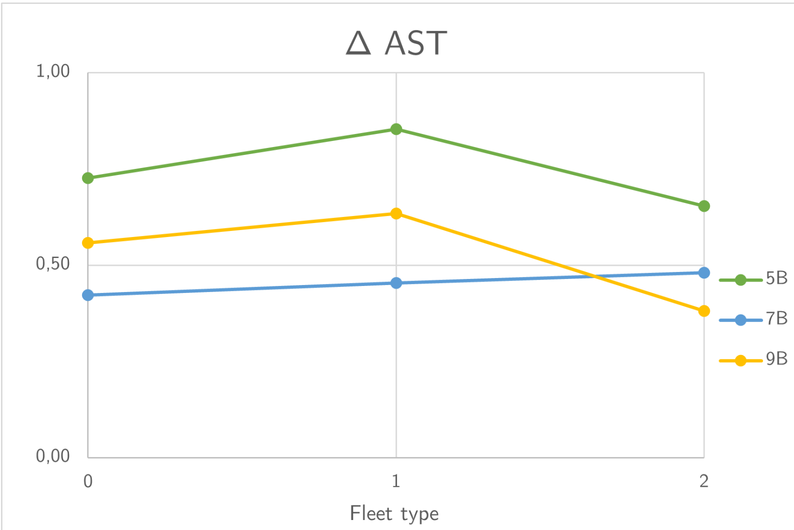


Figure 4.3: Dredging impact on ΔASL for 40 ships

Concerning ASL, it can be seen from Figure 4.2 that it tends to increase thanks to the dredging operations, with a significant difference in all the berths configuration, as reported in Table 4.3. Moreover, this increment grows with the scenarios, obtaining its maximum effect in the third scenario, in which more megaships require arrival in the port.

At the same time, AST does not modify considerably, as it is shown in Figure 4.3. In fact, even if more ships are served, on the average the increasing time required to serve a ship is less than one hour. This increment is completely reasonable, because more ships are served and so the terminal is more congested. Furthermore, there are more megaships to serve which requires more time to be loaded or unloaded. However, having bigger water depth, the predictable increasing of service time is partially compensated by the reduction in waiting time. In fact, ships have not to wait the same amount of time for tides, as before the dredging, to enter in the port and this leads to have a marginal increase in the AST. So, it can be said that dredging seems to be a very productive intervention in this case.

- **60 Ships**

#Berths	Fleet type	ΔASL	ΔAST [h]
5	0	14,89%	1,10
5	1	17,16%	1,23
5	2	19,88%	1,86
7	0	15,42%	0,69
7	1	15,46%	0,78
7	2	22,73%	0,78
9	0	14,83%	0,64
9	1	16,86%	0,54
9	2	19,99%	0,73

Table 4.4: 60 Ships cases results

For 60 ships cases, the same consideration made for the 40 ships ones can be made about the ASL. In fact, also here a considerable increment can be noticed, especially for the third scenario, as shown in Figure 4.4.

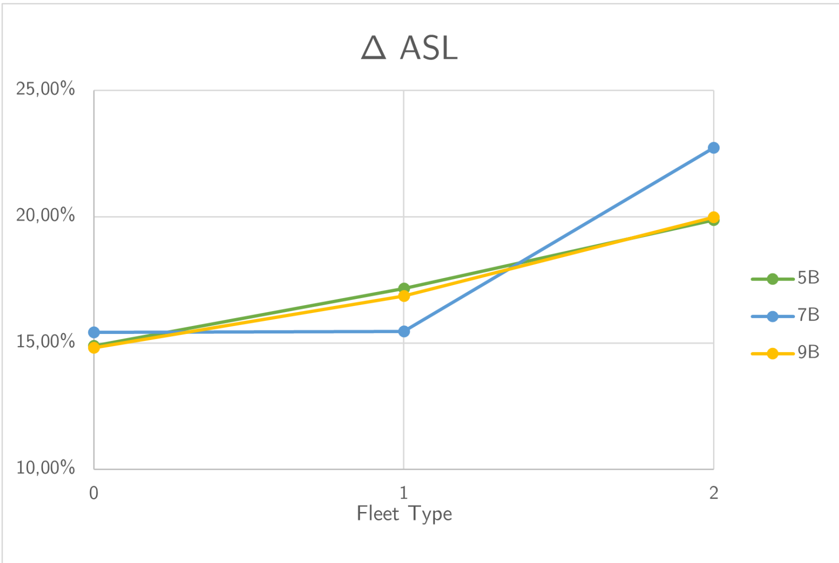


Figure 4.4: Dredging impact on ΔASL for 60 ships

Instead, for AST, the situation is different. In fact, if for the 7 and 9 berths configuration, the increasing service time is marginal and the previous considerations still apply, it is not the same for the 5 berths configuration. In fact, in this case, in the third scenario, the increasing service time is considerably bigger than the other cases, as it can be seen in Figure 4.5. However, this is not surprising. The increment in congestion that characterizes this specific port configuration should be in fact too high to obtain the same compensation mentioned before about reduction in waiting time. This is in fact a bigger instance, in which the volume of incoming ships is bigger and so, this can mean that a 5 berths configuration reduces the effectiveness of this type of intervention. Nevertheless, it keeps its value, because even if there is a bigger increase, it remains reasonable.

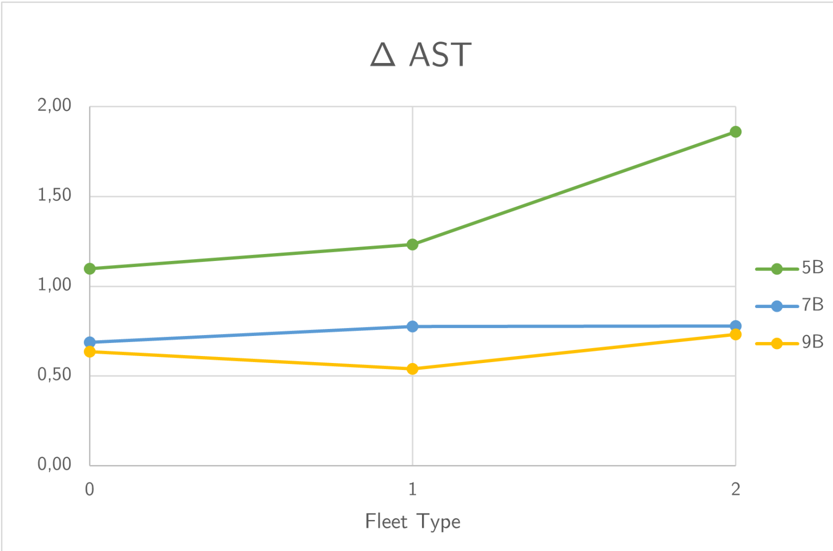


Figure 4.5: Dredging impact on ΔASL for 60 ships

- **80 Ships**

#Berths	**Fleet type**	ΔASL	ΔAST [h]
5	0	15,02%	2,80
5	1	15,79%	3,07
5	2	21,05%	-6,59
7	0	15,19%	0,86
7	1	15,52%	0,89
7	2	22,43%	-5,14
9	0	15,53%	0,80
9	1	15,76%	0,87
9	2	20,92%	0,72

Table 4.5: 80 Ships cases results

For 80 ships cases, the same consideration made for the 40 ships and 60 ships ones can be made about the ASL. In fact, a considerable increment can be noticed, especially for the third scenario, as shown in Figure 4.6.

Instead, an interesting situation appears for the AST. In particular, as shown in Figure 4.7, 9 berths configuration did not see a significant change, while 5 and 7 berths configuration are characterized by an increment in the first scenario, that it is completely reasonable, as described previously. However,

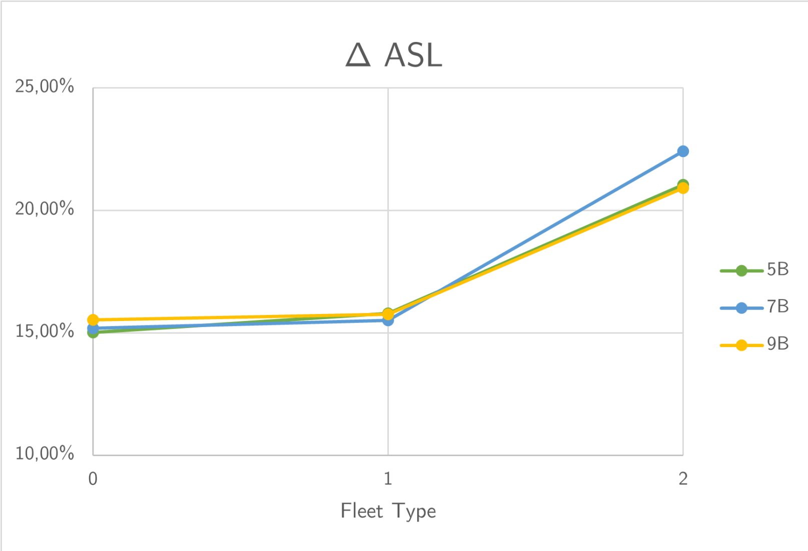


Figure 4.6: Dredging impact on ΔASL for 80 ships

the most interesting situation is the one related to these two configurations in the third scenario. In fact, a reduction of AST before and after dredging is evident. This can be caused by the compensation effect previously described for the 5 berths configuration. However, in this case this effect is extremely strong, enough to produce even a reduction, even if more ships enter in the port and require more time to be served. The greater impact caused by this compensation effect is due to the fact that the time required to serve a ship, in these big instances, is too large and so, with the dredging and the consequent reduction in waiting time, they considerably reduce. For the 9 berths configuration this effect lacks, because the port should be big enough, also before the dredging, to offer a contracted AST.

