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Investigation and optimization of a dry bulk terminal capacity using queuing theory. Application at the cement terminal in Barcelona Port.

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ABSTRACT

This report presents the analysis of the performance of Portcemen Terminal in Port of Barcelona. From the actual data of bulk carriers calls throughout the year 2015 collected and provided by such terminal, a statistical analysis of its patterns have been developed. At the same time, it is intended to provide an overview of solid bulk maritime transport and its operations.

In order to characterize and analyse the fulfilment of Portcemen Terminal, Queuing Theory has been applied as a function of different parameters such as the average waiting time of the vessels in the queue or the occupation factor of the berthing line, among other. As a first step of a terminal optimization process, service levels of the terminal have been investigated according the standard design parameters established by the Spanish Recommendations of Maritime Works (ROM) and UNCTAD. Finally, to carry out the resilience study of the cement terminal through performance indicators, various scenarios have been raised.

The main conclusions derived from this report are the following. Firstly, with the calculations of the parameters for the selected queuing model for the demand in 2015, it can be asserted that it is an over dimensioned system. With a demand of 58 vessels per year in 2015, the probability of the system being empty is extremely high (83%) and the probability of having one vessel in the system is only 14%. This fact reflects that most time of the year the terminal is empty.

Nevertheless, it has to be borne in mind that the traffic in 2015 was only the 60% approximately of the traffic before the financial crisis of 2008 in Spain that represented one of the most significant setback in global trade. Yet, maritime shipping is subject to fluctuations as commercial opportunities change. This is an added difficulty of predicting traffic to dimensioning maritime terminals. Although Portcemen terminal is not one of the biggest cement terminals in the world, for sure it has had and it will have greater volume of dry bulk traffic than it has now.

Moreover, port selection is especially relevant because of the strong link between ports and industrial activity, but particularly between the port and its hinterland. Bulk terminals are better discussed in terms of concentration. They are found in regions heavily involved in the bulk trades. These bulk ports, are not only engaged in linking sea and land transport but are also hubs of industrial activity. The maritime traffic associated with transport of semi-raw materials and intermediate products activities is thus highly consistent and varies according to cyclic demand patterns.

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LIST OF ABBREVIATIONS

APB	Barcelona Port Authority
BDI	Baltic Dry Index
CTMC	Continuous time Markov chain
dwt	Deadweight tonnage
FIFO	First In First Out
FO	Observed frequency
FOR	Relative observed frequency
FORA	Accumulated relative observed frequency
FERA	Accumulated relative expected frequency
IAT	Inter-arrival times
JIT	Just in time
LIFO	Last In, First Out
m	Meters
MT	Million tons
NED	Negative Exponential Distribution
PR	Priority
ROM	Recommendations of Maritime Works
RS	Random Service
t	Tons
Tm	Metric tons
UNCTAD	United Nations Conference on Trade and Development

1. INTRODUCTION

Shipping has been an important human activity throughout history, particularly where prosperity depended primarily on international and interregional trade. In fact, transportation has been called one of the four cornerstones of globalization, along with communications, international standardization, and trade liberalization [*Kumar and Hoffmann*, 2002]. Due to a number of technological, economic, and socio-cultural forces, seldom country can keep itself fully isolated from the economic activities of other countries. Indeed, many countries have seen impressive economic growth in the recent past due to their willingness to open their borders and markets to foreign investment and trade. This increased flow of knowledge, resources, goods, and services among our world's nations is called "globalization", formally defined as "the development of an increasingly integrated global economy marked especially by free trade, free flow of capital, and the tapping of cheaper foreign labor markets." (Merriam-Webster, www.merriam-webster.com/dictionary/globalization, accessed 2018).

The marine industry is an essential link in international trade, with ocean-going vessels representing the most efficient, and often the only method of transporting large volumes of basic commodities and finished products [Gardiner, 1992].

Maritime transport remains the dominant mode for international trade both for bulk transport of commodities and containerized break-bulk cargo. The economics of bulk transport still influence the trade patterns and industrial location. Intermodal transport has become a global phenomenon as mechanized handling and containerization have reduced handling costs between modes and promoted their efficiency. Ports have become elements in global commodity chains controlled by logistics companies, maritime shipping lines, freight forwarders and transport operators. Their strategies and the allocation of their assets have shaped the structure of maritime transport networks in terms of ports of call, hierarchy and frequency of services [Rodrigue J.P. and Browne M., 2014].

The development of bulk and containerized maritime transportation has been strongly influenced by technology [Pinder and Slack, 2004]. Port selection is especially relevant because of the strong link between ports and industrial activity, but particularly between the port and its hinterland. However, technology and vessel design are by no means the only factors at work to influence the patterns of the world maritime shipping; government policy, commercial buying practices and physical constraints such as water depth in ports also play a key role. Bulk terminals are better discussed in terms of concentration. They are found in regions heavily involved in the bulk trades. These bulk ports, are not only engaged in linking sea and land transport but are also hubs of industrial activity. In the bulk trades, as in maritime transport in general, there is now a realization that the integration of supply chains requires a high level of organizational interdependence. Maritime transportation and inland transportation must increasingly be seen as functionally integrated. In bulk the reduction of inventory and storage costs by just-in-time (JIT) shipments and door-to-door services are increasing in significance.

Geographically, bulk cargo shows a remarkable stability, particularly in terms of its origins. The extraction and shipment of natural resources, such as minerals and oil, is bound to the geological setting, require massive capital investments and takes place over decades. Globalization identified labor markets overseas that encouraged transport of semi-raw materials and intermediate products where manufacturing costs were lower. The maritime traffic associated with these activities is thus highly consistent and varies according to cyclic demand patterns.

Marine transportation is an integral, if sometimes less publicly visible, part of the global economy. The growth of maritime transportation is strongly correlated with the growth of international trade as maritime shipping and ports are the main physical support for international trade flows. From about 800 million tons of loaded cargo in 1955, maritime traffic exceeded 8 billion tons for the first time in 2007, which represents 32,500 ton-miles. Yet, maritime shipping is subject to fluctuations as commercial opportunities change. The financial crisis of 2008-2009 represented the most significant setback in global trade since the Great Depression in the 1930s, but global trade and maritime shipping recovered afterwards.

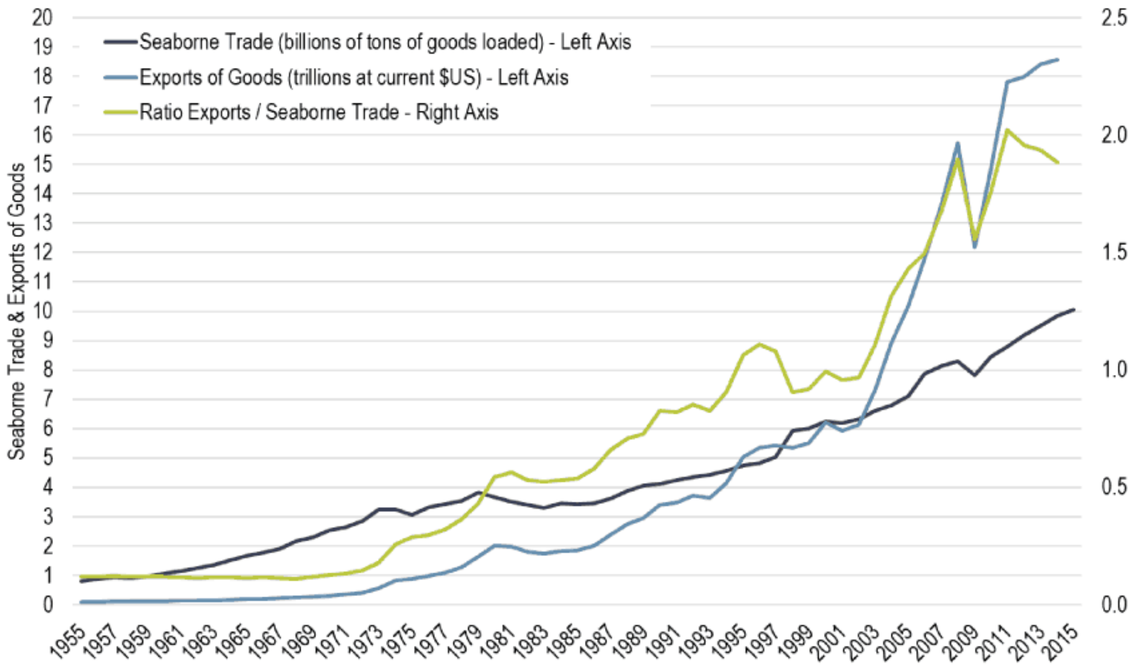


Figure 1. International Seaborne Trade and Exports of Goods Evolution, 1955-2016. Source: World Bank. United Nations, Review of Maritime Transport.

1.1.Objectives

The present minor thesis examines the performance of the Portcemen Terminal in Port of Barcelona. The main objective is to characterize and analyze the fulfilment of Portcemen terminal in Barcelona Port applying the queuing theory in order to investigate the service levels using standard design parameters (Spanish Recommendations of Maritime Works[1] or UNCTAD[2]) as a first step of a terminal optimization process. The sub-goal of the thesis is to carry out a resilience study of the cement terminal in Barcelona Port through performance indicators.

1.2.Stages of the research

So that the objectives above-mentioned can be achieved, the following work phases have been followed:

- First of all, some bibliographic review studies about cement and clinker trade, dry bulk terminals and queuing theory have been research.
- A main objective and other sub-goals have been defined considering all relevant factors.
- Description of the case study and data processing.
- Application of the methodology applied at the cement terminal in Barcelona Port.
- Contrasting and analysis of results.
- Discussion and conclusions.

1.3.Structure and summary of the contents

This document is organised as follows:

- In chapter 2 is presented the State-of-art. First, a brief resume of the international cement and clinker trade and the general distribution flows, as well as the description of specialized bulk ships and cement terminals with their required infrastructure. It is also described the loading and unloading process of cement and clinker and the required equipment to carry it out. Moreover, a brief overview of Barcelona Port and Portcemen terminal is provided to put the lector in situation about the characteristics of the terminal analysed.

- Chapter 3 presents the methodologies which have been used to carry out this minor thesis. The queuing theory and different models are presented in order to be applied in the Portcemen Terminal. Additionally, ship arrival process, inter-arrival time and service time are modelled in order to be expressed in terms of probability distributions. The Kolmogorov-Smirnov test it is used to determine the goodness of fit to such distributions.

[1] R.O.M., Recommendations of Maritime Works, is a Programme of recommendations materialized by Puertos del Estado that started in 1987 by order of the Directorate General for Ports and Coasts of the Ministry of Public Works and Urban Development.
[2] UNCTAD, United Nations Conference on Trade and Development, is a permanent intergovernmental body established by the United Nations General Assembly in 1964.

- In chapter 4 are presented the results obtained through the application of previous mentioned methods so as to investigate the levels of service of the terminal using standard design parameters (ROM and UNCTAD) as a first step of a terminal optimization process and its general performance. Besides, a manual simulation with the data provided has been carried out.

- Chapter 5 presents the discussion and conclusions of the results.

1.4.Justification of the thesis

Seaborne dry cargo shipments totalled 7.23 billion tons in 2016, reflecting an increase of 2% over the previous year. As shown in the table below, the share of the major bulk commodities (coal, iron ore, grain and bauxite, alumina, phosphate rock) amounted to about 43,9% of total dry cargo volumes, followed by containerized trade (23,8%) and minor bulks (23,7%).

Year	Oil and gas	Main bulks*	Dry cargo other than bulks	Total (all cargoes)
1970	1,440	448	717	2,605
1980	1,871	608	1,225	3,704
1990	1,755	988	1,265	4,008
2000	2,163	1,295	2,526	5,984
2005	2,422	1,709	2,978	7,109
2006	2,698	1,814	3,188	7,700
2007	2,747	1,953	3,334	8,034
2008	2,742	2,065	3,422	8,229
2009	2,642	2,085	3,131	7,858
2010	2,772	2,335	3,302	8,409
2011	2,794	2,486	3,505	8,785
2012	2,841	2,742	3,614	9,197
2013	2,829	2,923	3,762	9,514
2014	2,825	2,985	4,033	9,843
2015	2,932	3,121	3,971	10,023
2016	3,055	3,172	4,059	10,287

Figure 2. Growth in international seaborne trade between 1970-2016 (in millions of tons loaded). Elaborated by the author. Source: Compiled by the UNCTAD secretariat.

*Iron ore, grain, coal, bauxite, alumina and phosphate rock.

Dry bulk cargo is customarily divided into two groups, the “major bulk cargoes” and the “minor bulk cargoes”. The major bulk cargoes consist of a group of five commodities which almost invariably move by non-liner methods in full shiploads.

This information gives us an idea of the importance of supply chains for solid and liquid bulks. An important factor in the chain are the intermodal nodes in the ports, dynamic and complex systems, through which all material flows must flow efficiently.

The problems of handling bulk solids (storage, transport and process) are frequently the main causes of problems in bulk flow management. A bad design of the node of nodal exchange, can generate that the flow run into bottlenecks which generate delays and unnecessary costs. So looking for the maximum efficiency and productivity of the installation is key in the flow of the chain in the operation of bulk, bearing in mind those environmental problems derived from the activity.

A proper indicator for the analysis of the evolution of solid bulk transport is the Baltic Dry Index (BDI)[3]. It is reported around the world as a proxy for dry bulk shipping stocks as well as a general shipping market bellwether. This calculation is based on the transport of the main solid raw materials in bulk, such as iron, cereal, coal, etc., which is carried out in the 23 main maritime routes in the world within the vessels Handysize, Supramax, Panamax, Capesize. In this way, the number of maritime freight transport contracts is reflected. Most directly, the index measures the demand for shipping capacity versus the supply of dry bulk carriers. The demand for shipping varies with the amount of cargo that is being traded or moved in various markets (supply and demand).

Figure 3. Baltic Dry Index (2015-2018). Between these years, the highest value in the last years and the historic low have been achieved. Source: www.investing.com

As can be seen from the graphic above, in August 2018 the maximum value of BDI, almost 1,800 points, is produced. It is the highest value in the last years.

[3] The Baltic Dry Index (BDI), is issued daily by the London-based Baltic Exchange. The first daily freight index was published by the Baltic Exchange in January 1985.

When the world economy is in crisis, contracts for the transport of raw materials are reduced and consequently the Baltic Dry Index falls. Therefore, it is considered an advanced indicator of the market and is revealed as an effective thermometer of the evolution of the world economy.

As can be seen in the graphic above, this index of maritime freight of dry bulk cargo, on February 2016 reached the historic low of 290 points. By November 2016, it rebounded to over 1,000 sending the entire shipping industry to massive gains.

Cement is as vital a commodity to fast-growing economies as oil or steel. No other material is as versatile when it comes to building houses, roads and big chunks of infrastructure. It is a huge business: the world's cement-makers rake in revenues of $250 billion a year. Outside China, which accounts for half of global demand and production, six vast international firms—Buzzi, Cemex, Heidelberg, Holcim, Italcementi and Lafarge—together have 40% or so of the market.

Cement consumption in Spain closed 2017 with a growth of 11%, which places the domestic demand last year around 12.3 million tons. This confirms, therefore, the beginning of the recovery of the sector, although this percentage, in absolute values, only means a growth of just over one million tons, a reduced figure if we take into account that since 2007 the cement industry has lost 80% of its activity volume.

The consumption of cement in civil works has been reduced by 75% in the last decade, going from 19Mt in 2008 to 5Mt in 2017. This situation confirms that the construction activity remains stagnant at levels much lower than the normal volume of activity for a country like Spain, which according to the average of the last 40 years and excluding the decade of the boom, should be around 25 million tons annual.