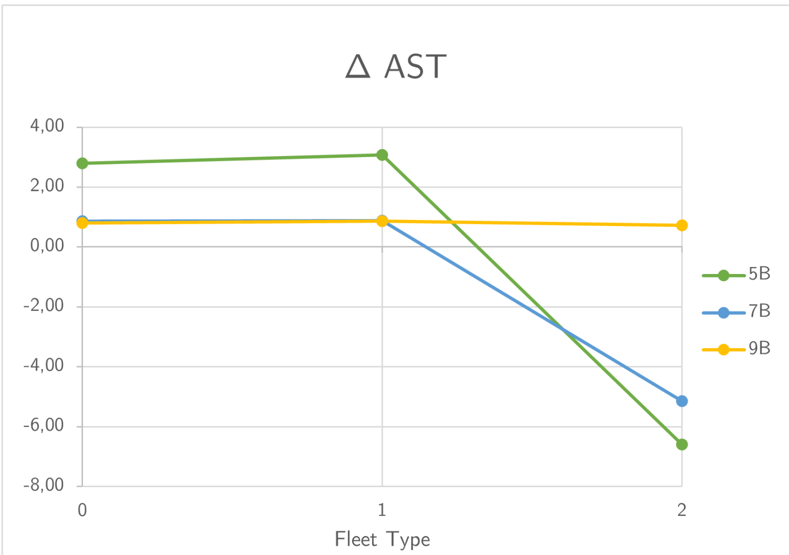


Figure 4.7: Dredging impact on ΔASL for 80 ships

4.3 Number of berths

Another way to improve service quality is to increase the number of berths. This means that more space is available for the incoming ships. This, in theory, could help to serve more ships and to reduce the waiting time, because ships should wait less to enter in the port. In order to increase the number of berths, some space should be obtained, towards land or towards sea. However, this could be a difficult activity, because sometimes ports and cities are in conflict, because they both want a specific area, but for different reasons and so, bureaucratic and administrative issues can arise. At the same time, new berths can be created thanks to new piers obtained from the seaside, but this is also a complex activity.

Figure 4.8: Berth layout in Port of Townsville

To understand the impact of this type of intervention, also in this case the two performance measure described in the beginning of the chapter are evaluated, organized by the number of ships. It must be noticed that the three fleet mix are defined in the tables as before, while the port type is indicated as 0 (in the tables) and "Ps" (in the graphs) for the port before the dredging operation and 1 (in the tables) and "PL" (in the graphs) for the port after the dredging. Moreover, it must be underlined that all the data provided in tables and graphs represent averages on the selected combinations.

- **40 Ships**

#Berths	**Fleet type**	**Port Type**	*ASL*	*AST* [h]
5	0	0	83,85%	4,97
5	1	0	77,43%	5,25
5	2	0	61,43%	7,87
5	0	1	98,28%	5,70
5	1	1	94,89%	6,11
5	2	1	81,35%	8,52
7	0	0	83,80%	5,11
7	1	0	80,44%	5,65
7	2	0	59,48%	7,83
7	0	1	98,31%	5,53
7	1	1	94,69%	6,11
7	2	1	82,98%	8,31
9	0	0	82,85%	4,98
9	1	0	77,65%	5,36
9	2	0	60,46%	7,89
9	0	1	98,37%	5,54
9	1	1	94,06%	5,99
9	2	1	81,02%	8,27

Table 4.6: 40 Ships cases results

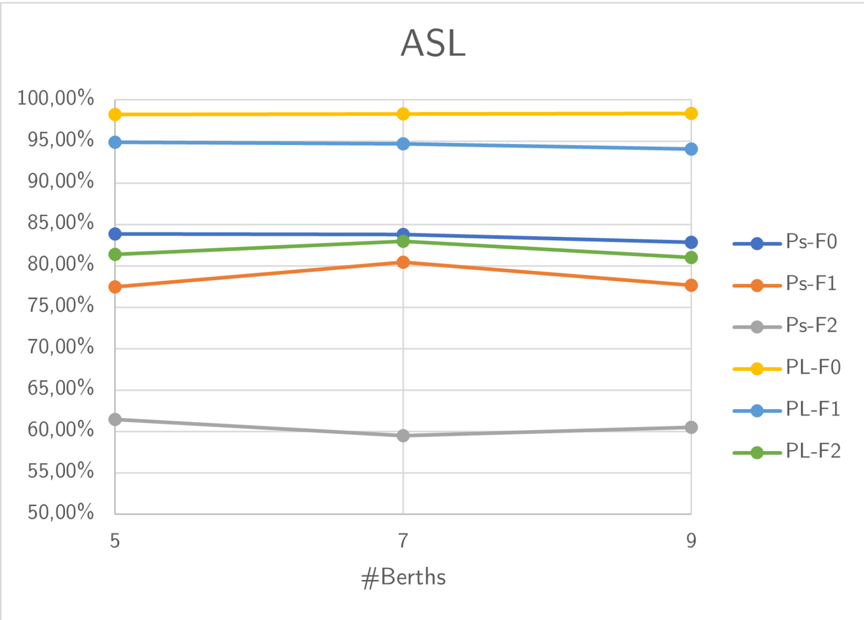


Figure 4.9: Increasing number of berths effect on *ASL* for 40 ships

As it can be seen from Figure 4.9 and 4.10 the effect of increasing the number of berths, switching from 5 to 7 to 9, has no significant effects both on ASL and AST, in the 40 ships cases. This lead to conclude that in this situation this type of intervention is not suggested. This can be caused by two main factors: tides constraints are too important to allow to serve more ships even

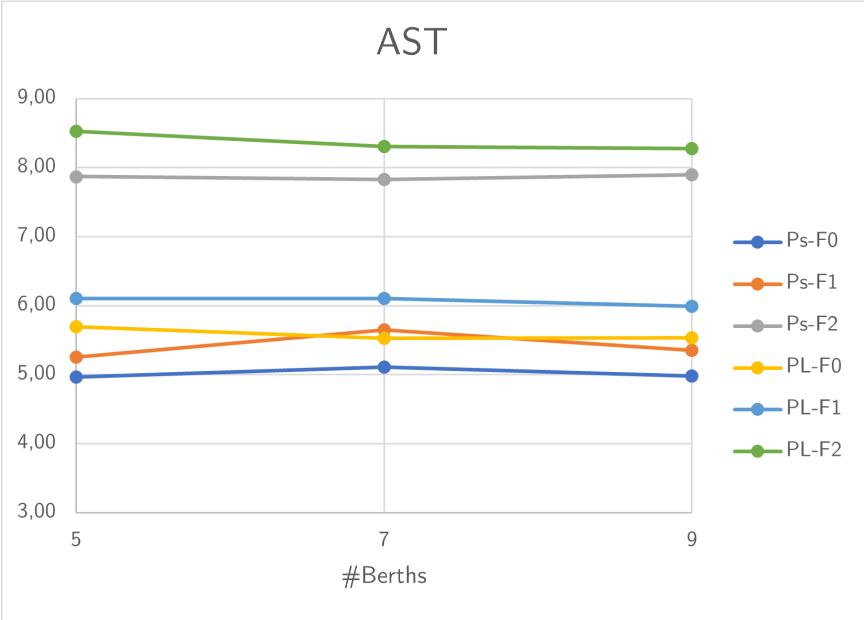


Figure 4.10: Increasing number of berths effect on *AST* for 40 ships

if there are more berths; secondly, a 5 berths configuration is big enough to manage this volume of incoming ships, so any particular gain in terms of AST cannot be seen.

- **60 Ships**

#Berths	**Fleet type**	**Port Type**	*ASL*	*AST* [h]
5	0	0	82,59%	5,18
5	1	0	76,91%	5,53
5	2	0	61,37%	8,10
5	0	1	97,48%	6,28
5	1	1	94,07%	6,77
5	2	1	81,25%	9,96
7	0	0	82,63%	4,87
7	1	0	78,43%	5,38
7	2	0	59,44%	7,94
7	0	1	98,05%	5,56
7	1	1	93,89%	6,15
7	2	1	82,17%	8,72
9	0	0	83,47%	4,87
9	1	0	77,41%	5,55
9	2	0	61,41%	7,84
9	0	1	98,30%	5,51
9	1	1	94,27%	6,08
9	2	1	81,40%	8,58

Table 4.7: 60 Ships cases results

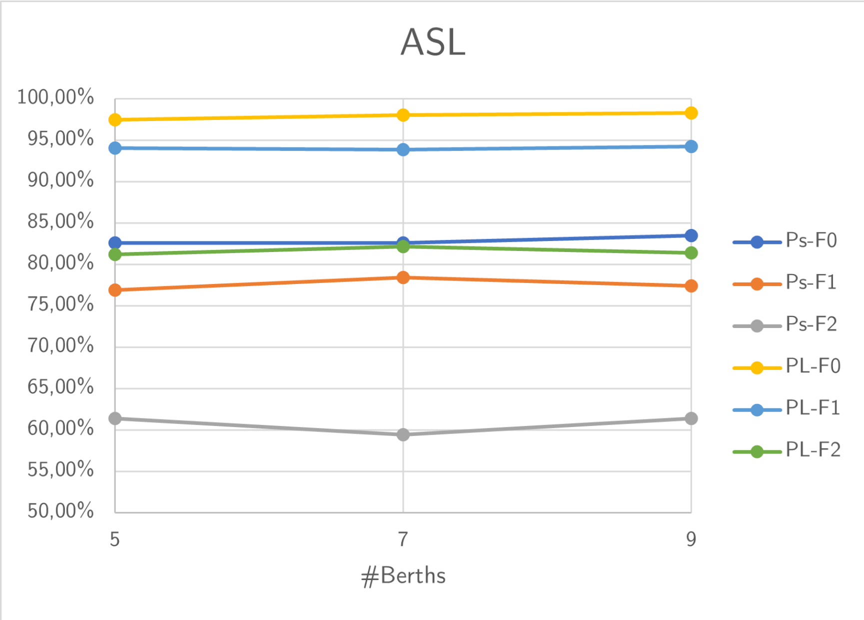


Figure 4.11: Increasing number of berths effect on ASL for 60 ships

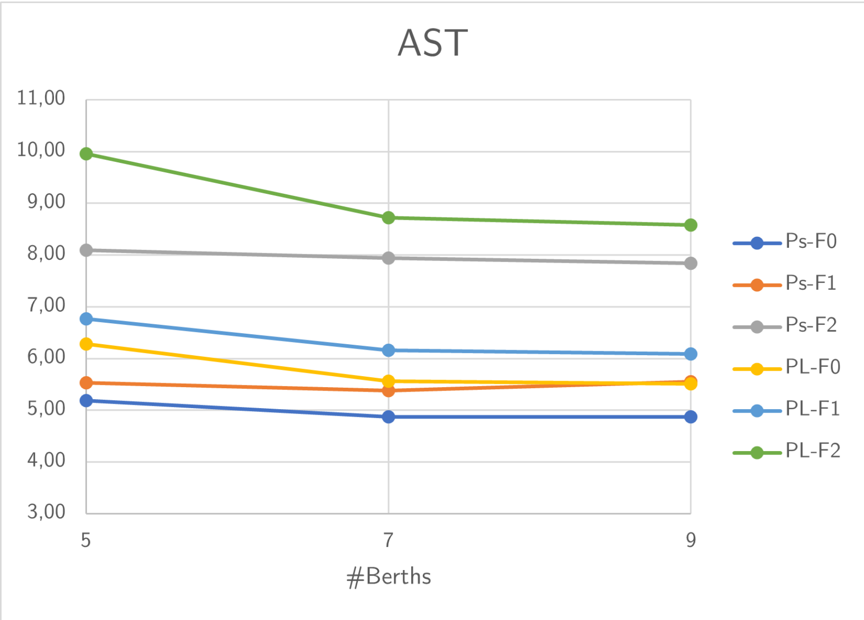


Figure 4.12: Increasing number of berths effect on AST for 60 ships

From Figure 4.11 the effect of increasing the number of berths, switching from 5 to 7 to 9, has no significant effects on ASL, for the same reason previously mentioned. However, considering the bigger volume of incoming ships, there are some situations in which, as Figure 4.12 shows, a gain in terms of AST is present. This effect is particularly noticeable in the case of the port after the dredging with the first and third fleet mix. In these cases, on average, more than an hour of AST is saved, passing from 5 to 7 berths. However, it should be carefully studied if this type of intervention, in this situation, could be worthy, because the gain is noticeable, but not so consistent.

- **80 Ships**

#Berths	**Fleet type**	**Port Type**	ASL	AST [h]
5	0	0	82,93%	5,89
5	1	0	77,48%	6,28
5	2	0	59,97%	20,74
5	0	1	97,94%	8,69
5	1	1	93,27%	9,35
5	2	1	81,03%	14,15
7	0	0	82,75%	5,03
7	1	0	78,22%	5,61
7	2	0	59,19%	14,71
7	0	1	97,94%	5,89
7	1	1	93,74%	6,49
7	2	1	81,62%	9,57
9	0	0	82,78%	4,87
9	1	0	78,47%	5,31
9	2	0	60,17%	7,83
9	0	1	98,31%	5,67
9	1	1	94,23%	6,18
9	2	1	81,09%	8,56

Table 4.8: 80 Ships cases results

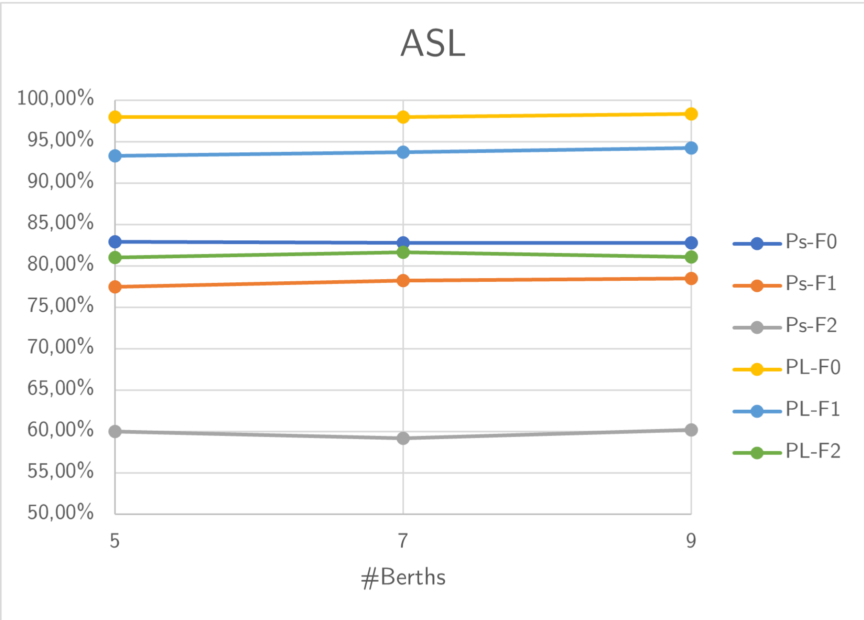


Figure 4.13: Increasing number of berths effect on ASL for 80 ships

Also, in this case increasing the number of berths has no impact on ASL, as shown in Figure 4.13. So, the hypothesized reason mentioned before is confirmed again. However, for AST the situation is totally different. With this amount of incoming vessels, the effect of increasing the number of berths is extremely consistent in a lot of cases, as represented in Figure 4.14. In

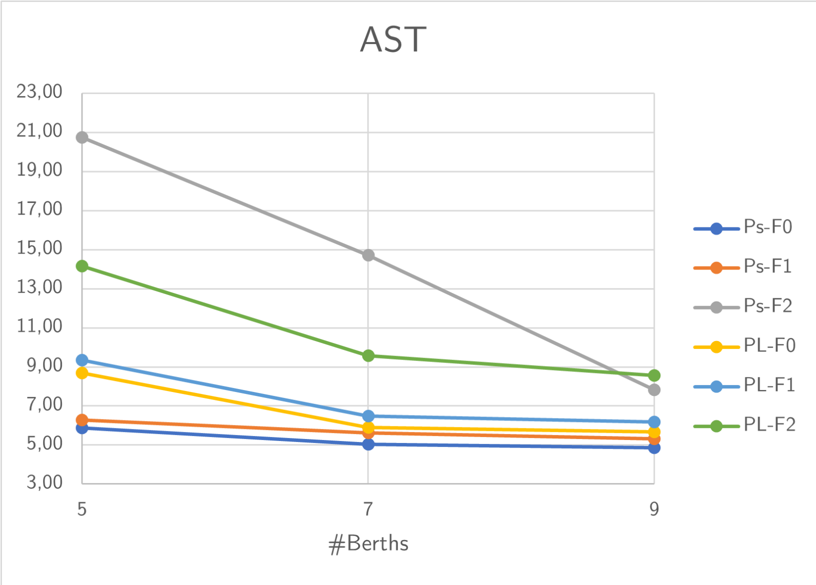


Figure 4.14: Increasing number of berths effect on *AST* for 80 ships

particular, in the two combinations related to the third fleet mix, there is the biggest gain in terms of time. This can lead to conclude that, with this volume of incoming ships, increasing the number of berths should be carefully considered, because it could have a significant impact on AST, making the port more competitive.

4.4 Superstructures improvements

The last intervention considered is the one related to the improvement of all the infrastructures that can consent to reduce the time required to serve a ship. This can be done in various different ways and surely, one of the simplest, is to improve all the equipment related to the transportation of the containers between the yard and the moored ships, increasing the number of cranes, forklifts, reach steackers, etc. or using faster ones. In addition, more **automation** started to be used in ports, even if a delay compared to other industries, as warehousing, is evident [30]. This can bring a major change in terms of productivity for port terminals, but for a definitive implementation of IT in port operations, a lot of work still needs to be done.

Figure 4.15: Automated port terminal in Qingdao, China

However, the conducted analysis is focused to understand how these improvements, reducing the service times, can impact the two performance measures of interest. The analysis is organized, as the previous ones, by number of ships. Nevertheless, differently from the previous ones, 18 cases, each one composed by 27 combinations, are represented in each Figure of Appendix A. These results are not aggregated as the previous ones and so they represent the average values obtained for each combination represented. There are two main figures per number of ships, one related to ASL and another to AST. Each Figure is organized in 3 graphs per row, which represent from left to right the first, the second and the third fleet mix, while the rows are organized in this way:

- First row: 5 berth configuration - port before dredging
- Second row: 5 berth configuration - port after dredging
- Third row: 7 berth configuration - port before dredging
- Forth row: 7 berth configuration - port after dredging
- Fifth row: 9 berth configuration - port before dredging
- Sixth row: 9 berth configuration - port after dredging

Understood how the results are presented, it is possible to notice that some main trends can be understood looking at them. It can be anticipated that the same conclusions can be made for every number of ships analysed. Concerning ASL, with the first fleet mix, the effect of modifying productivity levels usually does not generate significant changes, as shown in the example of Figure 4.16, even if there are some cases in which more variability is induced by the productivity changes, as it might be expected. A similar situation can be described also for the second fleet mix, while for the third one, changes in productivity level usually cause a significant variability, with some relevant increments in terms of ASL, especially in the situations before the dredging, as it can be seen in the example reported in Figure 4.17. So, it can be stated that, if a dredging is not possible, some improvements in terms of productivity can incredibly ameliorate the ability of the port to receive more ships, making this intervention quite worthy. More details on these graphs can be found in Appendix A.