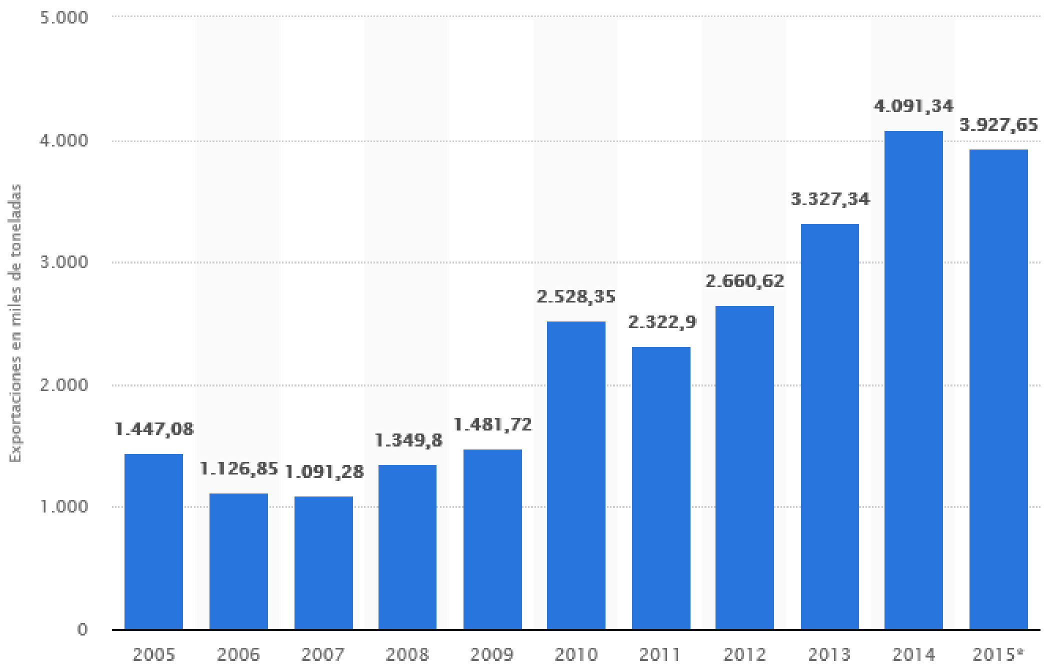


Figure 4. Annual evolution of cement export volumes (in thousands tons) of Spain between 2005 and 2015. Source: https://es.statista.com

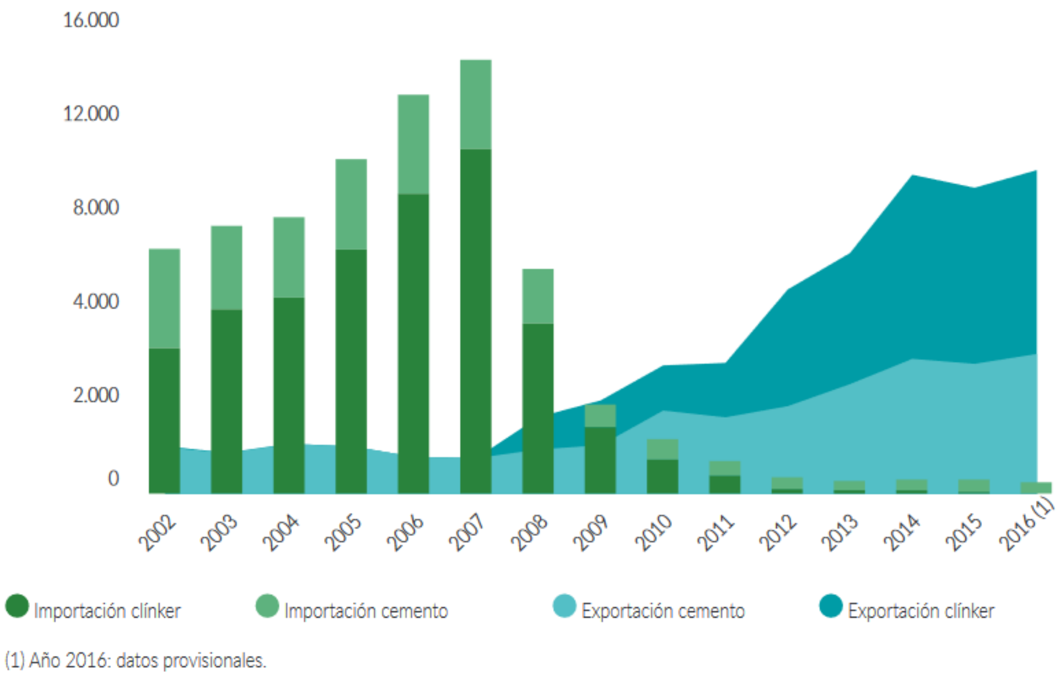


Figure 5. Evolution of foreign trade in the Spanish cement sector (in thousands tons) separated by type of cargo (cement and clinker) and type of activity (import and export). Source: Anuario del sector cementero español 2016. https://www.oficemen.com

The export volume closed the year 2017 below 4 million tons, exactly in 3,762,911 tons with a drop motivated by the loss of competitiveness of the sector due mainly to the increase in electricity costs. The Spanish industry currently sustain one of the highest costs in Europe - up to 30% more expensive - which penalizes its external competitiveness. This circumstance, which is reducing the margin gained with the improvement of the domestic market, has stagnated the production volumes of Spanish cement factories by 50% of its installed capacity, a level very similar to that reached in the last five years, in those that the internal consumption was smaller.

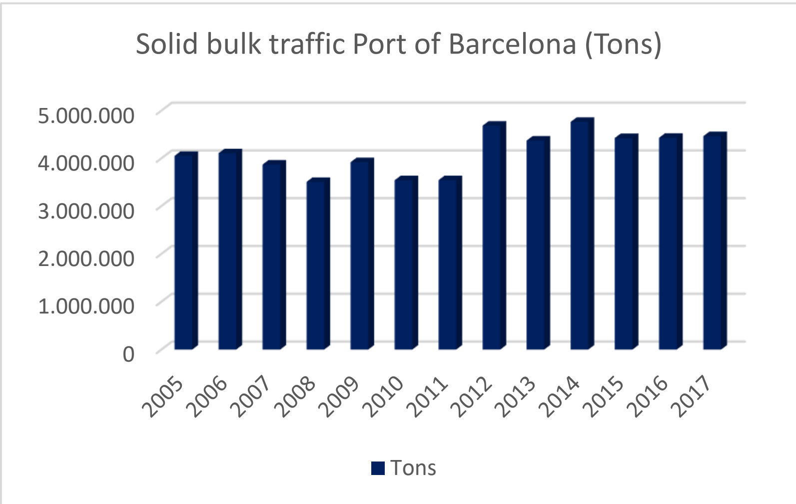
As can be seen in the figure 4, the graphic shows the evolution of cement and clinker both export and import separately. It can be noted a turning point in year 2008 due to the financial crisis that Spain suffered. The main cause of Spain's crisis was the housing bubble and the accompanying unsustainably high GDP growth rate. The ballooning tax revenues from the booming property investment and construction sectors kept the Spanish government's revenue in surplus, despite strong increases in expenditure, until 2007.

This fact is reflected in the graphic above, where until 2007 there was a substantial urbanization growth and consequently, a significant need of cement which have to be imported due to the lack of enough production in Spain. At this time, the consumption of this material was significantly higher than its production. For this reason, the most part of the cement and clinker was imported to Spain whereas exportations were nearly zero. From that moment, things were turned around by diminishing the importations to zero in 2017 and increasing the exportations for both cement and clinker. As can be noticed, cement trade is significantly variable and uncertain. For that reason, resilience studies based on this trade have particular importance for the lack of predictability of it.

2. STATE-OF-ART

2.1. Port of Barcelona

Although Port of Barcelona is specialized in containerized cargo and high added value goods, such as consumer goods and vehicles, the volume of solid bulk handled is significant and in 2017 it has reached 4,465,644 tons. The high volume in the last 10 years has positioned Port of Barcelona in 7th position in the Spanish port system, behind Gijón, Tarragona, Ferrol, Huelva, Cartagena and Bilbao.



Year	Tons
2005	4,051,927
2006	4,107,582
2007	3,870,253
2008	3,506,472
2009	3,921,099
2010	3,542,218
2011	3,544,297
2012	4,685,744
2013	4,373,720
2014	4,764,706
2015	4,426,087
2016	4,430,798
2017	4,465,644
TOTAL	**53,690,547**

Figure 6. Evolution of solid bulk volumes of Port of Barcelona between 2005-2017 in tons. Source: Elaborated by the author. Data compiled from Puertos del Estado.

In the Annex A it is showed a table with the market volumes of solid bulk for the last 10 years of all port authorities of Spain.

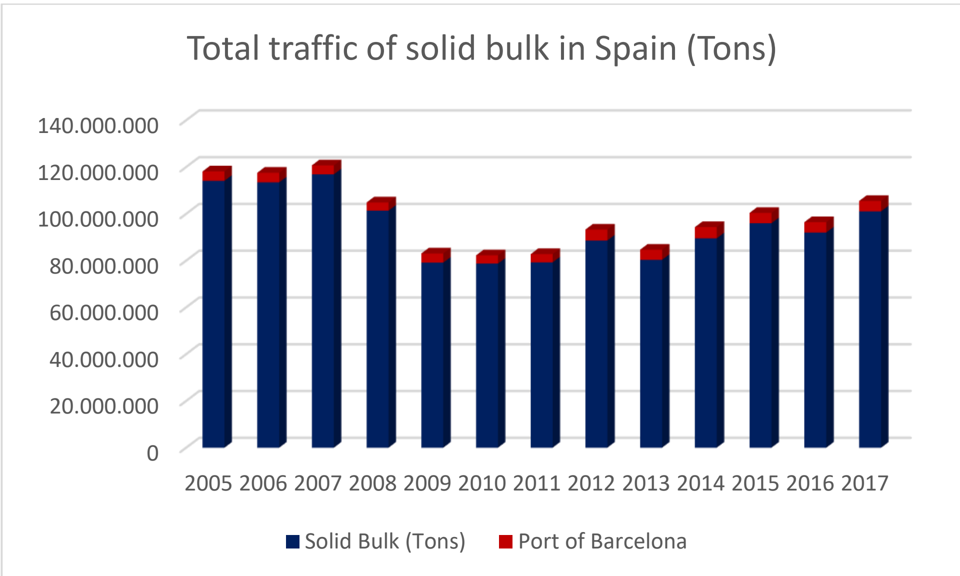


Figure 7. Evolution of solid bulk volumes of all Spanish port authorities between 2005-2017 in tons. Source: Elaborated by the author. Data compiled from Puertos del Estado.

With 4.5 million tons, this year (2017) almost the same solid bulk volume was channeled through the Port as compared to the previous year (+0,8%).

Although some products with huge volume have remained stable or have grown very lightly, such as cement and clinker and cereals and flour, the increase in feed and fodder stands out by 50.3% compared to 2015. In part, soy bean and potash have had decreases of 18.1% and 10.9% respectively, mainly driven by eventual market and operating circumstances.

The six large operators of solid bulk in Port of Barcelona have highly specialized facilities in different docks, but with a high concentration in Contradic wharf, to handle cement, grain, soy bean or potash, among other products. Among solid bulk operators include Portcemen, Ergransa, Cargill España, Bunge Ibérica and Tramer.

Figure 8. Aerial photo of Port of Barcelona. Source: Barcelona Port Authority.

2.2.Portcemen, S.A.

The facilities of PORTCEMEN, S.A. located in the Port of Barcelona and built in 1973, occupy a total surface of 10,675.20 m^2 at Contradic Sud Wharf. The Portcemen Terminal is owned by 3 Catalonian cement companies (Cementos Uniland, Cementos Molins and Cemex España) which each one owns 33% of it. The terminal handles 95% of the region's cement and clinker exports.

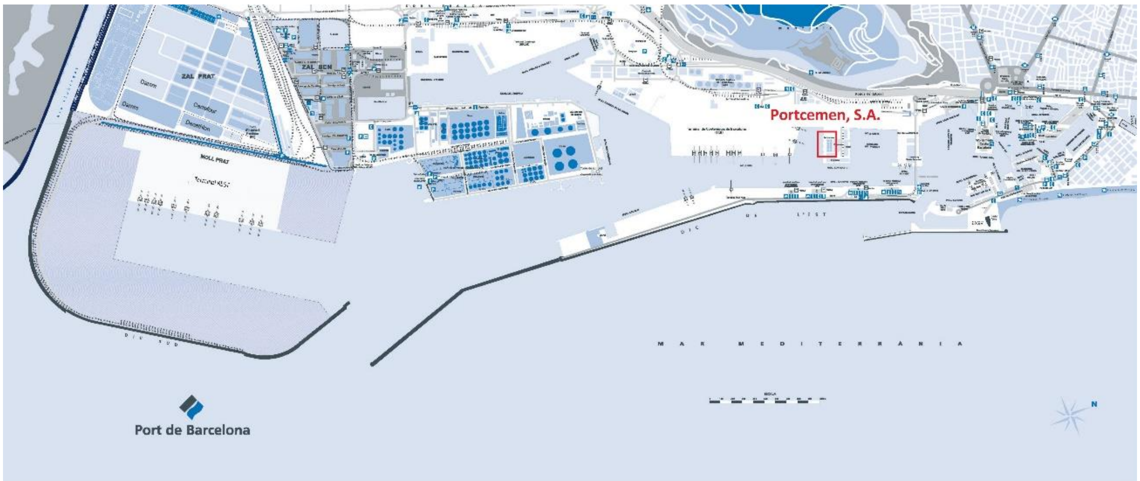


Figure 9. Localization of Portcemen terminal in Port of Barcelona. It is situated in Contradic Sud Wharf next to Ergransa and Bunge Ibérica (both dedicated to solid bulks). Source: Barcelona Port Authority.

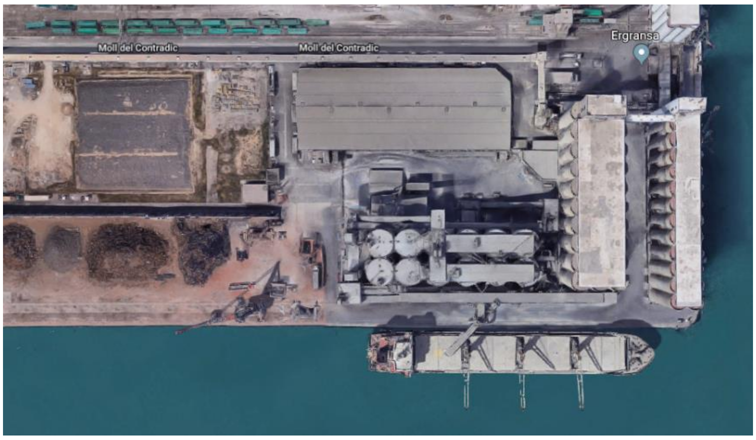


Figure 10. Aerial view of Portcemen Terminal. Source: Google Maps.

It has 12 concrete silos of 14 meters in diameter and 40 meters in height. Of those, 6 are used for the storage of cement in bulk and the remaining 6 are used for the storage of clinker.

They are located in a battery of 6 silos parallel to the dock. They have a storage capacity of 6,000 tons each, resulting in a total capacity of 36,000 tons of clinker and the same amount for cement.

The facilities have a berthing line for ships up to 225 meters in length and drafts of 12 meters, which allows loads up to 55,000 – 60,000 tons, therefore being able to operate with Panamax type vessels.

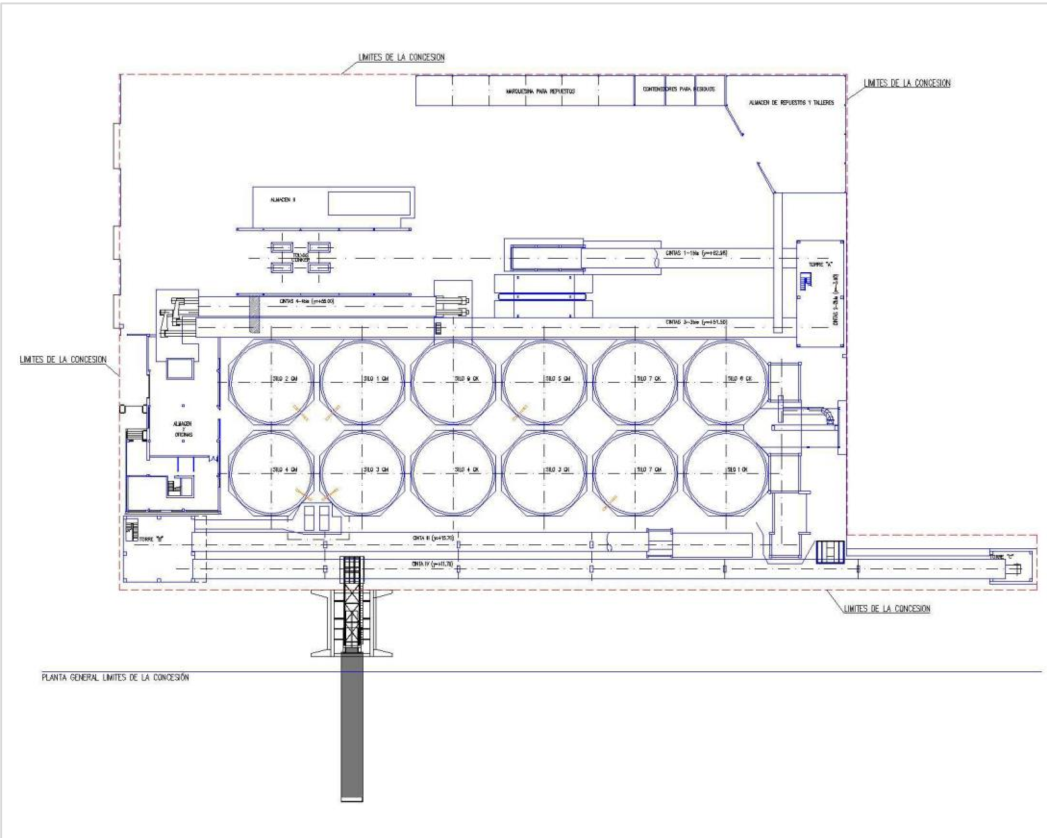


Figure 11. Floor plant of Portcemen facilities. It shows the arrangement of the 12 silos located in a battery of 6 silos parallel to the dock. It also shows the loading and unloading equipment and the conveyor belt. Source: http://www.portcemen.com

Figure 12. Portcemen terminal in Port of Barcelona. It can be seen the 12 silos, the conveyor belt and the loading and unloading equipment of the terminal. Source: Google Maps

The annual volume of Portcemen is around 1,000,000 tons. The attention to the local market, to which the factories must be attended in the first place for being its natural market, reduced in a very significant way the surplus destined to the export (limitation of the natural market of the cement distribution, by road, to 200 – 300 km of the production centres).

- Main traffic: Clinker and cement export
- Occupancy: 10,675 m^2
- Storage capacity: 12 silos (6 clinker and 6 cement)
- Pier: 200 meters
- Draft: 12 meters
- Boat type: Handymax (cargo> 40,000 tons)
- Annual volume:> 1,000,000 tons
- Loaders: 1 (> 1,000 tons/hour for clinker and > 500 tons/hour for cement)
- Modal exchange: By truck
- Others: Together with Escombreras (Cartagena, Murcia) the largest in Spain and one of the largest in the Mediterranean.

In essence, the industrial activity developed has 4 clearly defined processes:

1- Clinker reception from the factories, storing it in the clinker silos to later load it on ships.
2- Cement reception from the factories, storing it in the cement silos to later load it on ships.
3- Clinker reception by sea, storing it to clinker silos and subsequently load it on tubs to the factories.
4- Cement reception by sea, storing it to cement silos and subsequently load it on tanks to the factories.

2.3.Cement and clinker trade

Both cement and clinker are distributed in large quantities throughout the world. The difference between both products is that the clinker is an intermediate product, which is necessary to process in a mill for the subsequent production of cement. This greatly influences what type of product will be exported.

Establishing a clinker grinding plant supposes operating costs much higher than the establishment of a cement maritime terminal and, paradoxically, this is compensated by the fact that the clinker acquisition price, as well as the transport cost, is much lower than in the cement's case.

Additionally, the equipment destined to the handling of the clinker and the vessels for its transport are less specialized due to the own characteristics of the product.