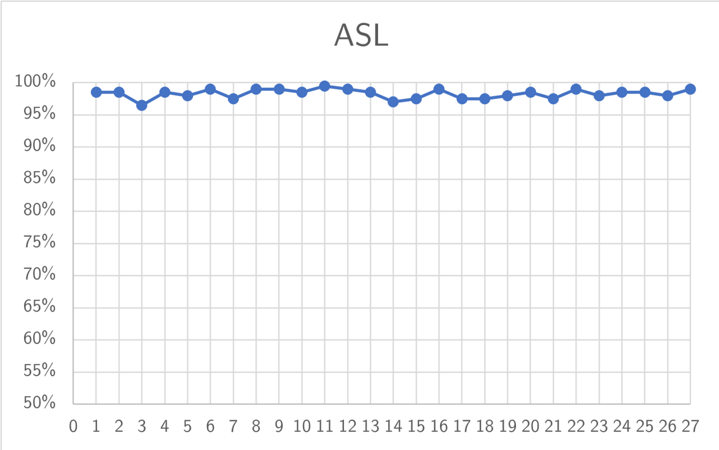


Figure 4.16: Example 1 for ASL behavior

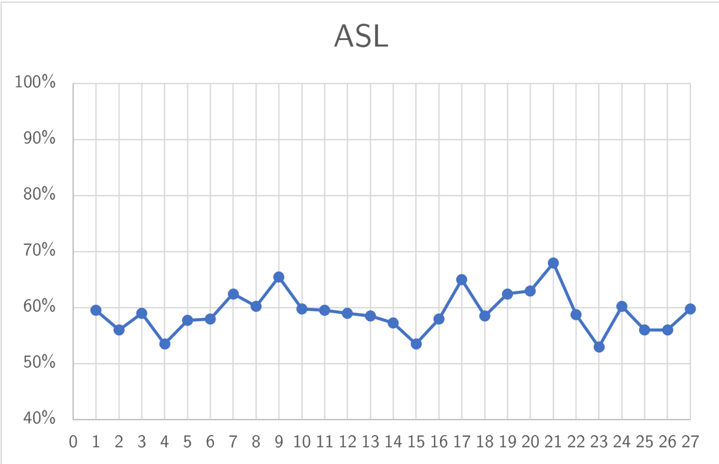


Figure 4.17: Example 2 for ASL behavior

Regarding AST the situation is totally different. Obviously, changes in productivity levels impact service times, that tend to grow with lower productivity levels, as represented in the Figures reported in Appendix A. In particular, in these charts some trends are evident. The most interesting is represented in Figure 4.18. In fact, there is a stepped trend every three combinations. This is due to the way in which combinations are derived. For example, the first three combinations are obtained considering the maximum level of productivity for megaships and deepsea vessels, while the second and the third triplets consider respectively the second and the third level of productivity for deepsea vessels, causing a gradual increment in terms of AST. The same behavior is repeated also for the other triplets, generating the stepped trend. This is quite self-explaining: a lower level of productivity causes an increase in the service time, but it must be analysed also taking into account the levels on the other types of ships. In general, it emerges from these charts that providing to the majority of ships the highest productivity level, the minimum service time can be offered, regardless of the type of ships privileged. In fact, it can be seen from Figure 4.18 that the three lowest triples, corresponding to the highest productivity level on deepsea vessels and feeders and the three different productivity levels on megaships, are roughly on the same level of AST. This highlight how much is important to provide the highest productivity to as many ships as possible.

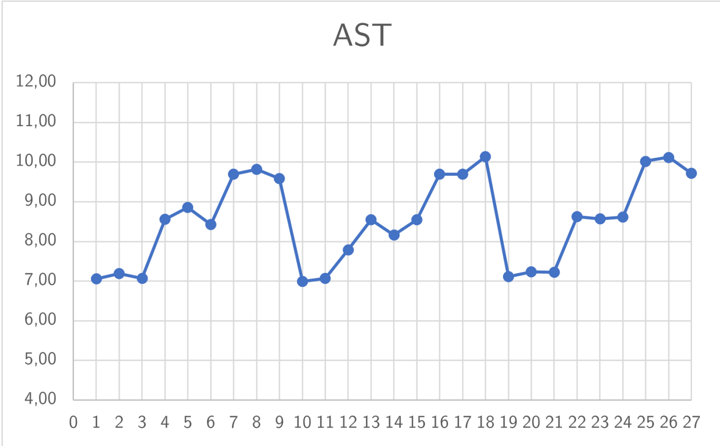


Figure 4.18: Example 1 for AST behavior

The previous example is one of the strongest in the analysis, but in the most cases it is lighter and it is more similar to the one reported in Figure 4.19, in which there is not a stepped trend, but some tendencies can clearly be seen, even if grouped in blocks of 9 combinations. However, also in this case the same considerations made before apply.

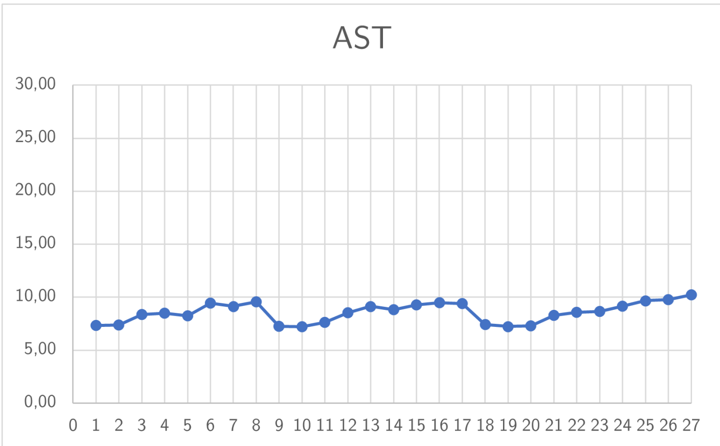


Figure 4.19: Example 2 for AST behavior

4.5 Policy advice

Concluded the analysis of results, to reach the aim of this thesis some policy advice are presented. In particular, it can be stated that **investing in superstructures and automation** can considerably reduce the amount of time necessary to serve a ship, even if the service level usually is not significantly changed by these investments. However, this seems to be the most realistic and effective intervention that can be taken to improve port operations. Clearly, the best in class action to take, in order to overpass the problems of water depth and megaships, is a **dredging**, but this is an extremely expensive activity, that, as can be seen in the case of the Port of Antwerp, can result ineffective after a limited period of time, requiring a further dredging. Furthermore, it must be taken into account also the **environmental impact** that this activity has on marine ecosystem and to the possible limits that the excavation can have, due to safety or also environmental reasons. Concerning the possibility to change the port layout, **increasing the number of berths**, this seems to be an unuseful intervention, except for big volumes of incoming ships, in which this intervention can reduce the service time, even if service level does not take advantage of that. Then, to conclude this analysis, it is likely that in the future, ports characterized by tides constraints, like river ports, should increase their productivity, trying to serve a bigger amount of a certain type of ships that is compatible with the constraints that the port will have. This will require big investments in automation and, if volumes will be big enough, also in enlarging port dimensions. Furthermore, it can be hypothesized that this situation, in the long term, could bring to more **ship-specialized ports**, in which a lot of deepsea vessels and feeder ships could berth in a port as the one analysed in this thesis, while other ports not characterized by these constraints could gradually reduce their services to smaller ships, concentrating only on megaships, that even if less in number, require more time and efforts to be served.

Conclusions

Global trade is increasing significantly in the last decades, due to changes in society and world economy, as it has been described in the first chapter. Shipping transportation is taking great advantage from this growth and it is also sustaining it, becoming an industry more and more structured. In particular, containerization has been one of the main causes that has allowed shipping to become the main transportation way for long distances, making global markets and supply chains. In order to make transportation of container more efficient, in the last years ship sizes are increased enormously, arriving nowadays to the so-called megaships. However, even if this tendency allows liner shipping companies to save money thanks to economies of scale, this growth in size has begun to create some problems to terminal operators and ports. One of the most important problem is related to water depth. In fact, these megaships have greater and greater drafts and so, especially some river ports, are experiencing problems to manage the arrival of these megaships. In particular, these problems are highlighted by tides effects, that can create some time windows in which the arrival of a megaships is preferred, while in other moments this is not possible. This led to the necessity to study carefully this type of problem. In order to do this operations research is the best science to use. In particular, optimization problem can be the right key to analyse this peculiar problem. In fact, defining some constraints, variables and objective function, it is possible to find an optimal solution to a specified problem, minimizing or maximizing the objective function analysed, as explained in the second chapter. The studied problem is a typical optimization problem in the context of terminal operators in a port and it is called Berth Allocation Problem. However, considering tides effect and water depth level, this is a variant of the problem, more actual, considering what has been said before. So, in the third chapter, an optimization model is defined, trying to minimize the time required to serve a ship from the moment in which it arrives in the port, but considering a lot of constraints, tides ones included. Besides, the optimization model defined allows also not to serve all the ships arriving in the port, focusing the attention also on the service level, i.e. the ability of the port to serve a certain percentage of arriving ships. A data analysis has been defined from literature review, in order to provide the model with adequate data and to define different scenarios, combining different features of the quantities considered. Furthermore, a process of data generation has been realized, defining some random numbers and using inverse-transform to generate data extracted by uniform continuous distributions. Then, considering the different combinations obtainable by the different scenarios, a total of 1458 combinations is analysed in the optimization model. The results are organized to be studied and focused on two main performance measures: ASL (Average Service Level) and AST (Average Service Time). These are studied and compared taking into account three possible area of intervention for a port: dredging, increasing the number of berths and superstructures improvements. This analysis led to the suggestion to invest in superstructures and automation, improving productivity, that can be considered the most realistic and practical possible intervention, because it can lead to a significant saving in terms of AST and a consistent increment in ASL, even if not in every cases. Dredging is theoretically the best option, but it could be a riskful operation, that can cost a lot of money and that could be ineffective after a limited amount of time. So, in this way, the road seems to guide to a situation in which in the future ports will become more and more ships-specialized.

Appendix A

Productivity improvements small multiples charts

Reported in the next pages.

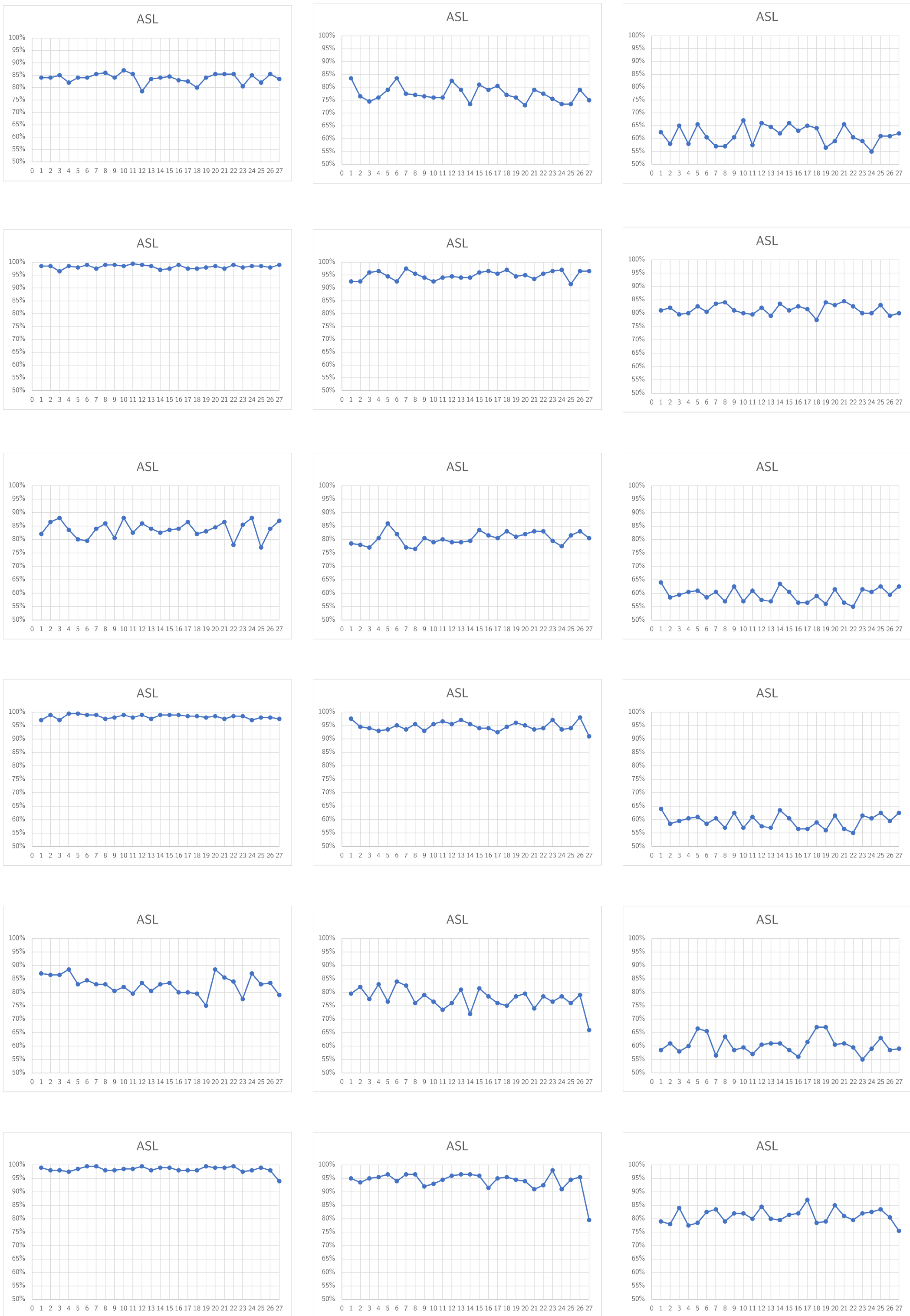


Figure A.1: ASL values for 40 ships cases

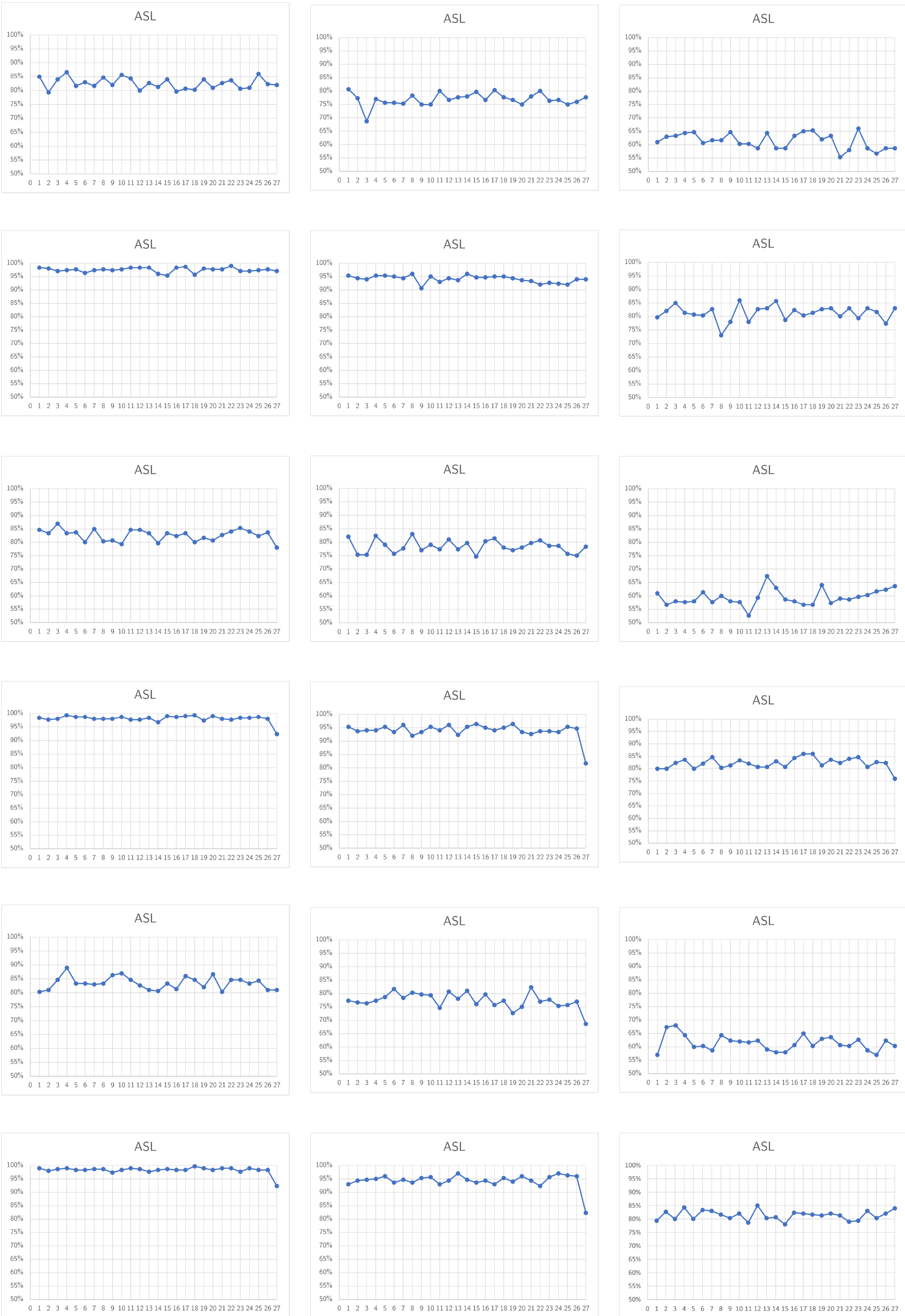


Figure A.2: ASL values for 60 ships cases

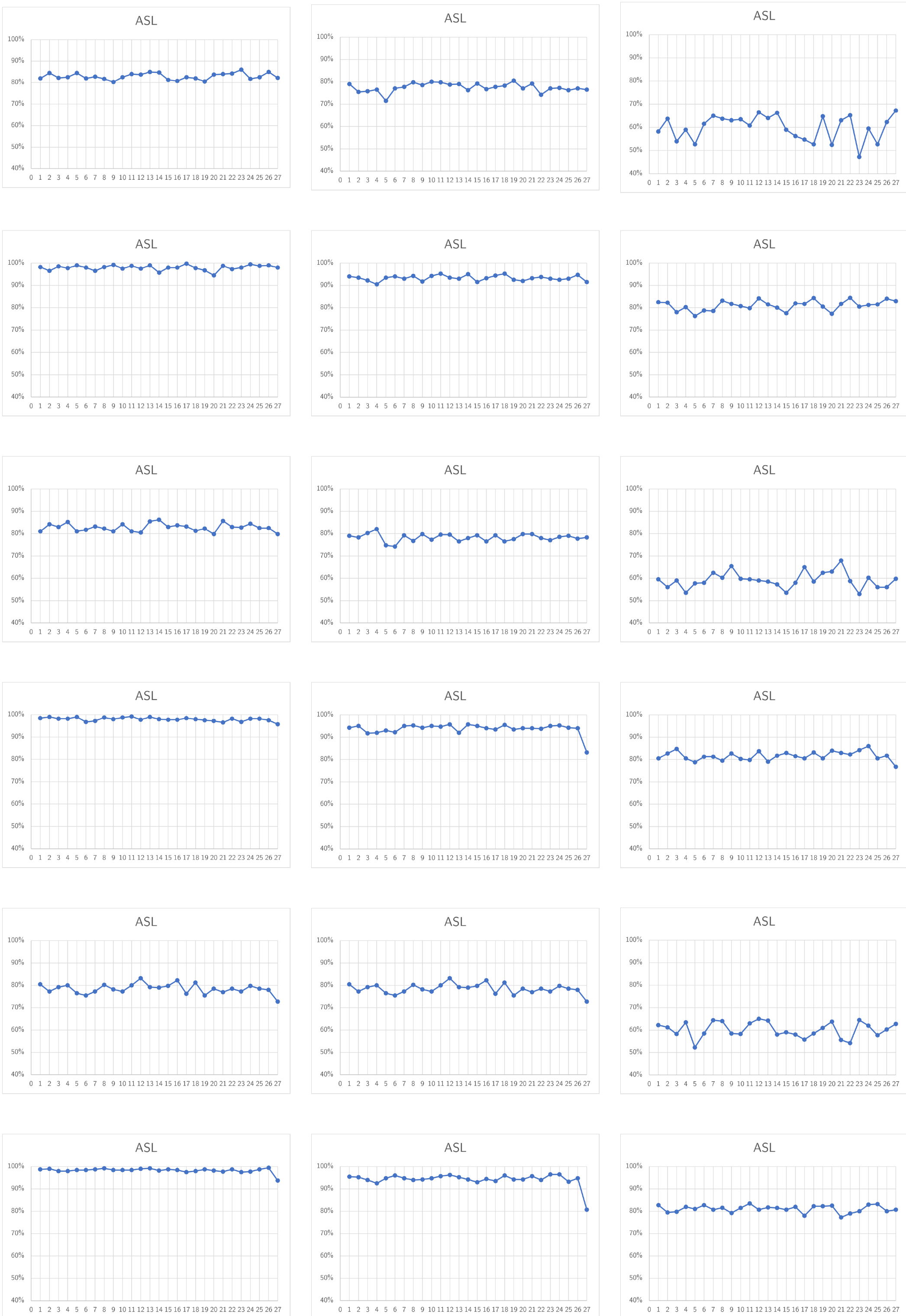


Figure A.3: ASL values for 80 ships cases

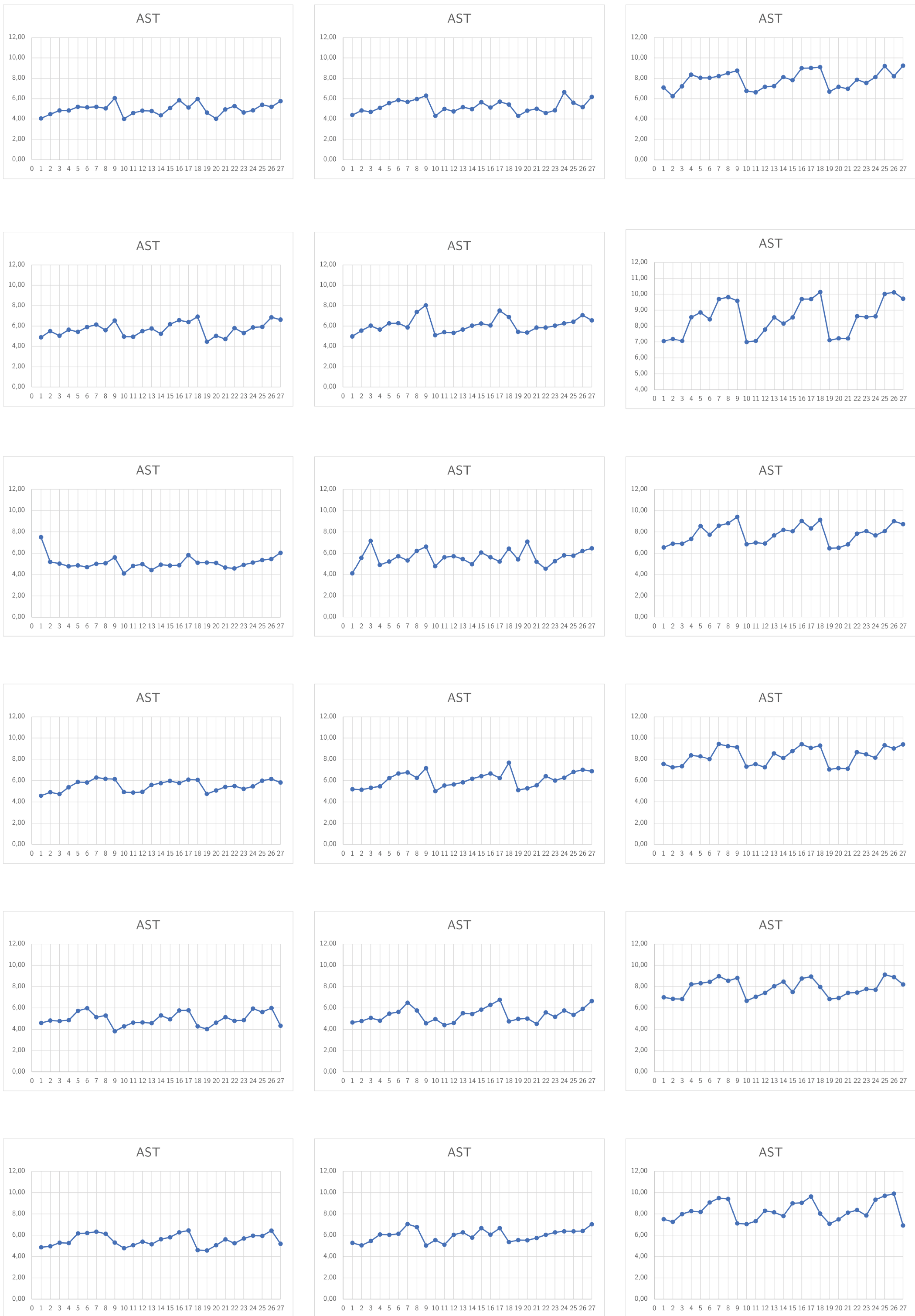


Figure A.4: AST values for 40 ships cases

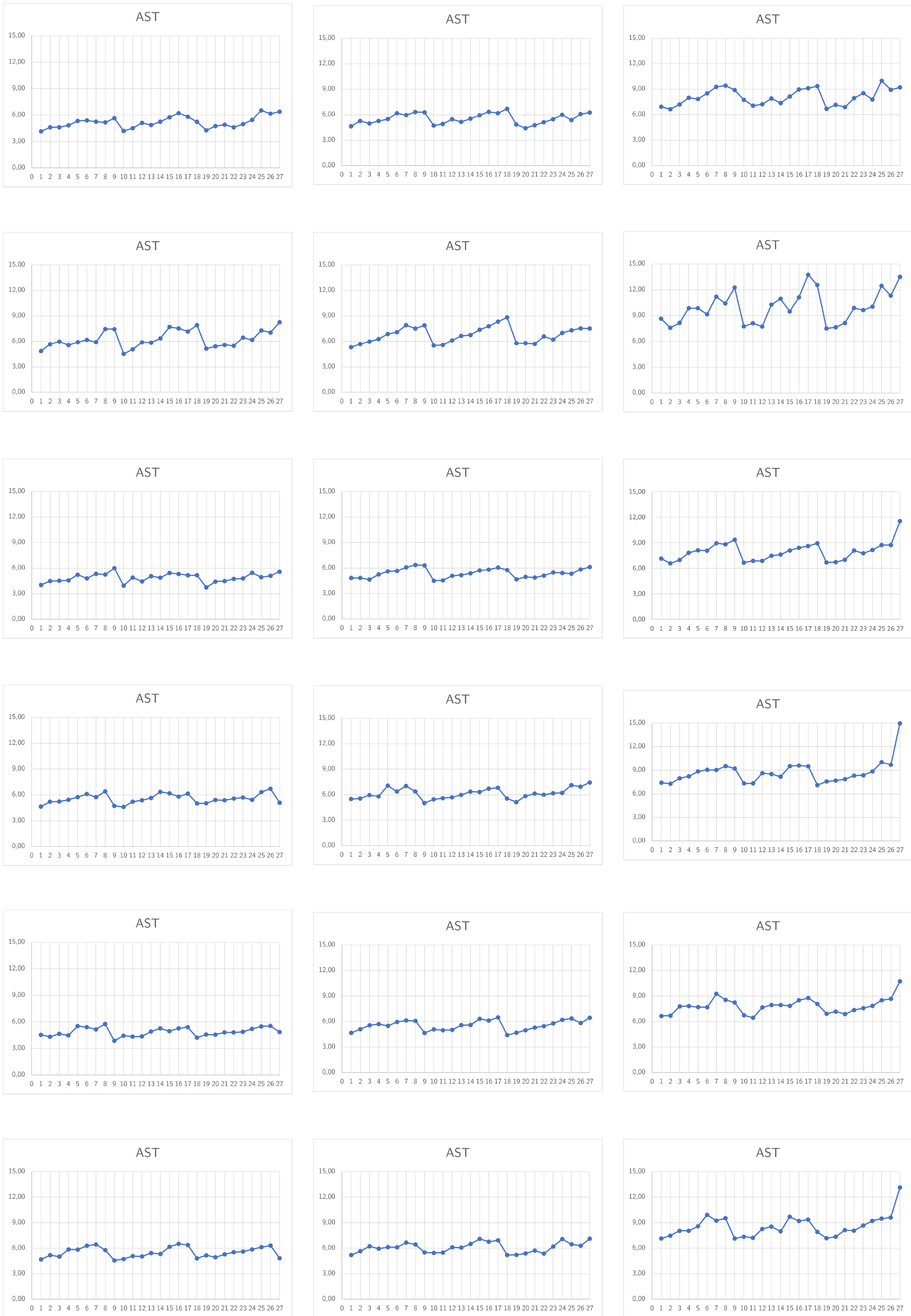


Figure A.5: AST values for 60 ships cases

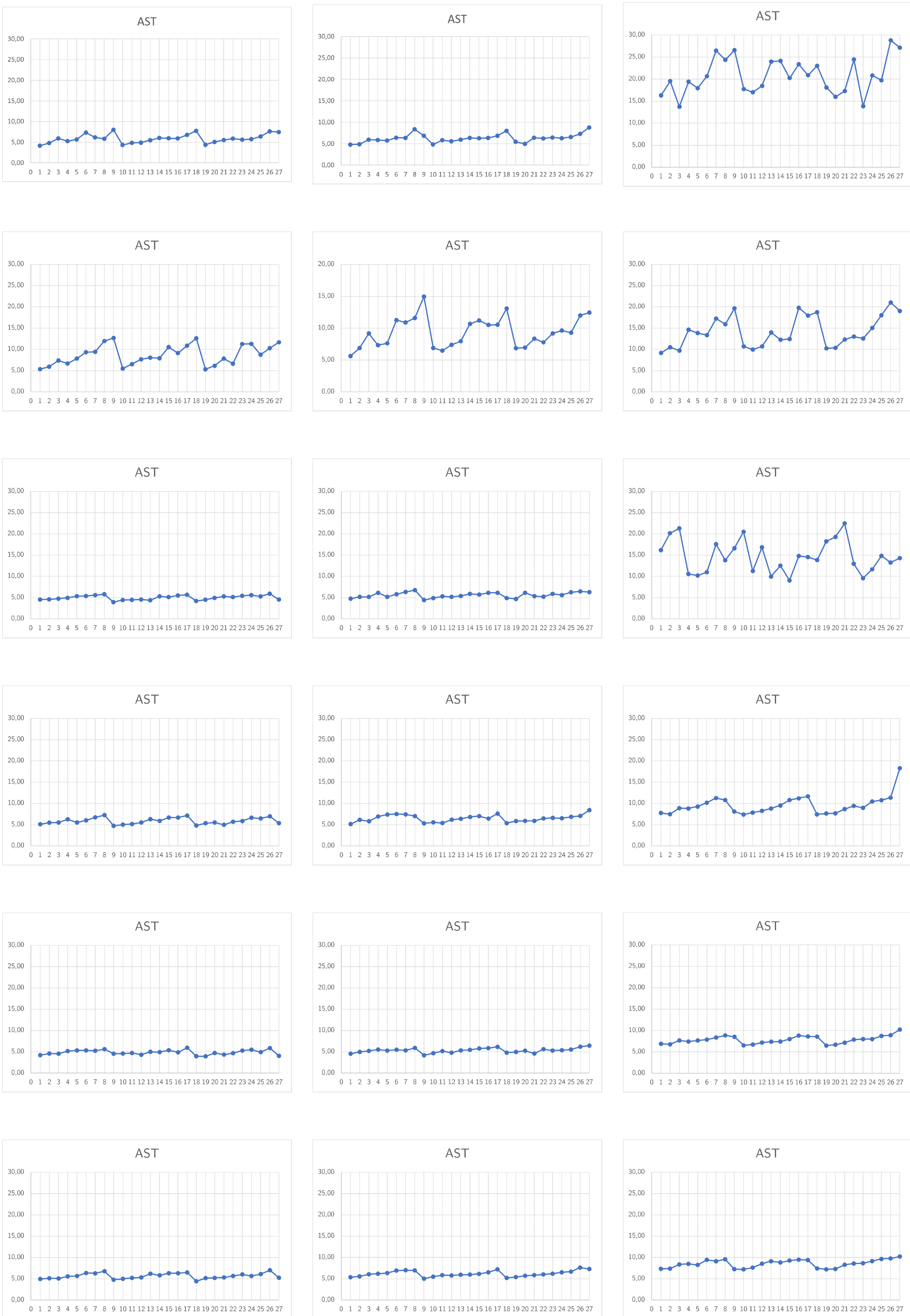


Figure A.6: AST values for 80 ships cases

Appendix B

Python code

B.1 Optimization Model for 7290 instances

```
#File per generare le 1458*5=7290 istanze con le varie combinazione e
    ottimizzarle. Tempo max = 30s

import random
from mip import *
import time
import sys

start = time.time()
elapsed = 0

# SCENARIOS
N_V = [40, 60, 80]
N_B = [15, 17, 19] # in realta' le banchine sono 10 in meno

fleet_mix_list = [[0.0086, 0.5, 0.4914], [0.05, 0.54, 0.41], [0.2, 0.7,
    0.1]]

draft_list = [[[5, 10], [10, 14.5], [14.5, 15.5]], [[5, 10], [10, 14.5],
    [14.5, 16.5]],
              [[5, 10], [10, 14.5], [14.5, 17.5]]]

proc_time_list = [[[18, 20], [20, 22], [22, 24]], [[12, 14], [14, 16],
    [16, 18]], [[6, 8], [8, 10], [10, 12]]]

initial_depth_list = [13.1, 14.6]
n = 1458

fp = open("stop_index_file.txt")
b_ind = int(fp.readline())
s_ind = int(fp.readline())
port_ind = int(fp.readline())
fleet_ind = int(fp.readline())
process_ind_1 = int(fp.readline())
process_ind_2 = int(fp.readline())
```

```
process_ind_3 = int(fp.readline())
fp.close()

# GENERAZIONE ISTANZE

while b_ind < 3:
    while s_ind < 3:
        while port_ind < 2:
            while fleet_ind < 3:#vale anche per i draft
                while process_ind_1 < 3:
                    while process_ind_2 < 3:
                        while process_ind_3 < 3:
                            n += 1

                            with open("stop_index_file.txt", "w") as st:
                                print(b_ind, s_ind, port_ind, fleet_ind,
                                    process_ind_1, process_ind_2,
                                    process_ind_3,
                                      sep="\n", file=st)

                            if elapsed > 28800:

                                elapsed = time.time() - start

                                sys.exit()

                            for stat_ind in range(5):
                                time_window = int(5 * 12 * (N_V[s_ind] /
                                    (N_B[b_ind] - 10)))
                                v_arrive = []
                                v_type = []
                                v_draft = []
                                v_proc_time = []
                                v_weigh = []
                                r = []

                                for i in range(N_V[s_ind]):
                                    v_arrive.append(random.randint(0, 168))

                                for i in range(N_V[s_ind]):
                                    rand_num = random.random()
                                    if rand_num <
                                        fleet_mix_list[fleet_ind][0]:
                                        v_type.append(1)
                                        v_draft.append(round(
                                            random.uniform(draft_list[fleet_ind][2][0],
                                                draft_list[fleet_ind][2][1]),
                                            1))
                                        v_weigh.append(round(random.uniform(0.8,