In general, and without taking into consideration other economic factors, the option of establishing a maritime terminal with the consequent import of cement or the establishment of a milling and import clinker, in a stable and long-term market, the milling will be more attractive than the cement terminal because of the clinker's own advantages such as:

- Being an intermediate product, makes that it does not need the quality controls that are necessary for the cement.
- It is manageable with stowage equipment for bulk merchandise;
- It does not need specialized facilities;
- There is a greater number of plants with capacity to export clinker than cement;
- The imported clinker can be adjusted to the quality needs of the local market or specific consumptions of large size thanks to the processing is controlled by the producer;

Milling has a lower environmental impact than that produced by a clinker production plant in terms of CO_2.

2.3.1. Cement and clinker evolution

Portland cement has existed since 1824 as well as its massive production and the subsequent need to export it. During this period, almost all the cement was transported in a bagged way, including maritime transport, although on a very small scale.

In 1930, bulk shipping began on the Great Lakes, between the USA and Canada, equipped with air guides and Fuller Kinyon pumps. After the Second World War, the number of concrete plants increased considerably, as a consequence the transport of cement over long distances increased. Along with it, bulk ships began to become self-discharges. In the mid-1950s, the first self-discharging pneumatic boat was built in the Netherlands, with the stevedoring company ENBO, allowing bulk cement to be transported in bulk ships. It was a former tug-boat on which a pneumatic conveying installation was mounted.

In the 60's, bulk cement transport had a strong growth. The domestic distribution systems carried out by Norcem and Cementia respectively in Norway and Sweden began to evolve. Norcem started exporting to a terminal in New York. On the other hand, the development of a domestic distribution network began in Japan. Blue Circle started with bulk exports from Bamburi (Kenya) to islands located in the Indian Ocean with self-discharging cement plants with Claudius Peters technology and with silo terminals. In Europe and the USA, river transport expanded very rapidly. The Carlsen and Nordstroms companies started manufacturing self-discharging cement vessels with different technologies. In Japan a new class of self-discharging boats were developed, the most notable of the company Supero Seiki.

In 1974, the first Swirtell mechanical unloader was delivered, and long-distance transport of cement with large bulk carriers could be carried out. Many of these large unloaders were installed in floating terminals located in the Near East, making possible the large-scale importation of bulk cement. In the 80s and 90s the Swirtell became the standard large unloader.

In 1977 the Dutch stowage company ENBO built the first mobile ship unloader with its fleet of floating pneumatic unloaders. This model became so popular that a new company, KOVAKO, was founded to sell it. In the 80s and 90s the company achieved spectacular growth with the sale of about 70 of these unloaders.

Many of them were purchased by independent concrete producers and traders who established independent operations combining these unloaders with low cost horizontal storage areas. It is difficult to determine if these operations caused a strong globalization and consolidation in the industry in these years or were a reaction to this phenomenon.

Before the 1970s, multinationals in the industry consisted of companies extending to friendly neighboring countries or former colonies. In the 70s, Sancem was one of the pioneers in establishing a chain of grinding plants in West Africa, supplying them with clinker from Norway and Sweden to increase the productive efficiency of these plants and benefit from the growth rates of these markets.

The huge growth of the multinationals between 1970 and the financial crisis in 2008 is due to the following strategic factors:

- The distribution of risks in the face of economic recessions in many markets with different characteristics.
- International trade that balances overcapacity in certain markets with the deficit in others, entry into new markets and provide less dependence.
- Vertical integration to have a better control of market share or price.
- The establishment and management of exchange centers and implementation of the best technology and management practices within the group.

Nearly 80% of the cement and clinker exchange is carried out by the largest 10 multinationals in the year 2000.

The financial crisis has put a brake on the growth of highly indebted multinationals, mostly established in developed countries. The least indebted groups and mostly based in developing countries are the new fast-growing actors. The global trade in cement and clinker has dropped substantially as a result of this local crisis, but is becoming more diverse. The shipments of bagged clinker and cement are increasing while those of bulk cement are decreasing. However, the trade of materials for the manufacture of cement, such as ash, is showing a strong growth. The key markets right now are Africa and South Asia and Southeast.

Regarding technologies, since the mid-1990s there have been no technical developments which have changed the industry with respect to grinding, cement terminals, ship unloaders or self-unloading ships. The number of equipment suppliers in this field has grown with the expansion of commerce and distribution. New suppliers are emerging in developing countries.

Nowadays, the transport of cement by sea is focused on dry cargo. In the case of clinker, the ships used are bulk carriers and in the case of cement, bulk carriers, tires and self-dischargers.

In 2012, about 98 million tons of cement and clinker were transported by sea. This refers specifically to international transport, but there are also domestic shipments of cement and clinker by sea. There is a clear relationship between international shipments and domestic ones, at the time when the seconds decrease, the number of the first one's increases and vice versa. Bearing in mind that the same vessels are used for both transports. Along with this type of shipments there is also domestic traffic in which waterways, lakes and canals are used.

The market conditions have changed; producers have been increasingly involved in the logistics part of the supply of products. Moreover, companies committed to the manufacture of machinery have also been involved in the production of unloading systems for pneumatic boats and terminal equipment, which will expand the demand for this type of equipment at a lower price. This would mean the reduction of costs, barriers to entry, for the establishment of a maritime terminal.

Clinker and cement traffic will depend mainly on the economic situation at a global level. In Europe there has been an increase in cement sales as well as cement materials. This has raised the need for new terminals and more self-unloading vessels.

The high demand cannot be completely replaced by self-discharging vessels, so there are volumes that must be transported through coastal vessels, a situation that is already happening.

The perspective for a short-term future is positive considering global economic growth and increased sales.

2.3.2. Global trade and distribution flows

Seaborne trade and distribution is an important part of the cement industry. However, cement trade and distribution is not a simple open market. A waterside cement plant with ship loading capabilities appears to be in an excellent position to export or distribute its surplus capacity, but without a trading network and firm receiving destinations it cannot ship anything.

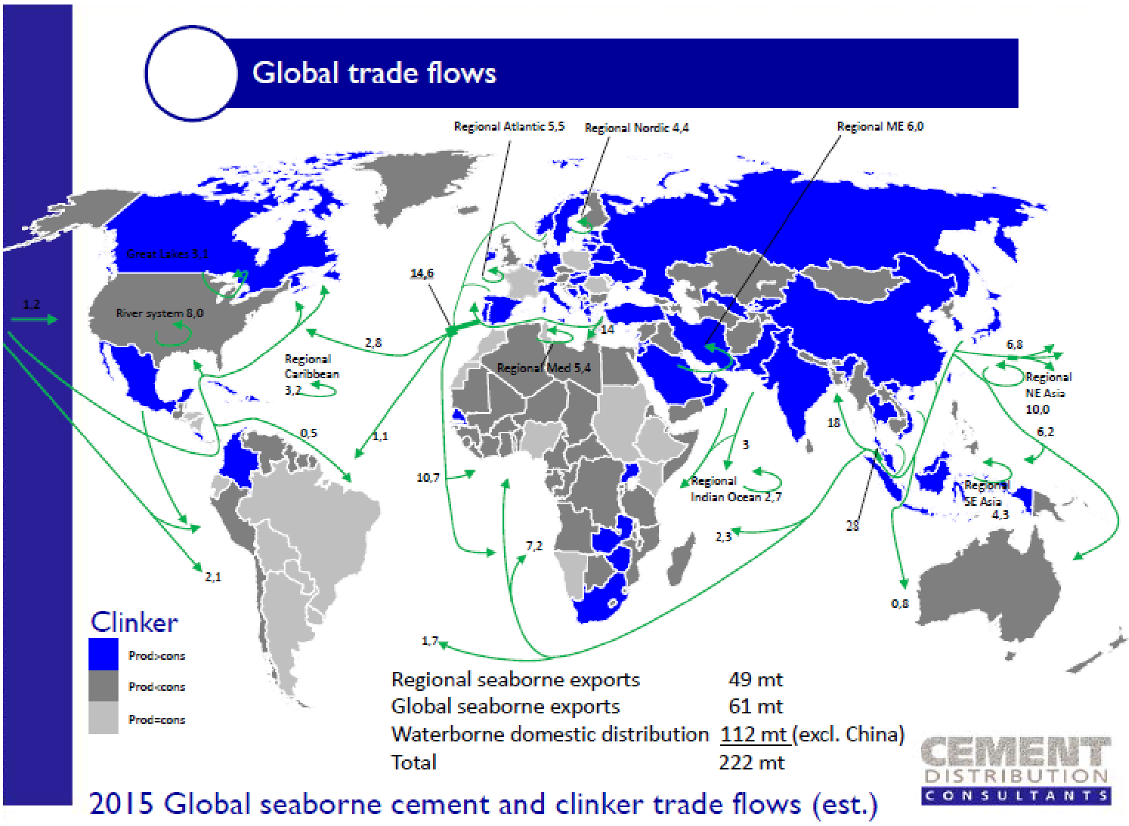


Figure 13. Global seaborne cement and clinker trade flows in 2015. As can be seen in Spain, since 2008, clinker production is bigger than its consumption when years ago, the situation was the opposite. Source: https://cementdistribution.com

As can be seen in the figure above, the sea transport of cement and clinker can be configured into three major types of flows:

1) Regional maritime exports (Atlantic Region, North Region, Middle East Region, Mediterranean Region, Indian Ocean Region, Northeast Asia Region, Southeast Asia Region, Caribbean Region), make up approximately 22% of the volume transported.
2) International maritime exports (Intercontinental), being approximately 27% of the total volume transported.
3) Domestic distribution (USA River System, Great Lakes USA-Canada, coastal and river transport among others).

Europe is the second-largest exporting area in the world, with the Mediterranean the key export basis. In 2015 a total of 43.9Mt was exported by sea from European plants, of which 15.3Mt was traded regionally within the continent, 14Mt was exported to North Africa, 10.7Mt to West Africa and 3.9Mt to the Americas.

Seaborne transportation can consist of bulk clinker, bulk cement and cement bagged in 25kg or 50kg bags and big bags. A total of 93Mt of cement and clinker was traded regionally and 110Mt was traded globally in 2015. 18.7Mt of cement was distributed by water domestically, excluding China.

CLINKER AND CEMENT TRADE BY WATER			
Clinker / cement type	Seaborne trade (Mt) International	Domestic	Inland water domestic trade (Mt)
Clinker	43.9	9,4	4,7
Cement – Bulk	49,1	72,1	10.3
Cement – Bagged	17,0	11,5	3,7
Total	**110,0**	**93,0**	**18.7**

Figure 14. Clinker and cement trade by water in 2015 in million tons. It is distinguished between seaborne trade (international and domestic) and inland water domestic trade by type of product. Source: https://cementdistribution.com

Although China is a large exporter of cement and clinker, it is not an influential country in global cement trade as it does not own any overseas cement terminals or coastal grinding plants. It exports because there is a shortage in other markets and its cement is being purchased, but when that ends, Chinese exports are expected to drop. Chinese cement producers simply do not have the required large bulk import terminals in these mature markets.

2.4.Overview of cement and clinker in maritime transport

2.4.1. Forms of transportation

The transport of cement by sea focuses on dry cargo. In the case of clinker, the ships used are bulk carriers and in the case of cement are bulk carriers, tires and self-dischargers. In the case of packaged cement, it may also be carried out by means of bulk ships and containers. In 2016, about 117 million tons of cement and clinker were transported by sea. There is different type of vessels for such transports according to the product to be transported. This is especially important since it gives us an idea of the type of ports that receive these products and the maximum draft of the terminal determines the type of boat to be used and the regularity of such transports. Of the 3,000 ports that exist worldwide, many of them cannot receive large ships. Self-discharging ships are mostly used for domestic distribution and short-distance regional trade.

CLINKER AND CEMENT TRADE BY VESSEL TYPE				
Clinker / cement type	Bulk Carriers (Mt) Large	Coastal	Self-disch. cement carriers (Mt)	Inland ships & water barges (Mt)*
Clinker	41,2	12,1	0	4,7
Cement – Bulk	12,7	11,5	97,0	10,3
Cement – Bagged	19,6	8,9	0	3,7
Total	**73,5**	**32,5**	**97,0**	**18,7**
* *excluding China*				

Figure 15. Clinker and cement trade by vessel type in 2015 in million tons. It is distinguished between bulk carriers, self-discharging cement carriers and inland ships and water barges. Source: https://cementdistribution.com

The table above makes a subdivision of the commodities relating to ship size and type used. It shows large bulk carriers (Handysize and Handymax), coastal bulk carriers, self-discharging cement carriers and vessels used for domestic distribution on inland waterways. The fleet of cement carriers is clearly overstretched. Including small coastal vessels between 500 and 2,000dwt, their total number is about 325. With an average ship size of 7,500dwt and an average annual tonnage transported of close to 300,000 t/vessel, round-trip times are about a week. The lower availability of self-discharging vessels in international trade has resulted in growing shipments in bagged cement and clinker in bulk carriers.

Due to the limits in size and capacity of the buckets, handymax and handysize bulk carriers are usually the most used.

The global seaborne trade of cement and clinker reached 117 million tons in 2016, and additionally, another 94 million tons were achieved domestically.

Of all the maritime transport of cement and clinker, approximately 80 million tons were transported by bulk carriers (handysize and vessels of higher tonnage), 34 million by coastal vessels and about 97 million by self-discharging cement ships.

2.4.2. Bulk ships

In 2015, a total number of 58 bulk ships carrying cement (26) and clinker (32) were received in Portcemen Terminal in Port of Barcelona. For these ships, values for the length, the draft, the beam and the deadweight[4], among others, were determined using the databases of *Sea-web* (http://www.sea-web.com) and *Marinetraffic* (http://www.marinetraffic.com). The required quay length relates to the number and length of the berthed ships that have to be served at the same time. In Annex C, there is listed an overview of the dimensions determined.

The graphic below shows the relationship between the length of the ship (m) versus its deadweight[1] in tons.

[4] The deadweight is the ship's carrying capacity including the weight of bunkers for fresh water, ballast water and fuel.

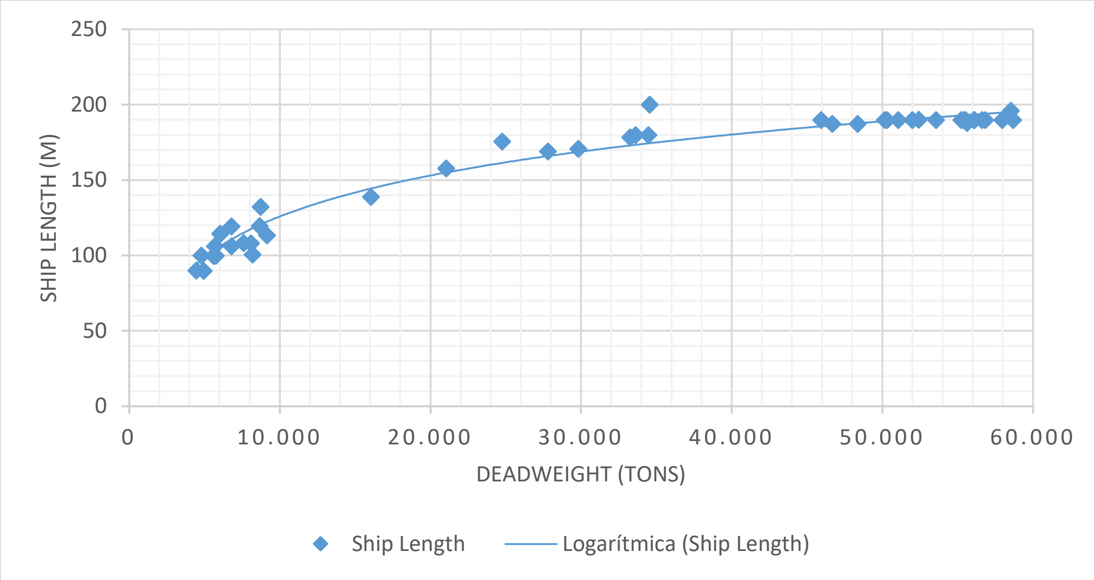


Figure 16. Ship's length versus the ship's deadweight. Source: Elaborated by the author based on the databases of the Sea-web and Marinetraffic.

The same method as mentioned above was used to determine relations for the ship's beam and the ship's maximum draft versus the ship's deadweight.

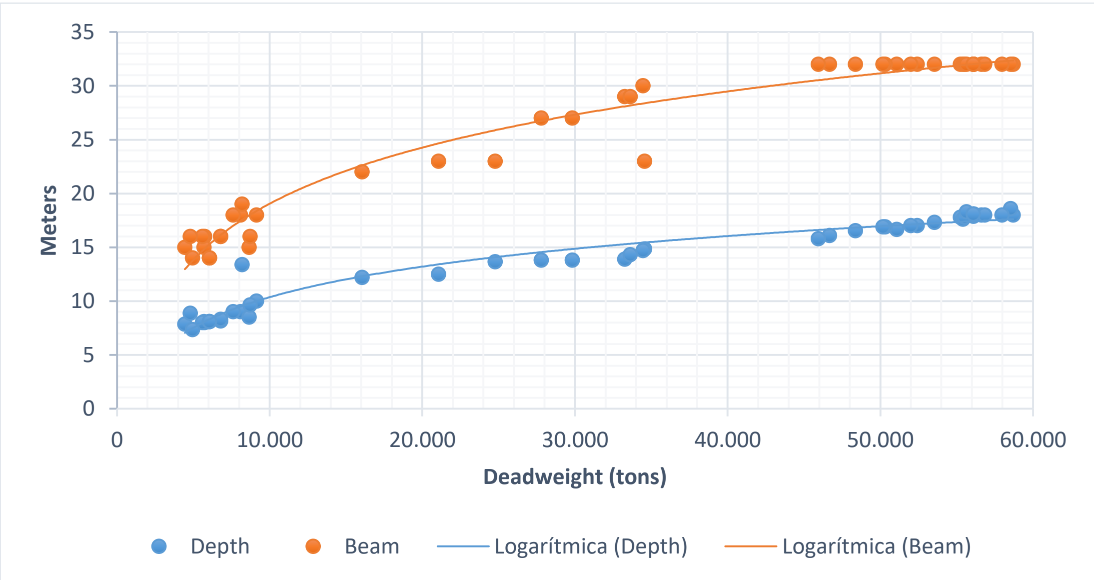


Figure 17. Ship's beam and ship's maximum draft versus the ship's deadweight. Source: Elaborated by the author based on the databases of the Sea-web and Marinetraffic.

Although these previous relationships between beam, depth and ship length with deadweight are representative, it would be more significant and interesting the relationship between capacity in m^3 and deadweight. However, this information is not provided by the databases queried.

2.4.3. Size categories

Bulk carriers are segregated into 6 major size categories: small, handysize, handymax, panamax, capesize and very large.

Type	Deadweight (DWT)	Length (m)	Draught (m)	Draft (m)	Holds (units)
Small	<10,000	<130	<10	3-6	1-3
Handysize	10,000 to 35,000	130-175	10	7-11	3-6
Handymax	35,000 to 60,000	175-200	11-12	8-13	5-7
Panamax	60,000 to 90,000	200-230	13-15	12-15	5-9
Small Capesize	90,000 to 150,000	230-270	17	13-17	7-9
Large Capesize	>150,000	270-350	>17	16-22	7-10

Figure 18. Classification by type and main characteristics of bulk ships. Source: Elaborated by the author through own research in vessels data basis.

Cargo vessels have been getting bigger for many years. So the increases in ship size are actually borne of the need to create ever greater economies of scale. Every aspect of these massive vessels is designed to make transport of cargo as fuel efficient and cost effective as possible. With less access to efficiencies of scale or speed, smaller carriers are losing ground fast. The challenge for ports is to invest ahead of the shipping capacity coming on-stream, and to try and be one step ahead of the game. The problem with the smaller terminals is that they cannot accept large vessels because of draft and length restrictions which makes them having an uncertain future.

In the current case of study of Portcemen Terminal and according to the abovementioned classification, the cement terminal in Port of Barcelona had served in 2015 a total number of 48 different types of ships.

Vessel type	# of ships per type
Handymax	22
Small	17
Handysize	9
Total	48

Figure 19. Number of vessels served in Portcemen terminal in 2015 by type of vessels. Source: Elaborated by the author.

In 2015 at cement terminal in Port of Barcelona, the ship with the maximum deadweight served was 58,701 tons. It loaded 41,223 tons of clinker to Tema, Ghana.

In the Annex C, there are listed all the ships that have been served in Portcemen Terminal in 2015 as well as all their characteristics.

- **Small (<10,000 dwt):** They are ships usually fitted with box-shaped warehouses which can be used to transport multiple types of cargo. They are mainly used for regional flows and occasionally for loads and/or special and long trips. In this case of study, the small ships are intended to France (Fós-sur-mer), United Kingdom (Sharpness) and Algeria (Djen-Djen).

- **Handysize (10,000-35,000 dwt):** Many of them have integrated cranes and spoons, which are suitable for most of the ports, have been widely used by the cement industry throughout these years, both in the transport of cement in bulk and clinker. They are usually used in trips of medium distance. They are also used for the transport of bagged cement in long-distance trips and in cases of ports with draft restrictions.

- **Handymax (35,000-60,000 dwt):** In the case of this type of ships, they have suffered an increase in its size in recent years, being currently a large part of the fleet of a size greater than 55,000dwt. This have been a problem for the cement sector since the maximum volume is usually between 45,000 and 55,000dwt due to the storage capacity of terminals. The average storage capacity of most terminals are between 40,000 to 45,000 tons and which in turn have cement unloaders. This type of ships is mainly used for the transport of clinker and cement in long-distance routes.

2.4.4. Port facilities

Regarding to maritime trade, the cement industry needs to place its production infrastructures at a maximum distance of approximately 200km due to it is not economically feasible to export products away from maritime terminals by sea.

It is necessary to distinguish the infrastructure needed for cement or clinker transport since it is not used the same loading/unloading machinery due to their physical characteristics.

Referring to clinker, the loading can be done through different systems; by means of the typical use of cranes and spoons, which can belong to the vessel or to the equipment in ground. It is also common loading the cargo through cement conveyors.

On the other hand, regarding the loading and discharging methods of cement, we are faced with two main forms: pneumatic and mechanical machinery. Both technologies allow loading and unloading the product avoiding dust emissions into atmosphere. Also both methods can be done from land as well as they can belong to the vessels.

2.4.5. Bulk cement terminals and coastal grinding plants

There are 857 cement terminals around the world who receive cement by sea or inland water which 169 of them are equipped with a ship unloader and can receive general bulk carriers. A total of 688 terminals, are served by self-discharging ships. Most of them are used for domestic distribution or regional trade whereas the ones with a ship unloader are used for international trade.

Global seaborne cement and clinker trade is controlled by the owners of the exporting and distributing cement plants, and even more, by the owners of the receiving bulk cement terminals and grinding facilities.

As can be seen from the table below, the top five multinationals own about 40% of all the facilities involved in global seaborne trade and distribution.

COMPANY	CEMENT PLANTS	GRINDING PLANTS	TERMINALS	TOTAL
Lafarge	23	16	89	128
Heidelberg Cement	11	19	88	118
Holcim	20	20	77	117

Cemex	19	3	71	93
Italcementi	10	7	21	38
TOTAL	**83 (38%)**	**65 (33%)**	**34 (40%)**	**494 (39%)**

Figure 20. Overview of facilities of the top five multinationals involved in waterborne trade and distribution in 2013. Cemex (the fourth in the world) is one of the three cement companies that owns Portcemen terminal. Source: www.cemnet.com.

As it is mentioned before, the Portcemen terminal, the one which is analysed in the current study, is owned by 3 cement companies which one of them is Cemex. Cemex is one of the biggest companies in the world in terms of cement transport volumes. As it is seen in the table above, it has 93 facilities around the world.

2.4.6. Cement terminals

Dry bulk terminals are crucial nodes in the supply chain for the dry bulk products. Two terminal functions can be distinguished:

- Tranship dry bulk materials between the different transport modalities
- Store the materials temporarily to absorb unavoidable differences in time and quantities between incoming and outgoing flows.

A dry bulk terminal contains three main subsystems: the seaside, landside and stockyard. The seaside and landside are the connections with the bulk supply chain where dry bulk materials are imported to or exported from the terminal.

Dry bulk materials can directly be transferred between the different transport modalities without being stored at the stockyard. Nevertheless, direct transfer is difficult to realize due to all kind of interruptions in the bulk supply chain. Most of the cargo is stored for a period of time in piles at the terminal's stockyard. Transportation of materials at terminals is generally performed using belt conveyors as in Portcemen terminal in Port of Barcelona.

In recent years, there has been an increase in cement sales in Europe, and this has raised the need for new terminals and more self-unloading vessels. On the other hand, new self-discharging ships have been delivered to northern Europe and this demand will surely increase, considering that due to the strict environmental policies, it is necessary to replace the old ships.

2.4.7. Required infrastructure in cement terminals

Regarding the required infrastructure in a port for the transport of cement or clinker, it is necessary to distinguish between both products, since it is used different machinery for each product due to their physical properties.

In reference to clinker, the loading operation can be done through different systems. By means of the habitual use of cranes or spoons, which can belong to the ship or to ground-based equipment. It is also common using cement conveyors for the loading operation.

In the case of cranes and buckets, shippers will have available without any additional cost the use of the loading and unloading machinery on board, this is usually the most used method. Furthermore, it has the disadvantage of being the slowest method and at the moment of depositing the material in the ship's hold, high emissions of particles are produced in the atmosphere, which is not appropriate due to the restrictions regarding the emissions.

Regarding the use of cranes and spoons, not being the machinery on board of the ship, implies an additional cost. It must be borne in mind that the margins of the clinker and cement exportations are reduced, consequently the stakeholders look for the economical practice. In this case, if the port has a hopper, it is possible the direct discharge to the truck despite the complexity of this technique since it is necessary to ensure a constant rate of unloading through the continuous availability of trucks.

An alternative method used, only in loading operation, is the use of conveyor belts. This system allows the load through omens made in ship's hull. Conveyor belts enable the loading in adverse conditions, as with storms, winds or rains, when it would be impossible to perform with cranes or spoons.

Regarding the methods of loading and unloading cement, there are two main forms through the use of pneumatic and mechanical machinery. Both technologies allow the procedure avoiding dust emissions into the atmosphere.

Both pneumatic and mechanical discharge systems can be combined with different storage options from domes to silos. Being mechanical discharge system the most versatile in terms of unloading capacity from different types of ships. However, it has a higher energy consumption than mechanical unloading systems.

In the case of pneumatic discharge, this is done through the vacuum extraction of the cement from the holds. The advantage of the machinery is that it is usually more flexible and easier to reach all the places in the holds when using hoses.

In the case of mechanical unloading, it is carried out by an endless screw. This method is slower than pneumatic discharge. They usually require systems of transport by conveyor belts until the storage of the product.

2.4.8. Loading and unloading process

Loading and unloading a bulk carrier is time-consuming and dangerous. All the process is planned by the ship's chief mate under the supervision of ship's captain. The captain and the terminal master agree on a detailed plan before the operations begin, as it is required in the international regulations.

- **Ship-loading equipment**

Ship-loading systems are simple in comparison with ship-discharging systems. They normally require only a feed elevator or conveyor, a loading chute and the force of gravity. With such technically simple systems, phenomenal rates can be achieved.

Other loaders are fitted with flight conveyors or spiral chutes to reduce the degradation of friable materials, or with telescopic tubes fitted with chutes or centrifugal slinger belts for distributing the material in the hold. Ship-loaders can normally be positioned adjacent to the hatch to be loaded, and they receive the material from high-capacity belt conveyors.

Ship-loader capacities are usually limited by the other parts of the installation such as the conveyors or reclaimers, but normal capacity ranges are between 1,000 and 7,000 tons an hour.

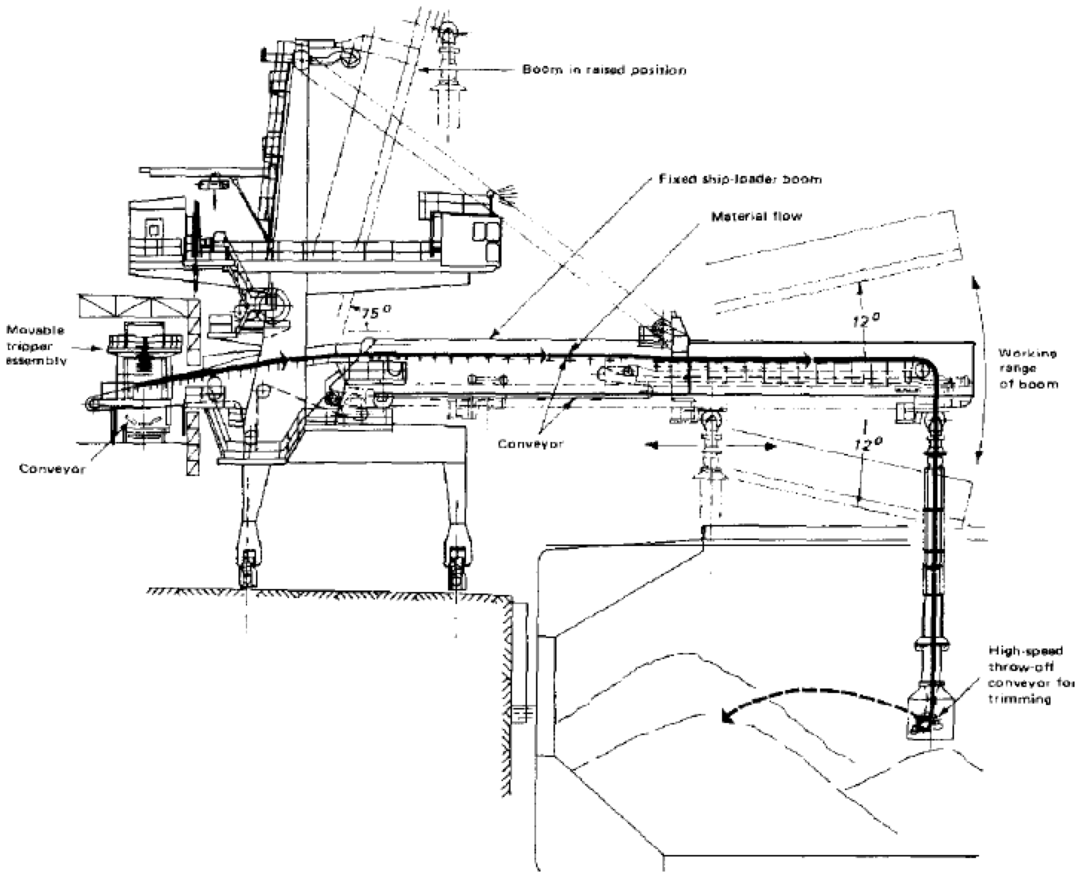


Figure 21. Example of travelling ship-loader with material from high-level conveyor. Source: Chapter II: Planning Principles. Port Development: A Handbook for Planners in Developing Countries (UNCTAD)

The ship loading machines used depends on both the cargo and the equipment available on the ship and on the dock. A widely used method is the double-articulation cranes, which can load at a rate of 1,000 tons per hour, and the use of shore-based gantry cranes, reaching 2,000 tons per hour, is growing.

Moreover, conveyor belts offer a really efficient method of loading, with standard rates varying between 100 and 700 tons per hour. Start-up and shutdown procedures with conveyor belts, though, are complicates and require time to carry out. Self-discharging ships use conveyor belts with load rates of approximately 1,000 tons per hour.

Regarding the conveying technologies, screw conveyors are particularly well suited for handling powdery and dusty materials and where limitations in height need to be considered. A screw-type loader is thus commonly used for handling commodities such as cement, cement clinker and combinations of both of them, and is applicable to ships up to Panama size.

It is crucial to keep the cargo level during loading in order to maintain stability. As the hold is filled, machines such as bulldozers are often used to keep the cargo in check. Levelling is particularly important when the hold is only partly full, since cargo is more likely to shift.

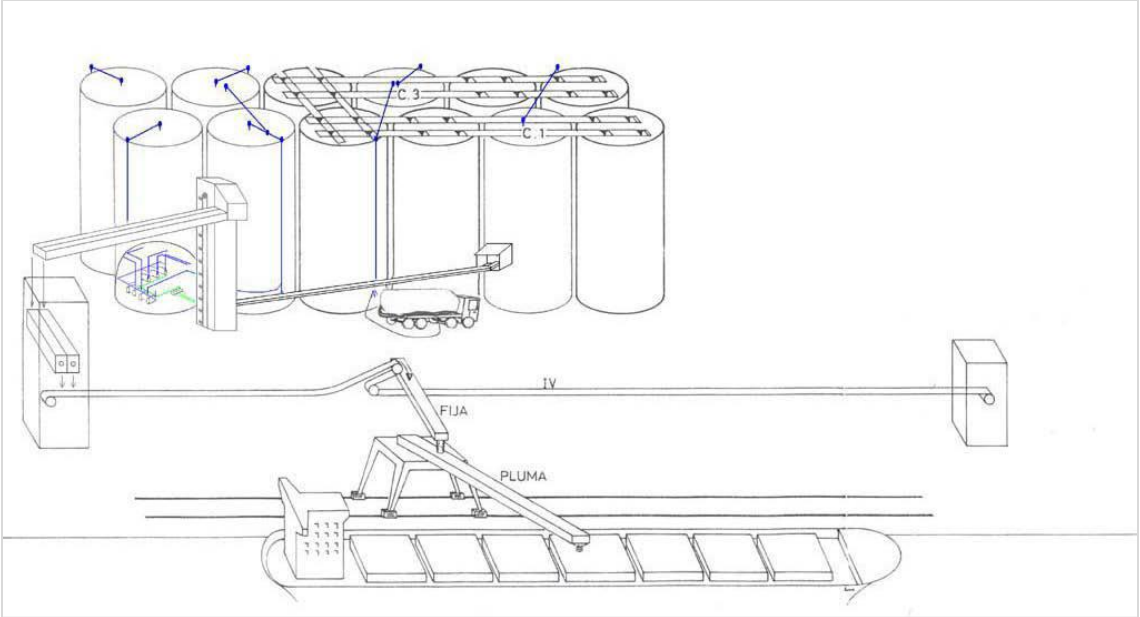


Figure 22. Functional diagram of cement or clinker loading operations in Portcemen terminal. Source: Duran E., Portcemen terminal

❖ **Ship-unloading equipment**

There exist two types of ship unloading machines for cement and clinker: mobile (rubber tyred or pontoon mounted) and rail-mounted harbour cranes. Mobile harbour cranes are more flexible but limited in unloading capacity whereas rail-mounted cranes can only move alongside the quay and cannot pass each other giving more complexity when dividing over various ships.

A crane's discharge rate is limited by the bucket's capacity (from 6 to 40 tons) and by the speed at which the crane can take a load, deposit it at the terminal and return to take the next. For modern gantry cranes, the total cycle time is about 50 seconds.

Once the cargo is discharged, it is necessary to clean the holds. This is particularly important if the next cargo is of a different type. When the holds are clean, the process of loading can start again.

There are four basic systems available to the terminal operator for the discharge of dry bulk material: grabs, pneumatic systems, vertical conveyors and bucket elevators. For a throughput per unit of between 50 and 1,000 tons per hour, pneumatic or vertical conveyor systems are adequate. For throughputs from 1,000 up to 5,000 tons per hour, grabs or bucket elevators are the only alternative. Grabs are the most widely used methods of loading and discharging bulk cargoes.

- Grabs

The grab is now normally used only for picking material up from the vessel hold and discharging it into a hopper located at the quay edge feeding on to a belt conveyor. The attainable handling rate for each grab is determined by the number of handling cycles per hour and the average grab payload. Grab unloading is the most widely used method for ship unloading.