                                            1), 1))
                                        v_proc_time.append(round(
```

```
            random.randint(proc_time_list[0][process_ind_1][0],
                    proc_time_list[0][process_ind_1][1]),1))
            elif rand_num <
                (fleet_mix_list[fleet_ind][0] +
                fleet_mix_list[fleet_ind][1]):
                v_type.append(2)
                v_draft.append(round(
                    random.uniform(draft_list[fleet_ind][1][0],
                        draft_list[fleet_ind][1][1]),
                    1))
                v_weigh.append(round(random.uniform(0.4,
                    0.8), 1))
                v_proc_time.append(round(
        random.randint(proc_time_list[1][process_ind_2][0],
                proc_time_list[1][process_ind_2][1]),1))
            else:
                v_type.append(3)
                v_draft.append(round(
                    random.uniform(draft_list[fleet_ind][0][0],
                        draft_list[fleet_ind][0][1]),
                    1))
                v_weigh.append(round(random.uniform(0,
                    0.4), 1))
                v_proc_time.append(round(
                random.randint(proc_time_list[2][process_ind_3][0],
                proc_time_list[2][process_ind_3][1]),1))

        for i in range(time_window):
            if (i % 12) <= 6:
                x = initial_depth_list[port_ind] +
                    int(i % 12) * 0.4
                r.append(x)
            else:
                x = r[i - 1] - 0.4
                r.append(round(x, 1))

        # print(v_arrive, v_weigh, v_type, v_draft,
            v_proc_time, r, sep="\n")

        v_draft_byarrive = [x for _, x in
            sorted(zip(v_arrive, v_draft))]
        v_weigh_byarrive = [x for _, x in
            sorted(zip(v_arrive, v_weigh))]
        v_type_byarrive = [x for _, x in
            sorted(zip(v_arrive, v_type))]
        v_proc_time_byarrive = [x for _, x in
            sorted(zip(v_arrive, v_proc_time))]
        v_arrive.sort()

        with open("scenari.txt", "a") as f:
```

```
    print("\nCombinazione " + str(n),
        "Replica" + str(stat_ind + 1),
        N_V[s_ind],
          str(N_B[b_ind] - 1), v_arrive,
              v_type_byarrive,
              v_draft_byarrive,
          v_proc_time_byarrive, r, sep="\n",
              file=f)

# MODEL

# SET DEFINITION
V = range(N_V[s_ind])
B = range(N_B[b_ind])
T = range(time_window)

# MODEL DEFINITION
m = Model("BAP 2016", sense=MINIMIZE,
    solver_name=GRB)

# VARIABLES
C = [m.add_var(name="C" + str(j + 1),
    var_type=CONTINUOUS) for j in V]
x = [[[m.add_var(name="x" + str(k + 1) +
    str(j + 1) + str(t + 1),
    var_type=BINARY) for t in
       T] for j in V] for k in B]

# CONSTRAINTS

# (2)
for j in V:
    for t in range(0, v_arrive[j]):
        for k in B:
            m += x[k][j][t] == 0

# (3)
for j in V:
    m += xsum(x[k][j][t] for k in B for t in
              range(0, time_window -
                  v_proc_time_byarrive[j] +
                  1)) == 1

# (4)
for k in B:
    for t in range(time_window - 1):
        m += xsum(x[k][j][s] for j in V for s
            in
                  range(max(0, t + 1 -
                      v_proc_time_byarrive[j]),
                      t + 1)) <= 1
```

```
# (5)
for k in range(N_B[b_ind] - 10):
    for j in V:
        for t in range(time_window - 1):
            m += xsum(v_draft_byarrive[j] *
                x[k][j][s] for s in
                      range(max(0, t + 1 -
                          v_proc_time_byarrive[j]),
                          t + 1)) <= r[t]

# (6)
for k in B:
    for j in V:
        for t in range(time_window -
            v_proc_time_byarrive[j] + 1,
            time_window):
            m += x[k][j][t] == 0

# (7)
for j in V:
    m += xsum((t + v_proc_time_byarrive[j])
        * x[k][j][t] for k in
        range(N_B[b_ind]-10) for t in
        range(0, time_window -
        v_proc_time_byarrive[j] + 1)) \
         + xsum((t + v_proc_time_byarrive[j])
             * 1000 * x[k][j][t] for k in
             range(N_B[b_ind]-10,N_B[b_ind])
             for t in range(0, time_window -
             v_proc_time_byarrive[j] + 1)) ==
             C[j]

# (9)
for j in V:
    m += C[j] >= 0

# OBJECTIVE FUNCTION

# (1)
m.objective = xsum((v_weigh_byarrive[j] *
    (C[j] - v_arrive[j]) for j in V))

status = m.optimize(max_seconds=1200)

not_served_ships = 0

if status == OptimizationStatus.OPTIMAL or
    status == OptimizationStatus.FEASIBLE:
    for j in V:
        for t in T:
```

```
                for k in
                    range(N_B[b_ind]-10,N_B[b_ind]):
                    not_served_ships +=
                        x[k][j][t].x

        corrected_fo = m.objective_value
        for j in V:
            if C[j].x > time_window:
                corrected_fo = corrected_fo -
                    (v_weigh_byarrive[j] * (C[j].x
                    - v_arrive[j]))

    with open("results.txt", "a") as f:
        if status == OptimizationStatus.OPTIMAL:
            print(n, stat_ind, "OPTIMAL",
                m.objective_value, "",
                corrected_fo, not_served_ships,
                s_ind, b_ind, port_ind,
                  fleet_ind, process_ind_1,
                      process_ind_2,
                      process_ind_3, sep=",",
                      file=f)
        elif status ==
            OptimizationStatus.FEASIBLE:
            print(n, stat_ind, "FEASIBLE",
                m.objective_value,
                m.objective_bound, corrected_fo,
                not_served_ships, s_ind,
                  b_ind, port_ind,
                  fleet_ind, process_ind_1,
                      process_ind_2,
                      process_ind_3, sep=",",
                      file=f)
        elif status ==
            OptimizationStatus.NO_SOLUTION_FOUND:
            print(n, stat_ind, "NO FEASIBLE
                SOLUTION", "X",
                m.objective_bound, "x", "x",
                s_ind,
                  b_ind, port_ind, fleet_ind,
                      process_ind_1,
                      process_ind_2,
                      process_ind_3, sep=",",
                      file=f)
        elif status ==
            OptimizationStatus.INFEASIBLE:
            print(n, stat_ind, "INFEASIBLE", "-",
                "-", "-", "-", s_ind,
                  b_ind, port_ind, fleet_ind,
                      process_ind_1,
                      process_ind_2,
```

```
                                                  process_ind_3, sep=",",
                                                  file=f)

                                elapsed = time.time() - start

                            process_ind_3 += 1
                        process_ind_3 = 0
                        process_ind_2 += 1
                    process_ind_2 = 0
                    process_ind_1 += 1
                process_ind_1 = 0
                fleet_ind += 1
            fleet_ind = 0
            port_ind += 1
        port_ind = 0
        s_ind += 1
    s_ind = 0
    b_ind += 1
```