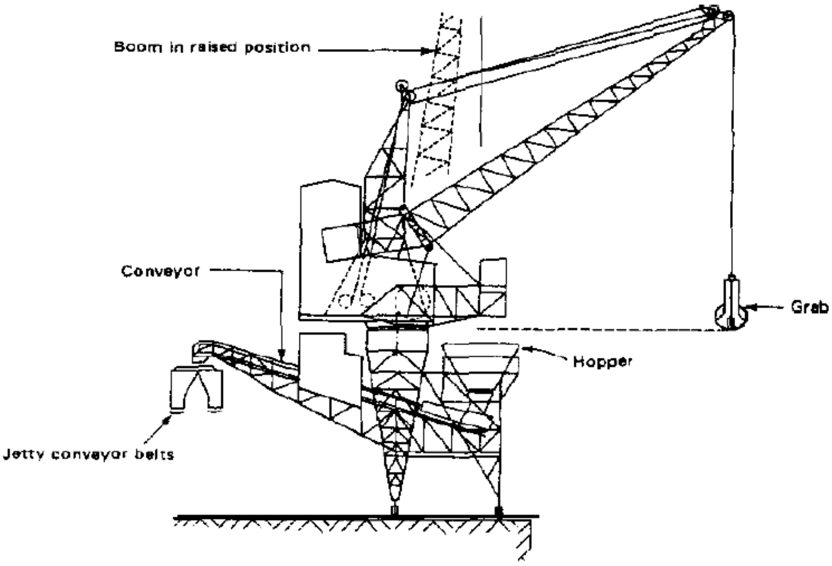


Figure 23. Revolving grabbing crane diagram. Source: Chapter II: Planning Principles. Port Development: A Handbook for Planners in Developing Countries (UNCTAD)

- Pneumatic systems

Pneumatic systems are suitable for handling bulk cargo of comparatively low specific gravity and viscosity such as grains, cement and powdered coal. Pneumatic equipment is classified into vacuum, or suction types and pressure, or blowing types. A combination of the two systems is also used, but it is generally restricted to portable equipment. Before a decision is taken whether to adopt a pneumatic handling system or a conventional mechanical handling system, not only must the capital, maintenance and operating costs be considered, but also health, cleanliness and other factors which cannot be directly evaluated.

Figure 24. Pneumatic system in an unloading operation suctioning cement from a bulk carrier. Source: https://www.conveyorspneumatic.com

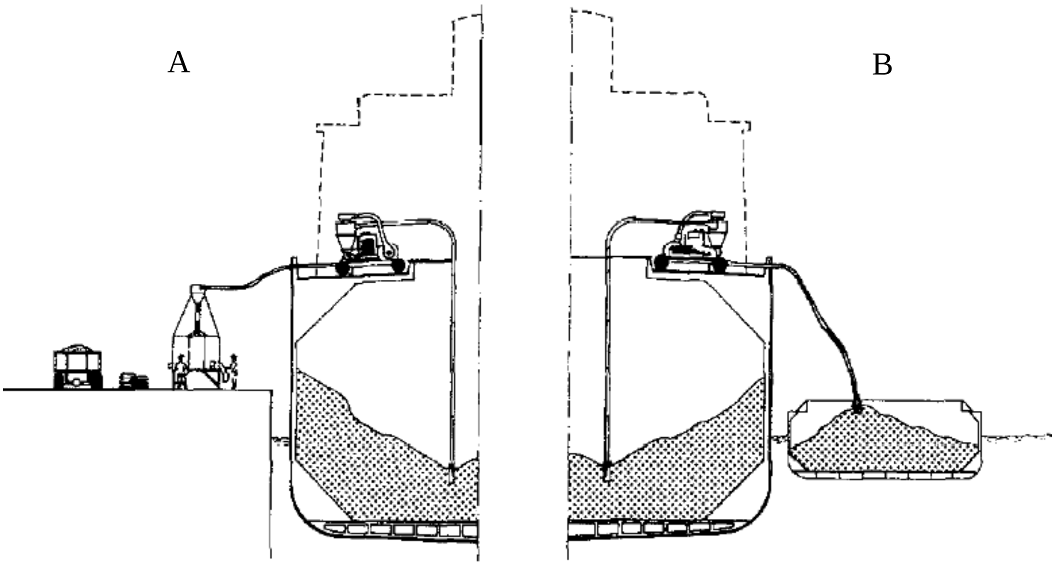


Figure 25. Portable pneumatic handling equipment. A: Combination vacuum/pressure system; conveying grain from ship into bagging hopper. B: Combination vacuum/pressure system; conveying grain from ship to barge. Source: Chapter II: Planning Principles. Port Development: A Handbook for Planners in Developing Countries (UNCTAD)

- Vertical conveyor:

The chain conveyor unloader is a self-contained unit working on the En Masse principle. The free digging rate is generally limited to 150 tons per hour. The conveying chain is carried inside a rectangular casing and its motion carries material from the hold. The vertical screw conveyor is a full blade screw contained in a tubular casing. The unit can be used at any angle from the horizontal to the vertical. Free digging rates of up to 600 tons per hour have been achieved.

- Bucket elevators:

Bucket elevators are another alternative for handling rates in the 1,000-5,000 tons per hour range. At present these continuous unloaders appear less efficient in terms of cost per ton unloaded than grabs, However, the free digging rates for these units will approach 5,000 tons per hour, while grabs have a maximum rate of 2,500 tons per hour.

- Self-discharging vessels:

At the beginning of 1982, 56% of the bulk carriers were equipped with gear for self-discharge, while only 12% of the ore carriers were so equipped. The average size of vessels so equipped was markedly smaller than that of vessels without gear. The gear usually consists of bucket cranes or derricks with a safe working load varying from 3 to 30 tons. These vessels require only a hopper and conveyor arrangement at the discharging terminal to transfer material from the ship’s system to the storage area.

2.4.9. Cement and clinker properties

Clinker is the main component of cement and it is formed by the calcination of limestone and clays. Depending on the plant in which has been produced, it may look dustier or rockier. This component will enter in one proportion or another in the cement depending on its quality. It has hydraulic properties, so any contact with water causes its setting.

Concerning the cement, it is also a hydraulic binder formed mostly by clinker and depending on the quality, characteristics and properties to be obtained with different cement products (fly ash, silica fume, limestone, pozzolan). The stowage factor for bulk cement is 0.61-0.64 m^3/t.

One of the main physical characteristics that have an impact in the treatment of both in transport is its dusty attribute. This is a typical characteristic of cement, but in presence of windy climatic conditions, it is possible that clinker is also affected.

Another consequence of this physical characteristic is that, according to the countries regulations, it can involve an environmental problem, facing up to sanctions due to dust emissions during discharges or limitations in ports located near tourist areas.

One of the problems of cement and clinker transportation is that they are really “dirty” materials. Moreover, they are aggressive with the coverages of the ship’s holds and their cleaning is not easy. On the one hand, these products cannot be cleaned with water due to the setting they would undergo and, on the other hand, the cleaning machines, which operate by pressurized air, are really dear, they are heavy and difficult to transport so that the operation is not easy.

Another disadvantage of cement and clinker is their acidic nature, which has the ability to erode the ship’s holds.

These characteristics abovementioned are the reason why the bulk carriers usually have an average age of 25 years.

Figure 26. Clinker in bulk. Source: http://www.wigginsbuildingsupplies.co.uk

Figure 27. Cement in bulk. Source: http://www.cargohandbook.com

2.5.Description of the data

The analysis of the cement terminal in Barcelona Port has been based on the data provided by Portcemen terminal. These data included all vessels calls in this terminal during the year 2015. In total, 58 bulk carriers were served in Portcemen terminal, on average, 5 vessels per month.

It is necessary to assume the random nature of the arrivals in case of non-programmed calls. Although the larger vessels (such as handysize or handymax) have scheduled arrivals, the smaller ones do not. In this case, when they arrive at the port, if the terminal is free, they can be served at the same time.

It should also be considered that the duration of the calls is not fixed, but dependent on the amount of cement and clinker to be loaded. Moreover, the crane performance sets the duration of the service.

Loading performance of clinker	1,100	tons/h
Loading performance of cement	500	tons/h

When the arrivals are independent of the number of customers in the system, it is considered an infinite-source model, resulting a mathematically tractable model.

For this minor thesis, it is assumed that data follows a stochastic model, also known as probabilistic model, which some factors are not known in advanced, thus incorporating uncertainty. Nevertheless, in reality, other types of models are used such as deterministic models. They are those where it is assumed that the data are known with certainty, that is, it is assumed that when the model is analyzed all the necessary information for decision making is available.

A stochastic process uses random magnitudes that vary with time or characterize a succession of random (stochastic) variables that evolve based on another variable, usually time. Each of the random variables in the process has its own probability distribution function and may or may not be correlated with each other. Moreover, the process follows the *Márkov property*[5], or memoryless, which means that the probability distribution of the future value of a random variable only depends on its present value, being independent of the history of said variable.

To sum up, although in reality vessels arrivals are considered as deterministic models, for this minor thesis it is considered as a stochastic model which we assume that arrivals are random. In addition, these arrivals only depend on the current state of the system (neither previous nor next).

In order to preserve the data confidentiality, the detailed information of the arrivals in Portcemen Terminal has not been shown in this document.

[5] The term Markov property refers to the memoryless property of a stochastic process. It is named after the Russian mathematician Andrey Markov.

3. METHODS

3.1. Queuing theory

A huge number of application research shows that queuing theory[6] is one of the effective methods to solve the optimization of system operation parameter in addition to find the most economic system operation cost. Also, queueing theory is generally considered as a branch of operational research became the resources needed to provide service. Then queueing theory is an application of stochastic processes in operations research.

The queuing phenomenon is widely disseminated in the field of logistics handling, such as how to design the pier berth, how to purchase the handling equipment, etc., and how to not only satisfy the arrival in punctual service demand but also design the best configuration scheme possible for the berth, handling equipment and service resources under the condition of saving port resources.

Although it does not solve all types of waiting line problems, it provides useful and vital information by forecasting or predicting multiple characteristics and parameters of the particular waiting line under study.

Since the predictions about the waiting times, the time for which the server remain busy, etc. rely on the basic concept of stochastic processes, it can very well be taken as an application of stochastic processes.

Cargo vessels arrive at the ports, and wait for the process of handling services. It can also be seen as a queuing process, the vessels are equivalent to the customers, the handling facilities are equivalent to servers.

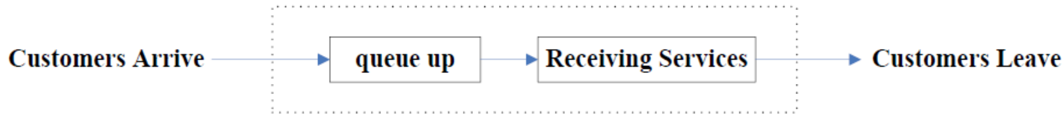


Figure 28. Queuing System Diagram. Source: Elaborated by the author.

The figure describes each vessel reach the port, first, join the queue and wait for handling services. Servers select the ships to load and unload from the queue in certain rules, then the vessels after being served, left.

The basic queuing system can be extended to a queuing system of variety of queuing methods. There are three main concepts in queueing theory, which are queue (waiting line), customer and server. The queueing theory is the probabilistic study of waiting lines.

[6] Queueing theory has its origins in research by Agner Krarup Erlang when he created models to describe the Copenhagen telephone exchange.

3.1.1. Fundamentals

Queuing theory involves the mathematical study of queues, or waiting lines. The waiting phenomenon is the direct result of randomness in operation of service facility, and customer's arrivals.

The following are the six basis characteristics of a queueing system. They are explained below.

- Arrival pattern of customers
- Service pattern of servers
- Queue discipline
- System capacity
- Service channels
- Stages of service

The principal's elements in a queuing situation are the customer (ship) and the server (handling equipment). In queuing models, customer arrivals and service times are expressed in terms of probability distributions normally referred to as arrivals and service time distributions that fit the pattern of time difference between two consecutive arrivals. Generally, the arrival of clients can be defined as a stochastic process.

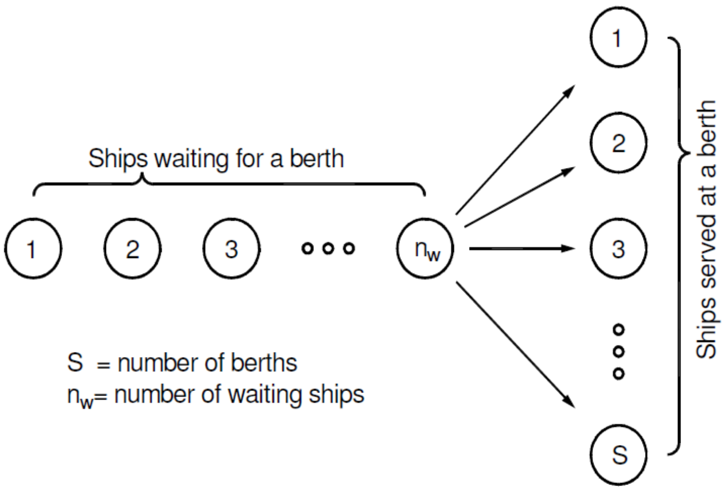


Figure 29. Ship queue at the seaport diagram. Source: Elaborated by the author.

– **Arrival pattern of customers**

The **arrival process** consists of describing how customers arrive to the system. The system may have either a limited or an unlimited capacity for holding units. The source from which the units come may be finite or infinite.

The interval between two consecutive arrivals is called the inter-arrival time. The arrival pattern of a system is measured in terms of the average number of arrivals per unit time (mean arrival rate) or by the average time between successive arrivals (mean inter-arrival time). In queueing theory, the inter-arrival times and the services times (sometimes it is called service request) are usually assumed to be independent and identically distributed random variables.

If the arrival pattern is *deterministic*, then it is fully determined by either the mean arrival rate or the mean inter-arrival time. On the other hand, if it is *probabilistic*, then further characterization is required in the form of the probability distribution associated with the random process. If the arrival pattern does not change with time, then it is called a *stationary* arrival pattern, otherwise, it is called *non-stationary*.

Another factor to be considered regarding the arrival pattern is the reaction of the customers in the queue. If the queue is too long, a customer may decide not to enter it upon arrival and in this situation he is said to have balked. On the other hand, a customer may enter the queue but after some time lose patience and decide to leave. In this case, he is said to have reneged.

In many studies, analytical distributions were applied to represent the ship inter-arrival times. The table below presents an overview of these suggested distributions. When distributions were derived from real-world data, the number of ships (n_s) is listed in the table.

IATDist	Reference	n_s [-]	Cargo[1]	IAT Dist	Reference	n_s [-]	Cargo[1]
Weibull	Tengku-Adnan et al. (2009)	408	DB	NED	Kia et al. (2002)	372	C
	Tahar and Hussain (2000)	-	C		Demirci (2003)	297	C
Erlang-2	UNCTAD (1985)	-	DB		Pachakis and Kiremidjian (2003)	142	C
Erlang-k	Kuo et al. (2006)[2]	7,729	C				
NED	UNCTAD (1985)	-	DB		Van Asperen et al. (2003)	-	LB
	Radmilovich (1992)	-	-		Dragovic et al. (2006)	711	C
	Kozan (1997)	679	C		Bugaric and Petrovic (2007)	-	DB
	Shabayek and Yeung (2002)	12,610	C		Legato and Mazza (2013)	1030	C

[1] Where C stands for containers, DB for dry bulk and LB for liquid bulk.

Figure 30. Overview of proposed inter-arrival time distributions (IATDist). For dry bulk cargo, it proposes Weibull, Erlang-2 and negative exponential (NED) distributions. Source: Van Vianen, T., Simulation-Integrated Design of Dry Bulk Terminals

As referred in the PhD thesis *Simulation-Integrated Design of Dry Bulk Terminals* (Van Vianen, T., 2015), most papers used the negative exponential distribution (NED) to represent the ship inter-arrival times. The arrival process can then be represented by a Poisson arrival process. The ships arrive randomly and independently. The proposed NED distribution for container terminals is remarkable. At container terminals, ship arrivals are scheduled and therefore expected not random. However, Pachakis and Kiremidjian (2003) stated that the superposition of several independent container shipping lines with uniformly arrival rates yields approximately a *Poisson arrival pattern*.

In this thesis, Kolmogorov-Smirnov test is used for curve fitting between measured and analytical distributions (See Chapter 4).

– **Service pattern of servers**

Service pattern can be described by the number of services per unit time (service rate) or by the time required to service customer (service time). Service may also be in single or in batch, further it can be stationary or non-stationary. One important difference between arrival and service is that service rate or service time are conditioned on the fact that the system is not empty. If the system is empty, the server is idle.

For both of the characteristics abovementioned, although their pattern could change in time, it will be considered as stationary. The time needed to load or unload ships is called the ship service time (W_s).

The handling of containers at the terminal's seaside has similarities with bulk ship unloading; in each crane cycle a container is handled or a certain tons of material is unloaded from the hold. Other similarities are that the handling capacity per crane reduces when multiple cranes are deployed at a ship and the crane cycle time increases when the ship becomes more emptied.

The table below lists an overview of proposed service time distributions for both container and dry bulk cargo. When distributions were derived from real-world data, the number of ships (n_s) is listed in the table.

W_sDist	Reference	n_s [-]	Cargo[1]	W_sDist	Reference	n_s [-]	Cargo[1]
Normal	Tahar and Hussain (2000)	150	C	Erlang-k	Shabayek and Yeung (2002) [k:117]	12,610	C
	Bugaric and Petrovic (2007)	-	DB		Kozan (1997) [k:4]	679	C
NED	Radmilovich (1992)	-	-		Kia et al. (2002) [k:4]	372	C
	Demirci (2003)	297	C		Altiok (2000) [k:4]	248	DB
Beta	Legato and Mazza (2013)	1,030	C		Dragovic et al. (2006) [k: 3,7,12]	711	C
Gamma	Jagerman and Altiok (2003)	304	DB		UNCTAD (1985) [k:2]	-	DB

[1] Where C stands for containers and DB for dry bulk.

Figure 31. Overview of proposed service time distributions (WsDist). For dry bulk cargo, it proposes Normal, Gamma and Erlang-k distributions. Source: Van Vianen, T., Simulation-Integrated Design of Dry Bulk Terminals

In the PhD thesis *Simulation-Integrated Design of Dry Bulk Terminals* (Van Vianen, T., 2015), several proposed service time distributions were compared with the measured service time distributions from three dry bulk terminals. The chi-square method was used to fit these measured distributions with one of the analytical distributions proposed for dry bulk terminals (Erlang-k, Normal and Gamma). All three service time distributions show the best fit with an Erlang-2 distribution. Therefore, the accuracy of the seaside designs will increase when empirical shipload data and realistic ship service rates are used to represent the service times.

– **Queue discipline**

The structure of service and service discipline tell us the number of servers, the capacity of the system, that is the maximum number of customers staying in the system including the ones being under service. The **service discipline** determines the rule according to the next customer is selected. The most commonly used laws are:

- FIFO – First In First Out: The customer that finds the service centre busy goes to the end of the queue. Who comes earlier, leaves earlier.
- LIFO – Last In, First Out: The customer that finds the service centre busy proceeds immediately to the head of the queue. She will be served next, given that no further customers arrive. Who comes later, leaves earlier.
- RS – Random Service: The customer in the queue is served randomly.
- PR – Priority: Every customer has a priority; the server selects always the customers with the highest priority. This scheme can use pre-emption or not.

The **system capacity** is the maximum number of customers staying in the system including the ones being under service. When the arrivals are independent of the number of customers in the system, it is considered an infinite-source model, resulting a mathematically tractable model.
In some queueing process, there is a finite upper bound to the queue size. In this situation, a customer is forced to balk if he arrives at a time when queue size is at its limit. This is a simple case of balking, since it is known exactly under what circumstance arriving customers must balk.

– **Service channels**

The **number of servers** are the numbers of parallel channels of service which can provide identical service facilities and assist the customers simultaneously.

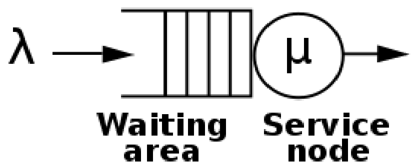


Figure 33. Single server M/M/1 diagram.

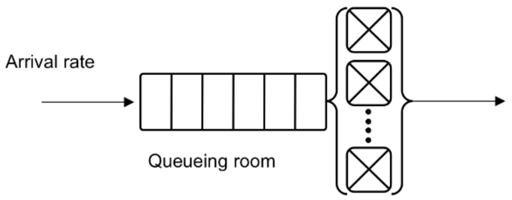


Figure 32. Multiple server M/M/c diagram.

– **Stages of service**

A service station may have several **stages of service**. That is, there may exist a series of service stages through which each customer must progress prior to leaving the system. They are called tandem queues.

The aim of all investigations in queueing theory is to get the main performance measures of the system which are the probabilistic properties (distribution function, density function, mean, variance) of the following random variables: number of customers in the system, number of waiting customers, utilization of the server/s, response time of a customer, waiting time of a customer, idle time of the server, busy time of a server. Of course, the answers heavily depend on the assumptions concerning the distribution of inter-arrival times, service times, number of servers, system's capacity and service discipline.

❖ Kendall's notation

The Kendall Notation is used for a short characterization of queueing systems. A queueing system description is described by the following notation:

A / B / m / K / n / D

Where:

- ***A*** denotes the distribution function of the inter-arrival times
- ***B*** denotes the distribution function of the service times
- ***m*** denotes the number of service channels. The M/M/1 queue has a single server and the M/M/c queue has *c* servers.
- ***K*** denotes the capacity of the system, the maximum number of customers allowed in the system including those being serviced. When the number is at this maximum, further arrivals are turned away. If this number is omitted, the capacity is assumed to be unlimited, or infinite.
- ***n*** denotes the population size. If this number is omitted, the population is assumed to be unlimited, or infinite.
- ***D*** denotes the service discipline (FIFO, LIFO, RS, PR, etc.). If it is omitted, the service discipline is always FIFO.

For the values of A and B, the following abbreviations are generally applied:

- **M** (Markovian Process): This denotes the exponential distribution. The name M stems from the fact that the exponential distribution is the only continuous distribution with the markov property (memoryless).
- **D** (Deterministic): All values from deterministic "distribution" are constant (have the same value).
- $\mathbf{E_k}$ (Erlang-k): Erlang Distribution with *k* phases ($k \geq 1$)
- $\mathbf{H_k}$ (Hyper-k): Hyperexponential distribution with *k* phases
- **G** (General): General distribution. In most cases at least the mean and the variance are known.

❖ Little's Law

Little's law[7] is a theorem by John Little which establishes a relationship between the average number of customers in the system, the mean arrival rate and the mean time between entering and leaving the system in the steady state.

Expressed algebraically the law is:

$$N = \lambda \cdot W$$

Where,

N = Average number of customers in the system

λ = Mean arrival rate of clients that enter the system

W = Average time that a client spends in the system

This relationship applies to all systems or parts of systems in which the number of clients entering the system is equal to those completing service. The only requirements are that the system be stable and non-preemptive.

Little's theorem does not assume any specific distribution for the arrivals as well as the service process and any queuing discipline. Also, it does not depend upon the number of parallel servers in the system. The theorem can be applied to all types of queuing systems as long as the servers kept busy when the system is not empty.

[7] In a 1954 paper Little's law was assumed true and used without proof. The form $L = \lambda W$ was first published by Philip M. Morse where he challenged readers to find a situation where the relationship did not hold. Little published in 1961 his proof of the law, showing that no such situation existed. Little's proof was followed by a simpler version by Jewell and another by Eilon. Shaler Stidham published a different and more intuitive proof in 1972. *Graves, S. C. (2008). "Little's Law" Building Intuition.*

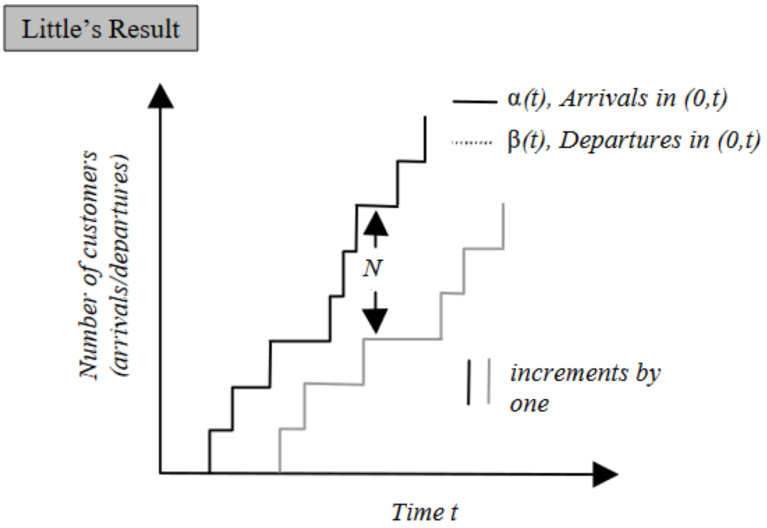


Figure 34. Graphical illustration and verification of Little's Result. N is the average number of customers in the system shown in the graphic as the gap between arrivals and departures. Source: Sanjay K. Bose

3.1.2. Main parameters. Notation of queuing theory

Some of the parameters that can be directly obtained once the features such as system capacity, number of servers, arrivals pattern, etc. are defined. The rest of them are the result of the data processing provided by the application of queuing theory formulas. These parameters are described below:

Parameter	Definition	Unit of measure
λ	Number of arrivals per unit of time	Arrivals/Time unit
μ	Number of services per unit of time	Services/Time unit
c	Number of channels of service in parallel	Units of servers
ρ	System congestion factor. Traffic density. $\rho = \frac{\lambda}{c \cdot \mu}$ *	Time unit
N (t)	Number of clients in the system at instant t	Number of clients
Nq (t)	Number of clients in the queue at instant t	Number of clients
Ns (t)	Number of clients being served at instant t	Number of clients
N	Average number of clients in the system at the stable state	Number of clients
Pn(t)	Probability of having n clients at an instant t	%
Pn	Probability of having n clients at the stable state	%
Pb	Probability that all the servers are occupied	%
L	Average number of clients in the system	Number of clients
Lq	Average number of clients in the queue	Number of clients
Ts	Time of service. Time the ship spends in the server	Time unit
T	Total time the client spends in the system. $T = W_q + T_s$	Time unit
Wq	Average waiting time in the queue. $W_q = E[T_q]$	Time unit
W	Average time that a client spends in the system. $W = E[T]$	Time unit
η	Relative waiting. $\eta = \frac{W_q}{T_s}$	--

Figure 35. Description of the main parameters applied in queuing theory formulas. Apart from their notation, it is also shown their unit of measure. Source: Elaborated by the author.

*The system congestion factor represents the relation between the arrivals and the capacity of the system. If μ> λ, then there is the possibility that a queue is generated so the system is not capable of satisfy the demand. In contrast, if μ< λ, there is the possibility that the system is over dimensioned.

In pursuit of these parameters, it is necessary to distinguish the different probabilistic models which are applied in each case.

Down below, it is shown a diagram with the relationships between the parameters abovementioned.

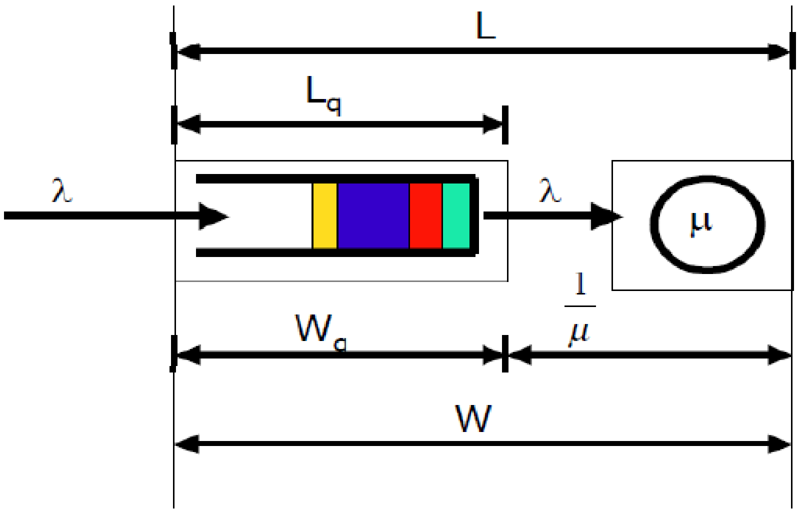


Figure 36. Representation of the relationships between the main parameters of queuing theory based on the waiting area and the service node. Source: University of Pittsburg.

3.1.3. Modelling ship arrival process

The most common arrival pattern of ships in a seaport are the random and scheduled arrivals with considerable delays. Thus, to predict the number of ships that arrive in a port in a certain time of period, the arrival pattern of ships may be approximated by a **Poisson function**[8] (See Chapter 4). The Poisson distribution is defined as:

$$P(n,\lambda) = \frac{\lambda^n \cdot e^{-\lambda}}{n!}$$

Where,

P (n, λ) = Probability of the arrival of *k* ships in the port in a given time

λ = Average arrival rate of *n* ships during the given time

e = Base of natural logarithm (e=2.718289…)

n! = Factorial of ship number

[8] The Poisson Distribution, named after French mathematician Siméon Denis Poison, is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time or space if these events occur with a known constant rate and independently of the time since the last event.

The time between arrivals is defined, in this way, as the probability that no client arrives:

$$p_0(t) = e^{-\lambda t}$$

being therefore an exponential distribution.

The expected value and variance are:

$$E(X) = Var(X) = \lambda$$

The distribution of ships arrivals with Poisson function can be calculated only if the average arrival rate during the entire period is known. The expected frequency F_n of n ships in port in a given time T is:

$$F_n = T \cdot P_{(n,\lambda)}$$

3.1.4. Modelling inter-arrival time

It is assumed that the ships arrival follows a Poisson process. The inter-arrival times are modelled as continuous variables. Therefore, the time between two consecutive arrivals can be adjusted to an **Exponential Distribution**[9] (See Chapter 4):

$$f(x) = P(x) = \begin{cases} \lambda e^{-\lambda x}, & For\ x \geq 0 \\ 0, & In\ other\ case \end{cases}$$

The Cumulative Distribution Function (CDF) will be:

$$F(x) = P(X \leq x) = \begin{cases} 0, & For\ x < 0 \\ 1 - e^{-\lambda x}, & For\ x \geq 0 \end{cases}$$

The expected value and variance are:

$$E[X] = \frac{1}{\lambda} \qquad Var[X] = \frac{1}{\lambda^2}$$

[9] The exponential distribution (also known as negative exponential distribution) is the probability distribution that describes the time between events in a Poisson point process, i.e., a process in which events occur continuously and independently at a constant average rate. It is a particular case of the gamma distribution. It is the continuous analogue of the geometric distribution, and it has the key property of being memoryless.

3.1.5. Modelling service time

The service facility can have one or more servers, each of them is capable of serving one customer at a time. In our case of study, there is only one server. The service times needed for every customer are also modelled as random variables.

The duration of ships at a berth for handling cargo may be described as an **Erlang-function[10]**. There is the assumption that the service time is split into two or more operating phases following one another, and the ship does not leave the berth until all phases *k* are completed.

In the general case, the total service time probability is:

$$P_0 = e^{kb \cdot \sum_{n=0}^{n=k-1} (kb) \cdot \frac{n}{n!}}$$

Where,

b= Average berth service times

k= Erlang number (k=1,2,3…)

n= Counter

3.1.6. Research methodology

Over the years, many empirical studies and research methodologies have been performed in order to categorize the development of the port system.

Modeling and designing entire dry bulk terminals is complicated due to the dependencies between several terminal tasks. For example, a typical terminal performance indicator is the average waiting time of ships. But for the complete terminal, ships may wait for several reasons; due to limited service capacity at the terminal's seaside, due to an absence of available storage area or due to the fact that all stockyard machines are occupied. The terminal has to be decomposed in multiple subsystems (seaside, stockyard and landside) to analyze each one and connect them into a total terminal model. In this minor thesis, it is going to be analyzed the seaside subsystem. Simulation tools will be developed to take the stochastic variations of the operational parameters, which occur during daily operation, into account.

A large number of application research shows that queuing theory is one of the effective methods to find the most economic system operation cost, to solve the optimization of system operation parameter. The queuing phenomenon is widely existed in the field of logistics handling, such as how to design the pier berth, how to purchase the handling equipment and etc., and how to not only satisfy the arrival in timely service demand but also design the best configuration scheme for pier berth, handling equipment and service resources under the condition of saving port

[10] The Erlang distribution is a two-parameter family (shape and rate) of continuous probability distributions. It was developed by Agner Krarup Erlang to examine the number of telephone calls which might be made at the same time to the operators of the switching stations. This work on telephone traffic engineering has been expanded to consider waiting times in queueing systems in general. The distribution is now used in the fields of stochastic processes and of biomathematics.

resources. So applying queuing theory and method to solve the optimization of port handling service system is of important theoretical and practical significance.

Over the years, many empirical studies and research methodologies have been performed in order to categorize the development of the port system. *Ducruet, C.* (2013) proposes an analysis of worldwide inter-port shipping flows from a strength-clustering perspective. A variety of factors seem to explain the formation of clusters: geographic proximity among closely located ports, trade proximity and historical path-dependency among more distant ports.

A huge number of application research shows that queuing theory is one of the effective methods to solve the optimization of system operation parameter in addition to find the most economic system operation cost. *Roes, P. B. M.* (1966) prove in this study “Operations Research” the theory of derived Markov chains applied to a queuing system with *n* servers and group service. The same methodology was applied by *Harris, C. M.* (1970) proving it in bulk-arrival queues with state dependent service times. Accordingly, *Hess, M. et al* (2007) demonstrates the application of the queuing theory in modelling the port's bulk cargo unloading terminal on the basis of a bulk cargo terminal observation as a queuing system defined by basic parameters: the rate of bulk cargo ship arrivals or quantity of bulk cargo and the rate of ship servicing i. e. quantity of bulk cargo, in an observed time unit.

Moreover, *Bugaric, U., et al.* (2007) prove that work of the terminals with its optimal capacity assumes prompt accommodation of vessels with minimal waiting time in the port and with maximal use of berth facilities, i.e. bigger unloading capacity. A simulation model of the terminal work with strategy is developed. Some of the obtained results are applied and verified on existing system.

Regarding dry bulk terminals, *Van Vianen, T.A. et al* (2012) focus their paper on route selection to transport the materials. Due to several sources of uncertainty, selecting routes is complicated and is now predominately based on the human operators' experiences. A decision support system, so-called Dynamic Planner, is proposed which consists of a primary simulation model, that simulates the dynamics of the terminal, and within this primary simulation model, a secondary simulation model that simulates and proposes routes.

In this direction, *Wadhwa, L. C.* (2000) in his study deals with finding an optimal solution to an interesting situation where using one shiploader results in unacceptable ship waiting times and a high level of demurrage, whereas continuous deployment of two shiploaders results in inefficiency and high operating costs. So this paper describes an approach for developing a strategy that considers a trade-off between the ship waiting cost and the cost of deploying the additional shiploader and results in the optimal deployment of resources.

All of these research methodologies have been used to solve the optimization of port handling service system. These methodologies are widely used in the current literature, specifically, the queuing theory and simulation scenarios.

3.2.M/M/1

The type of vessels queuing is the key to establish a fine handling queuing system, making the operation of handling queuing system unproblematic. According to the characteristics of handling in the ports and ships as well as a great deal of statistics data, it can be shown that, in most queuing systems for handling service, the arrival of the ships follows the Poisson distribution while the time for handling service follows the negative exponential distribution.

In normal circumstances, improving service levels and increasing the number of servers, can improve the service efficiency and reduce the waiting time. However, improving the level of service and increasing the number of servers will increase the service costs too. Therefore, to achieve the purpose of optimization, we must make the sum of service cost and waiting cost to be minimal.

To analyse the movement of the ships using the queuing theory, the following conditions are assumed:

i. Ships arrivals and service times comply with the pattern of random occurrences.
ii. Ships are processed on the FIFO queue discipline.
iii. The queue length is unlimited, that is, if a ship arrives and finds a long queue, it joins the waiting ships and does not leave the port.