B.2 Results averages

```
# SERVE PER PASSARE DALLE 7290 ISTANZE ALLE 1458 COMBINAZIONI VALUTATE IN
   MEDIA

import pandas

col_1 = ["Value"]
col_2 = ["Corrected_OF"]
col_3 = ["Not_Served_Ships"]
col_4 = ["Ships"]
col_6 = ["Berths"]
col_7 = ["Port_Type"]
col_8 = ["Fleet_Type"]
col_9 = ["Pr_1_Level"]
col_10 = ["Pr_2_Level"]
col_11 = ["Pr_3_Level"]

value_column = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_1)
cof_column = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_2)
nss_column = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_3)
s_col = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_4)
b_col = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_6)
p_col = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_7)
f_col = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_8)
pr1_col = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_9)
pr2_col = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_10)
pr3_col = pandas.read_csv("results_csv_v5_DEF.txt", usecols=col_11)
```

```
of = value_column.Value.to_list()
corrected_of = cof_column.Corrected_OF.to_list()
not_served_ships = nss_column.Not_Served_Ships.to_list()
s_ind = s_col.Ships.to_list()
b_ind = b_col.Berths.to_list()
p_ind = p_col.Port_Type.to_list()
f_ind = f_col.Fleet_Type.to_list()
pr_1_ind = pr1_col.Pr_1_Level.to_list()
pr_2_ind = pr2_col.Pr_2_Level.to_list()
pr_3_ind = pr3_col.Pr_3_Level.to_list()

infeasibility_list = []
no_solution_list = []
average_of = []
average_cof = []
average_nss = []

"""s_list=[]
b_list=[]
p_list=[]
f_list=[]
pr1_list=[]
pr2_list=[]
pr3_list=[]"""

i = 0

while i < 7290:
    j = 0
    sum_of = 0
    sum_cof = 0
    sum_nss = 0
    infeasibility_count = 0
    no_solution_count = 0
    divisor = 0
    while j < 5:
        if of[i + j] != "-" and of[i + j] != "x":
            sum_of += float(of[i + j])
            sum_cof += float(corrected_of[i + j])
            sum_nss += float(not_served_ships[i + j])
            divisor += 1
        elif of[i + j] == "-":
            infeasibility_count += 1
        elif of[i + j] == "x":
            no_solution_count += 1
        j += 1
        if j == 5:
            if divisor != 0:
                average_of.append(sum_of / divisor)
                average_cof.append(sum_cof / divisor)
```

```
                average_nss.append(sum_nss / divisor)
                infeasibility_list.append(infeasibility_count)
                no_solution_list.append(no_solution_count)
            else:
                average_of.append("X")
                average_cof.append("X")
                average_nss.append("X")
                infeasibility_list.append(infeasibility_count)
                no_solution_list.append(no_solution_count)
    i += 5

for k in range(1458):
    with open("average_results_DEF.txt", "a") as f:
        print(str(k + 1), average_of[k], average_cof[k], average_nss[k],
            infeasibility_list[k], no_solution_list[k],
              s_ind[k * 5], b_ind[k * 5], p_ind[k * 5], f_ind[k * 5],
                  pr_1_ind[k * 5], pr_2_ind[k * 5], pr_3_ind[k * 5],
              sep=(","), file=f)
```

Bibliography

[1] Council of Supply Chain Management Professionals. *CSCMP Supply Chain Management Definitions and Glossary*. URL: `https://cscmp.org/CSCMP/Educate/SCM_Definitions_and_Glossary_of_Terms.aspx`.

[2] Paul R Murphy and A Michael Knemeyer. *Contemporary logistics*. Pearson, 2018.

[3] *Review of Maritime Transport 2019*. Tech. rep. UNCTAD, 2019.

[4] Marc Levinson. *The Box: How the Shipping Container Made the World Smaller and the World Economy Bigger-with a new chapter by the author*. Princeton University Press, 2016.

[5] Daniel M Bernhofen, Zouheir El-Sahli, and Richard Kneller. "Estimating the effects of the container revolution on world trade". In: *Journal of International Economics* 98 (2016), pp. 36–50.

[6] The Geography of Transport Systems. *Advantages and Drawbacks of Containerization*. URL: `https://transportgeography.org/?page_id=2638`.

[7] *Container shipping: The next 50 years*. Tech. rep. McKinsey & Company, 2017.

[8] Port of Rotterdam website. *HMM Algeciras, the largest container ship worldwide, on its way to Rotterdam*. URL: `https://www.portofrotterdam.com/en/news-and-press-releases/hmm-algeciras-the-largest-container-ship-worldwide-on-its-way-to-rotterdam`.

[9] *The Impact of Megaships*. Tech. rep. International Transport Forum for OECD, 2015.

[10] Carter Michael, Price Camille, and Ghaith Rabadi. *Operations Research: A practical introduction*. 2nd ed. Taylor & Francis, 2019.

[11] David G Luenberger, Yinyu Ye, et al. *Linear and nonlinear programming*. 4th ed. Springer, 2016.

[12] Chaojue Yi and Ming Lu. "Mixed-Integer Linear Programming–Based Sensitivity Analysis in Optimization of Temporary Haul Road Layout Design for Earthmoving Operations". In: *Journal of Computing in Civil Engineering* 33.3 (2019), p. 04019021.

[13] Yann Collette and Patrick Siarry. *Multiobjective optimization: principles and case studies*. Springer Science & Business Media, 2013.

[14] Bradley Stephen, Hax Arnoldo, and Magnanti Thomas. *Applied mathematical programming*. Addison-Wesley, 1977.

[15] Claudia Caballini. *Shipping: trends, organization and stakeholders.* Politecnico di Torino. Ingegneria Gestionale, 2020.

[16] Francesco Rebora. "MODELLI ED ALGORITMI PER L'OTTIMIZZAZIONE DI "FREIGHT HANDLING" IN TERMINAL LOGISTICI PORTUALI". PhD thesis. Ingegneria dei sistemi di trasporto e logistici: Università degli studi di Genova, Scuola Politecnica.

[17] Christian Bierwirth and Frank Meisel. "A survey of berth allocation and quay crane scheduling problems in container terminals". In: *European Journal of Operational Research* 202.3 (2010), pp. 615–627.

[18] Yujian Song et al. "The berth allocation optimisation with the consideration of time-varying water depths". In: *International Journal of Production Research* 57.2 (2019), pp. 488–516.

[19] Dongsheng Xu, Chung-Lun Li, and Joseph Y-T Leung. "Berth allocation with time-dependent physical limitations on vessels". In: *European Journal of Operational Research* 216.1 (2012), pp. 47–56.

[20] Tianbao Qin, Yuquan Du, and Mei Sha. "Evaluating the solution performance of IP and CP for berth allocation with time-varying water depth". In: *Transportation Research Part E: Logistics and Transportation Review* 87 (2016), pp. 167–185.

[21] Arianna Alfieri. *Random variate generation.* Politecnico di Torino. Ingegneria Gestionale, 2020.

[22] AM Law. *Simulation Modeling and Analysis. Vol. 5th International Edition.* 2014.

[23] Arianna Alfieri. *Random number generation.* Politecnico di Torino. Ingegneria Gestionale, 2020.

[24] Qiang Meng, Jinxian Weng, and L Suyi. "Impact analysis of mega vessels on container terminal operations". In: *Transportation Research Procedia* 25 (2017), pp. 187–204.

[25] *Propulsion trends in container vessels.* Tech. rep. MAN Diesel, 2008.

[26] Nam Kyu Park and Sang Cheol Suh. "Tendency toward mega containerships and the constraints of container terminals". In: *Journal of Marine Science and Engineering* 7.5 (2019), p. 131.

[27] The Geography of Transport Systems. *Evolution of Containerships.* URL: `https://transportgeography.org/?page_id=2232`.

[28] Port of Antwerp. *Deepening of the Scheldt.* URL: `https://www.portofantwerp.com/en/deepening-scheldt-new-regulations-upstream-and-downstream-navigation`.

[29] Port of Antwerp. *The Scheldt.* URL: `https://www.portofantwerp.com/en/scheldt`.

[30] McKinsey & Company. *The future of automated ports.* URL: `https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/the-future-of-automated-ports`.