Thus, the most typical queuing system is the M/M/1[11] which can be described as:

- A single server
- No restriction on the capacity of the system and infinite waiting line
- FIFO discipline
- Customer inter-arrival times are identically and exponentially distributed with parameter λ. They are determined by a Poisson process.
- Customer service times are identically and exponentially distributed with parameter μ. They are determined by an exponential distribution.

Exponentially distributed random variables are notated by M, meaning Markovain or memoryless. Furthermore, if the population size and the capacity is infinite, the service discipline is FIFO, then they are omitted. What makes the M/M/1 system really simple is that the arrival rate and the service rate are not state-dependent.

- Customers arrive according to a Poisson process with exponentially distributed inter-arrival times (IAT).

$$P(IAT \leq t) = 1 - e^{-\lambda t}, \qquad mean\ interarrival\ time = \frac{1}{\lambda}$$

- Customers are served by a single server with exponential service time distribution P.

[11] Morse (1955) studied the M/M/1 queue and obtained the transient state probabilities of the number in the system at time t. The problem was studied and a complete solution was obtained in the 1950's by several researchers using different methods. The steady state behavior of the queueing system was primarily investigated by Erlang (1917) and he obtain the steady state probabilities for M/M/1/infinite. The main limitation observed in the steady state distribution is that there may exist many stochastic processes with the same stationary distribution.

$$P(service\ time < t) = 1 - e^{-\mu t}, \qquad mean\ service\ time = \frac{1}{\mu}$$

- The arrival rate (λ) and service rate (μ) do not depend upon the number of customers in the system or time.

- Consider behavior of N(t) – Number of customers in the system at the time t

Hence **M=M=1** denotes a system with Poisson arrivals, exponentially distributed service times and a single server. **M=G=m** denotes an *m*-server system with Poisson arrivals and generally distributed service times. **M=M=r=K=n** stands for a system where the customers arrive from a finite-source with *n* elements where they stay for an exponentially distributed time, the service times are exponentially distributed, the service is carried out according to the request's arrival by *r* severs, and the system capacity is *K*.

The ideal situation is the one in which all berths are occupied at all times and no ship is ever kept waiting. This situation is nearly impossible to achieve in practice because of the random arrivals of cargo ships and the different service time depending on the size of it.

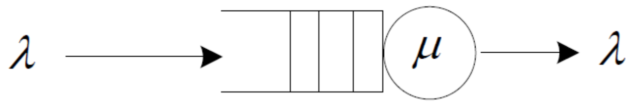


Figure 37. Diagram of M/M/1/infinite/FIFO queue. It shows the queue and the server along with the arrival rate and service rate. Source: Elaborated by the author.

The common characteristic of all markovian systems is that the distribution of the inter-arrival times and the distribution of the service times are exponential distributions and thus exhibit the markov (memoryless) property. From this property we have two important conclusions:

- The state of the system can be summarized in a single variable, namely the number of customers in the system. (If the service time distribution is not memoryless, it is not applied, since not only the number of customers in the system is needed, but also the remaining service time of the customer in service.)
- Markovian systems can be directly mapped to a *continuous time markov chain* (CTMC) which can then be solved.

According to abovementioned, and following Kendall's notation of the Queuing Theory Model assumed in cement terminal analysed in this minor thesis is **M/M/1/infinite/FIFO** assuming that:

- Vessels arrivals follow a Poisson distribution (discrete variables)
- Times of the service follow an Exponential distribution (continuous variables)
- There is only one server
- Unlimited capacity of the service
- Unlimited population size (Omitted)
- "First come, first served" queuing discipline

4. RESULTS

4.1.Current situation

This chapter explains the current situation of the terminal with detailed information about the assumptions done, the calculations of the parameters for the selected queuing model, a manual simulation with the data provided and the calculations of the levels of service.

4.1.1. Sources of the data

The analysis of the cement terminal in Barcelona Port has been based on the data provided by Portcemen terminal. These data included all the vessel calls in this terminal during the year 2015. Specifically, the information provided included the following details:

- Sequence
- Cargo type (cement or clinker)
- Date
- Vessel name
- Destination
- Metric tons

There was some data that was missing in the information provided by the terminal. For example, there were few calls which didn’t have date. In these cases, an extrapolation of data has been carried out to complete the information.

In order to preserve the data confidentiality, the detailed arrivals have not been showed in the present document. The only information that can be found in the document is the date of the calls, but not the vessel, the type of cargo that carries nor the volume to load or unload. The characteristics of the vessels that were served in Portcemen terminal are listed in Annex C and D in alphabetic order, but are not associated to any traffic. The information displayed in this document came from Barcelona Port Authority, PORTIC, Sea-Web, Marinetraffic and Vesselfinder.

4.1.2. General information

❖ **Total traffic**

In 2015, a total number of 58 vessels were served in Portcemen terminal in Barcelona Port. All of them were exportations, so they were involved in loading operations. Every month were served, on average, 5 vessels, always in the interval between 3 and 6 vessels per month. The calls evolution is shown hereunder.

Month	Calls x month
January	5
February	3
March	6
April	5
May	5
June	3
July	6
August	4
September	6
October	5
November	6
December	4
TOTAL 2015	**58**

Figure 38. Calls per month in Portcemen terminal in 2015. Source: Elaborated by the author

It is assumed that the population size is unlimited and so it is the capacity of the service. Thus, there is no restriction on the capacity of the system and it can be an infinite waiting line.

When the arrivals are independent of the number of customers in the system, it is considered an infinite-source model, resulting a mathematically tractable model.

The diagram bellow illustrates the volumes of clinker versus the volumes of cement that were loaded in Portcemen Terminal in 2015. As can be seen, the volumes of clinker loaded are much greater than cement ones (almost 5 times more). Overall, a sum of 247,513 tons of cement and 1,090,558 tons of clinker.

The month with more tons loaded was April with 155,717 tons, whereas the month with less loadings was August with only 39,563 tons.

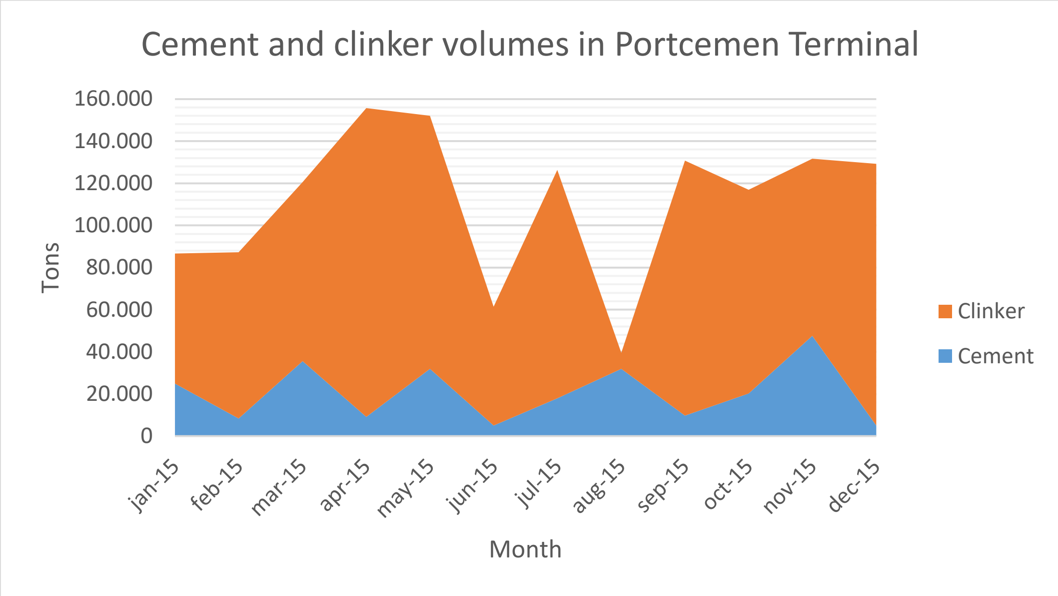


Figure 39. Cement and clinker volumes in Portcemen terminal in 2015. As can be noted, clinker volumes are much higher than cement volumes. Moreover, it can be seen the significant fluctuation of the volumes. Source: Elaborated by the author

Cargo type\Month	jan-15	feb-15	mar-15	apr-15	may-15	jun-15	jul-15	aug-15	sep-15	oct-15	nov-15	dec-15
Cement	25,015	8,415	35,563	9,078	31,978	5,000	17,997	31,900	9,696	20,208	47,616	5,047
Clinker	61,604	78,918	85,027	146,639	120,067	56,391	108,345	7,663	120,975	96,754	83,973	124,202
TOTAL	**86,619**	**87,333**	**120,590**	**155,717**	**152,045**	**61,391**	**126,342**	**39,563**	**130,671**	**116,962**	**131,589**	**129,249**

Figure 40. Cement and clinker month evolution in Portcemen terminal in tons. Source: Portcemen Terminal

❖ **Inter-arrival time**

With the analysis of the inter-arrival time, the probabilistic model that will adjust better to data can be determined. The classification of the data gave us the following histogram:

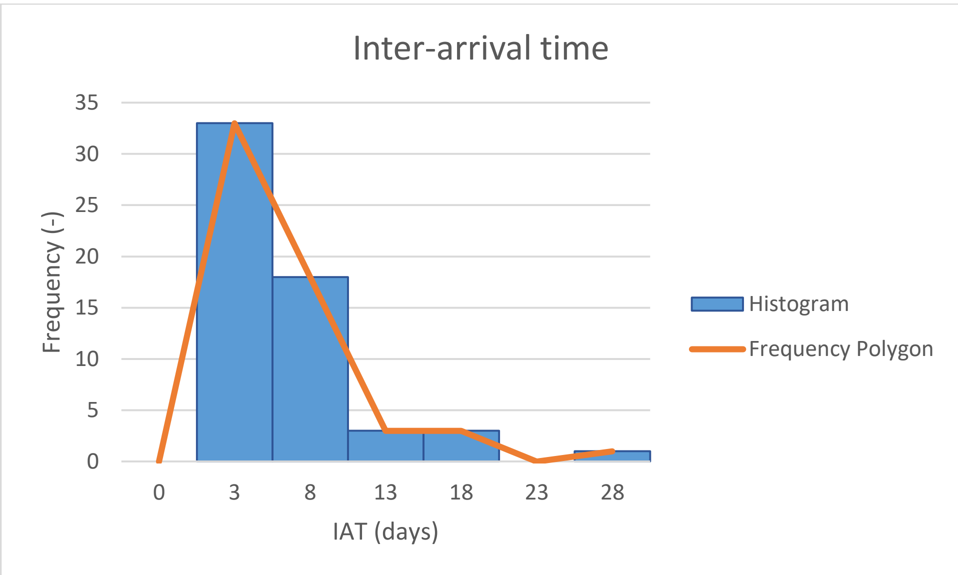


Figure 41. Inter-arrival histogram with the frequency polygon. Source: Elaborated by the author

The table below shows the values calculated to draw the inter-arrival diagram.

H	Lower limit	Upper limit	x	ni	fi	Ni	Fi
0	0	0	0	0	0%	0	0%
1	1	5	3	33	57%	33	57%
2	6	10	8	18	31%	51	88%
3	11	15	13	3	5%	54	93%
4	16	20	18	3	5%	57	98%
5	21	25	23	0	0%	57	98%
6	26	30	28	1	2%	58	100%

Figure 42. Parameters of inter-arrival histogram. Source: Elaborated by the author

Where,

H: Class interval

x: Mean between lower and upper limit

ni: Absolute frequency

fi: Relative frequency (%)

Ni: Cumulative frequency

Fi: Cumulative frequency (%)

Based on these parameters and through the cumulative frequency, the following histogram can be performed.

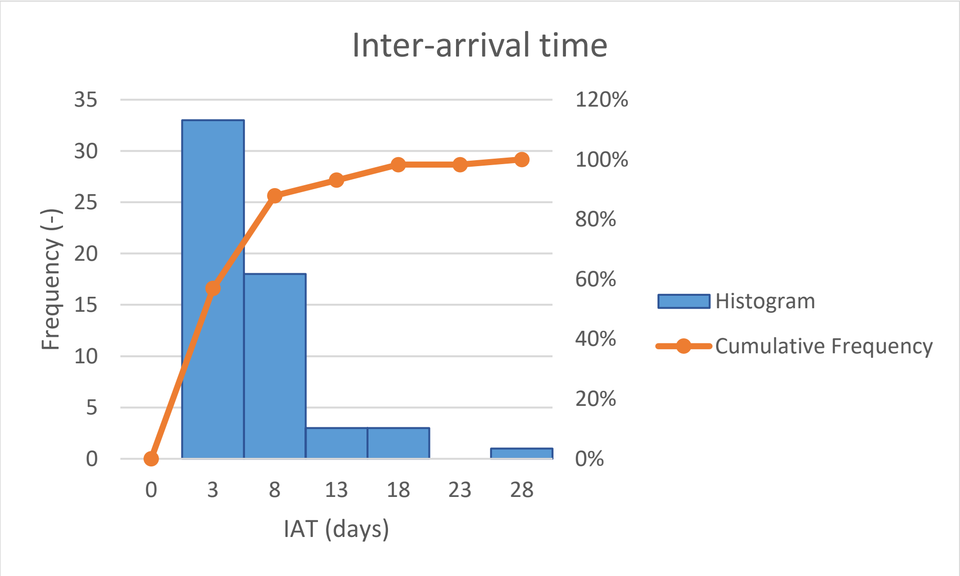


Figure 43. Inter-arrival histogram with the cumulative frequency. Source: Elaborated by the author

Most stochastic queue models assume that the time between different customer arrivals follows an exponential distribution. Or what is the same, the arrival rhythm follows a Poisson distribution. It is also customary to admit that the rate of customer attention when the server is busy has a Poisson distribution and the length of customer service an exponential distribution.

As we can see from the above histogram of data distribution, we can consider that the inter-arrival time can be fitted in an **Exponential Distribution.** Nevertheless, the Kolmogorov-Smirnov test is applied in order to verify that the analysed data follows an exponential distribution.

If the number of arrivals follows a Poisson distribution, the time between arrivals follows an exponential distribution of mean (1 / λ) and vice versa.

$$P_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \iff P_0(t) = e^{-\lambda t}$$

The goodness of fit of a statistical model describes how well it fits a set of observations. Measures of goodness of fit typically summarize the discrepancy between observed values and the values expected under the model in question.

The **Kolmogorov–Smirnov test (K–S test)** is a nonparametric test of the equality of continuous, one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution, or to compare two samples. The Kolmogorov-Smirnov test it is used in the present thesis to determine the goodness of fit to the exponential distribution of the interval variables.

H	Lower limit	Upper limit	x	FO	FOR	FORA	FERA	ABS
0	0	0	0	0	0.0000	0.0000	0.0000	0.0000
1	1	5	3	33	0.5690	0.5690	0.5482	0.0208
2	6	10	8	18	0.3103	0.8793	0.7959	0.0834
3	11	15	13	3	0.0517	0.9310	0.9078	0.0233
4	16	20	18	3	0.0517	0.9828	0.9583	0.0244
5	21	25	23	0	0.0000	0.9828	0.9812	0.0016
6	26	30	28	1	0.0172	1.0000	0.9915	0.0085

Figure 44. Parameters of Kolmogorov-Smirnov test to determine the goodness of fit to the exponential distribution. Source: Elaborated by the author

Where,

H: Class interval

x: Mean between lower and upper limit

FO: Observed frequency

FOR: Relative observed frequency

FORA: Accumulated relative observed frequency

FERA: Accumulated relative expected frequency

ABS: Absolute frequency (ABS=FORA-FERA)

Hypothesis to contrast:

H_0: The data follow an exponential distribution

H_1: The data do not follow an exponential distribution

Test Statistic: The Kolmogorov-Smirnov test statistic is defined as:

$$D = \sup_{l \leq i \leq n} \left| \hat{F}_n(x_i) - F_0(x_i) \right|$$

Where,

x_i is the i-th value observed in the sample.

$\hat{F}_n(x_i)$ is an estimator of the probability of observing values that are less than or equal to x_i.

$F_0(x_i)$ is the probability of observing values less than or equal to x_i when H_0 is true.

Significance Level: $\alpha = 0.05$

Therefore, the criteria for making the decision between the 2 hypothesis will be:

$$If\ D \leq D_\propto \Rightarrow Accept\ H_0$$

$$If\ D > D_\propto \Rightarrow Reject\ H_0$$

Where $D_\propto$ is defined:

$$D_\propto = \frac{c_\propto}{k(n)}$$

Where $c_\propto$ and $k(n)$ are extracted from the table in Annex F.

	Nivel de significación α							
n	0.20	0.10	0.05	0.02	0.01	0.005	0.002	0.001
40	0.16547	0.18913	0.21012	0.23494	0.25205	0.26803	0.28772	0.30171
41	0.16349	0.18687	0.20760	0.23213	0.24904	0.26482	0.28429	0.29811
42	0.16158	0.18468	0.20517	0.22941	0.24613	0.26173	0.28097	0.29465
43	0.15974	0.18257	0.20283	0.22679	0.24332	0.25875	0.27778	0.29130
44	0.15795	0.18051	0.20056	0.22426	0.24060	0.25587	0.27468	0.28806
45	0.15623	0.17856	0.19837	0.22181	0.23798	0.25308	0.27169	0.28493
46	0.15457	0.17665	0.19625	0.21944	0.23544	0.25038	0.26880	0.28190
47	0.15295	0.17481	0.19420	0.21715	0.23298	0.24776	0.26600	0.27896
48	0.15139	0.17301	0.19221	0.21493	0.23059	0.24523	0.26328	0.27611
49	0.14987	0.17128	0.19028	0.21281	0.22832	0.24281	0.26069	0.27339
50	0.14840	0.16959	0.18841	0.21068	0.22604	0.24039	0.25809	0.27067
$n > 50$	$\frac{1.07}{\sqrt{n}}$	$\frac{1.22}{\sqrt{n}}$	$\frac{1.36}{\sqrt{n}}$	$\frac{1.52}{\sqrt{n}}$	$\frac{1.63}{\sqrt{n}}$	$\frac{1.73}{\sqrt{n}}$	$\frac{1.85}{\sqrt{n}}$	$\frac{1.95}{\sqrt{n}}$

Figure 45. Table of Kolmogorov-Smirnov test estimator of Goodness of Fit. Marked in red, the calculation of $D_\propto$ for an n>50 and α=0.05. Source: http://www4.ujaen.es/~mpfrias/TablasInferencia.pdf

With the calculations of D and $D_{\propto}$ done, the criteria for making the decision between the 2 hypothesis can be applied. The result is the following:

Estimator Smirnov-kolmogorov (D)	0.0834
Degrees of freedom	58
$D_{\propto}$ (α=0.05)	0.1786
Test	Accept

There is no contrary statistical evidence to reject the proposed model. Thus, it can be assumed the data follows an exponential Distribution.

The exponential distribution occurs naturally when describing the lengths of the inter-arrival times in a homogeneous Poisson process. In queuing theory, the service times of agents in a system are often modelled as exponentially distributed variables. The arrival of customers for instance is also modelled by the Poisson distribution if the arrivals are independent and distributed identically. The length of a process that can be thought of as a sequence of several independent tasks follows the Erlang distribution (which is the distribution of the sum of several independent exponentially distributed variables). Reliability theory and reliability engineering also make extensive use of the exponential distribution. Because of the memoryless property of this distribution, it is well-suited to model the constant hazard rate portion of the bathtub curve used in reliability theory.

- **Vessels arrivals**

The mode for ships queuing is the key to establish a fine handling queuing system, making the operation of handling queuing system smoothly. According to the characteristics of handling in the ports and ships as well as a great amounts of statistics data and study abroad, it can be shown that, in most queuing systems for handling service, the arrival of the ships obeys the Poisson distribution while the time for handling service obeys the negative exponential distribution.

The ships arrivals and service times are totally random so they comply with the pattern of random occurrences. Moreover, it is assumed that the queue length is unlimited, that is, if a ship arrives and finds a long queue, it joins the waiting ships and does not leave the port. Vessels are processed on the "First come, first served" queue discipline.

For customers who arrive and find the queue as a stationary process, the response time they experience (the sum of both waiting time and service time) follows the probability density function:

$$f(x) = \begin{cases} (\mu-\lambda)e^{-(\mu-\lambda)^{t}}, & t > 0 \\ 0, & otherwise \end{cases}$$

The diagram below shows the arrivals in Portcemen terminal in 2015. As can be seen, the maximum number of vessels that overlap in the same day is 2. This fact only happens in 4 cases during this year. All year round, there are 307 days in which no vessels arrived, 54 days that served 1 vessel and 4 days that overlap 2 vessels in the same day.

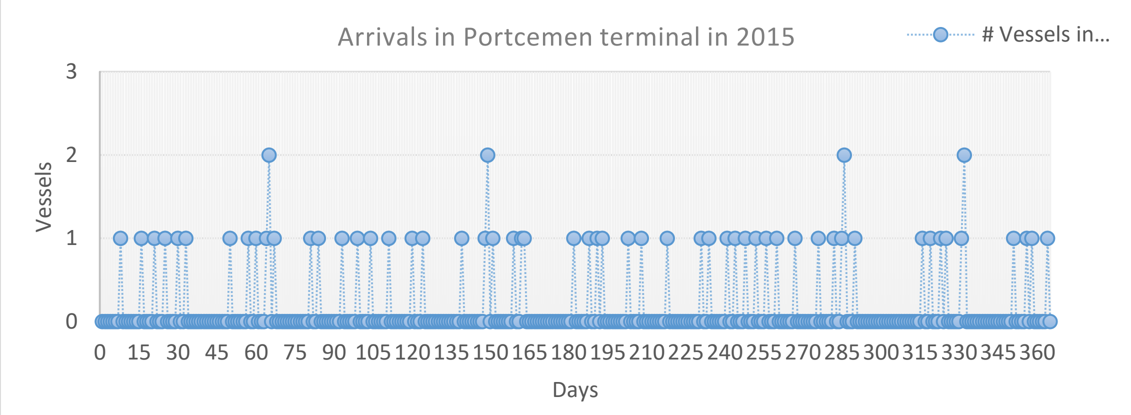


Figure 46. Arrivals in Portcemen terminal in 2015. Source: Elaborated by the author

The number of arrivals per month is very small so the sample from which the goodness of fit test is applied is representative but limited. Nevertheless, the Kolmogorov-Smirnov test is applied in order to verify that the analysed data follows a Poisson distribution.

Month	Arrivals
1	5
2	3
3	6
4	5
5	5
6	3
7	6
8	4
9	6
10	5
11	6
12	4

Figure 48. Number of arrivals per month in Portcemen Terminal in 2015. Source: Elaborated by the author.

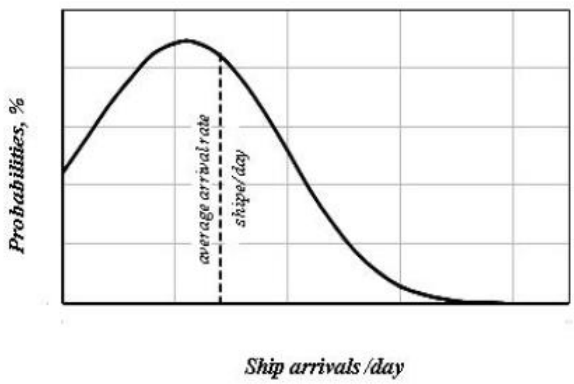


Figure 47. Ships arrival distribution as Poisson function, hypothetical port. Source: El-Naggar, M. E., Application of queuing theory to the container terminal at Alexandria seaport.

The Kolmogorov-Smirnov test it is used in the present thesis to determine the goodness of fit to the Poisson distribution of the interval variables.

H	Lower limit	Upper limit	x	FO	FOR	FORA	FERA	ABS
0	0	0	0	0	0.0000	0.0000	0.0000	0.0000
1	3	3	3	2	0.1667	0.1667	0.2892	-0.1225
2	4	4	4	2	0.1667	0.3333	0.4702	-0.1369
3	5	5	5	4	0.3333	0.6667	0.6452	0.0215
4	6	6	6	5	0.3333	1.0000	0.7861	0.2139

Figure 49. Parameters of Kolmogorov-Smirnov test to determine the goodness of fit to the Poisson distribution. Source: Elaborated by the author

Where,

H: Class interval

x: Mean between lower and upper limit

FO: Observed frequency

FOR: Relative observed frequency

FORA: Accumulated relative observed frequency

FERA: Accumulated relative expected frequency

ABS: Absolute frequency (ABS=FORA-FERA)

Hypothesis to contrast:

H_0: The data follow a Poisson distribution

H_1: The data do not follow a Poisson distribution

Test Statistic: The Kolmogorov-Smirnov test statistic is defined as:

$$D = \sup_{l \le i \le n} \left| \hat{F}_n(x_i) - F_0(x_i) \right|$$

Where,

x_i is the i-th value observed in the sample.

$\hat{F}_n(x_i)$ is an estimator of the probability of observing values that are less than or equal to x_i.

$F_0(x_i)$ is the probability of observing values less than or equal to x_i when H_0 is true.

Significance Level: $\alpha = 0.05$

Therefore, the criteria for making the decision between the 2 hypothesis will be:

$$If\ D \le D_{\propto} \Longrightarrow Accept\ H_0$$

$$If\ D > D_{\propto} \Longrightarrow Reject\ H_0$$

Where $D_{\propto}$ is defined:

$$D_{\propto} = \frac{c_{\propto}}{k(n)}$$

Where $c_{\propto}$ and $k(n)$, where n=12, are extracted from the table in Annex F.

With the calculations of D and $D_\propto$ done, the criteria for making the decision between the 2 hypothesis can be applied. The result is the following:

Estimator Smirnov-kolmogorov (D)	0.2139
Degrees of freedom	12
$D_\propto$ (α=0.05)	0.3754
Test	Accept

There is no contrary statistical evidence to reject the proposed model. Thus, it can be assumed the data follows a Poisson Distribution.

4.1.3. Assumptions

Due to the stated above, we can assert that the notation of the Queuing Theory Model assumed in our cement terminal is **M/M/1/infinite/FIFO (M/M/1).**

- Vessels arrivals are fitted in a Poisson distribution (discrete variables)
- Times of the service follow an Exponential distribution (continuous variables)
- There is only one server
- Unlimited capacity of the service
- Unlimited population size
- "First come, first served" queuing discipline

4.1.4. Inputs and outputs of the model

The inputs that will be implemented into the Queuing Theory formulations are:

- Probabilistic distribution of the arrivals (Poisson)
- Probabilistic distribution of the inter-arrival time (Exponential)
- Probabilistic distribution of the time of service (Exponential)

The outputs that will be obtained are:

- Average number of clients in the system (L)
- Average number of clients in the queue (L_q)
- Average time that a client spends in the system (W)
- Average waiting time in the queue (W_q)
- Probability of the system being empty (P_0)
- Probability of having *n* vessels in the system (P_n)
- Congestion factor (ρ)
- Relative waiting (η)

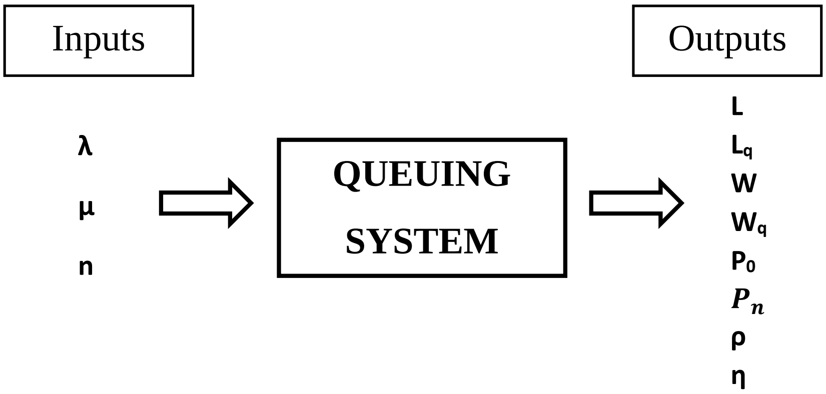


Figure 50. Inputs and outputs in a queuing system. Source: Elaborated by the author

4.1.5. Calculations of the parameters for the selected queuing model

On the basis of the following considerations, we obtain all the parameters described for the selected Queuing Model M/M/1.

The parameters from which we start applying the model are described here below:

Arrivals per year (n)	58	vessels
Loading performance of clinker	1,100	tons/h
Loading performance of cement	500	tons/h
Average loading time	25.6	h

The ratios of loading performance for both cement and clinker were given by Portcemen terminal as well as the list of the bulk ships (58) served in 2015 in this terminal. They are listed in the Annex C.

The value of the average loading time has been calculated as the average duration of all services using the values abovementioned of loading performance and the loading volumes in tons.

After the initial parameters are defined, outputs are calculated below.

- **λ:** Number of arrivals per unit of time

$$\lambda = \frac{Total\ arrivals\ in\ a\ year\ (n)}{365\ days \cdot 24\ h} = 0.0065\ arrivals/h$$

Or 0.16 arrivals/day, or 1.10 arrivals/week, or 4.75 arrivals/month.

- **μ:** Number of services per unit of time if the server is occupied

$$\mu = \frac{1}{average\ duration\ of\ the\ service\ (h)} = 0.039\ services/h$$

Or 0.938 services/day.

Where the average duration of the service is 25.6 hours.

- **ρ:** Congestion factor

$$\rho = \frac{\lambda}{\mu} = 0.167$$

Where λ<< μ.

- **P_0:** Probability of the system being empty

$$P_0 = 1 - \rho = 0{,}833 = 83\%$$

- **P_n:** Probability of having n vessels in the system

$$P_n = (1 - \rho) \cdot \rho^n$$

In case of n=1, $P_1 = 13.88\%$

In case of n=2, $P_2 = 2.312\%$

- **L:** Average number of clients in the system

$$L = \frac{\rho}{1 - \rho} = \frac{\lambda}{\mu - \lambda} = 0.1998\ vessels$$

- **L_q:** Average number of clients in the queue

$$L_q = \frac{\lambda^2}{\mu \cdot (\mu - \lambda)} = \frac{\rho^2}{1 - \rho} = 0.033\ vessels$$

- **W:** Average time that a client spends in the system

$$W = \frac{L}{\lambda} = \frac{1}{\mu - \lambda} = 30.717\ h$$

- **W_q:** Average waiting time in the queue

$$W_q = \frac{\rho}{\mu - \lambda} = 5.117\ h$$

- **η:** Relative waiting

$$\eta = \frac{\rho}{1-\rho} = 0.1998$$

Summary table with the values of all parameters calculated:

λ	0.160 arrivals/day
μ	0.938 services/day
ρ	0.167
$\mathbf{P_0}$	83%
$\boldsymbol{P_1}$	14%
$\boldsymbol{P_2}$	2.3%
L	0.20 vessels
$\mathbf{L_q}$	0.03 vessels
W	30.7 hours
$\mathbf{W_q}$	5.1 hours
η	0.2

Figure 51. Summary of the values of the parameters calculated for the selected queuing model M/M/1. Source: Elaborated by the author.

As can be seen from the results above, with a demand of 58 vessels per year in 2015, the probability of the system being empty is extremely high which at first gives the impression of an over dimensioned system. The terminal receives on average 1.10 arrivals/week, or in other words 4.75 arrivals/month. With only 1 loading and unloading equipment, the number of services if the server is occupied is 1 service/day approximately with an average duration of 25.6 hours/service.

It has to be borne in mind that the traffic in 2015 was only the 60% approximately of the traffic before the financial crisis of 2008 in Spain that represented one of the most significant setback in global trade. Yet, maritime shipping is subject to fluctuations as commercial opportunities change. This is an added difficulty of predicting traffic to dimensioning maritime terminals.

Having estimated the parameters, the probabilities are calculated:

- $\boldsymbol{P(n \geq X)}$**:** Probability of having in the system more clients (n) than X

$$P(n \geq X) = \rho^X$$

- $\boldsymbol{P(W > t)}$**:** Probability of the waiting time in the system (W) is greater than t

$$P(W > t) = e^{-\mu(1-\rho)t}$$

- $\boldsymbol{P(W_q > t)}$**:** Probability of the waiting time in the queue (W_q) is greater than t

$$P(W_q > t) = \rho \cdot e^{-\mu(1-\rho)t}$$

- $\boldsymbol{P(X = x)}$**:** Probability of x arrivals per unit of time

$$P(X = x) = \frac{\lambda^X}{x!} \cdot e^{-\lambda}$$

- $\boldsymbol{P(X = x)}$**:** Probability of x ships receive the service per unit of time

$$P(X = x) = \mu \cdot e^{-\mu x}$$

Summary table with the values of all probabilities calculated:

X (vessels)	1	2	3	4	5	6	7
P(n>X)	**16.66%**	**2.77%**	**0.46%**	**0.08%**	**0.01%**	**0.00%**	**0.00%**

t (h)	1	12	24	48	72	96	120
P(W>t)	**96.80%**	**67.66%**	**45.78%**	**20.96%**	**9.59%**	**4.39%**	**2.01%**

t (h)	1	12	24	48	72	96	120
P(Wq>t)	**16.12%**	**11.27%**	**7.63%**	**3.49%**	**1.60%**	**0.73%**	**0.33%**

x (vessels)	1	2	3	4	5	6	7
P(X=x)	**0.65%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

x (vessels)	1	2	3	4	5	6	7
P(X=x)	**3.76%**	**3.61%**	**3.47%**	**3.34%**	**3.21%**	**3.09%**	**2.97%**

Figure 52. Summary table of the values of all probabilities calculated. Source: Elaborated by the author.

❖ Model M/D/1

In the current analysis of the performance of Portcemen Terminal, it is assumed the M/M/1 queue model based on the assumptions above-mentioned. However, it is interesting to compare the results of the parameters calculated for the M/M/1 model (stochastic service times) and M/D/1 model (deterministic services times).

In queueing theory, a discipline within the mathematical theory of probability, an M/D/1 queue represents the queue length in a system having a single server, where arrivals are determined by a Poisson process and job service times are fixed (deterministic).

The M/D/1 model has exponentially distributed arrival times but fixed service time (constant). We can compute the same result using M/D/1 equations, shown in the Annex B, the results are shown in the table below.

- Arrivals occur at rate λ according to a Poisson process.
- Service times are deterministic time D (serving at rate μ = 1/D).
- A single server serves vessels one at a time from the front of the queue, according to a first-come, first-served discipline.
- The buffer is of infinite size, so there is no limit on the number of vessels it can contain.

Summary table with the values of all parameters calculated for M/M/1 and M/D/1 model:

	M/M/1	**M/D/1**
λ	0.160 arrivals/day	0.160 arrivals/day
μ	0.938 services/day	0.938 services/day
ρ	0.167	0.167
L	0.20 vessels	0.19 vessels
L_q	0.03 vessels	0.02 vessels
W	30.7 hours	28.1 hours
W_q	5.1 hours	2.6 hours

Figure 53. Summary of the values of the parameters calculated for the selected queuing model M/M/1 versus M/D/1 model. Source: Elaborated by the author.

In the above discussion the average number of clients in the system, the average number of clients in the queue, the average time that a client spends in the system and the average waiting time in the queue are calculated for both models. Comparing these two models the values of M/M/1 model are greater than the values of M/D/1 model but they are very similar.

4.1.6. Simulation

Although the larger vessels have real scheduled arrivals, the smaller ones do not. It is necessary to assume the random nature of the arrivals in case of non-programmed calls.

It should also be considered that the duration of the calls is not fixed, but dependent on the amount of cement and clinker to be loaded. Moreover, the crane performance sets the duration of the service. Departures are also considered random due to their dependency on the volume of commodities loaded and unloaded.

For this reason, a temporal analysis of the traffic patterns is developed on Portcemen terminal so as to simulate the dynamics of the terminal and determine feasible scenarios.

This analysis evaluates how many vessels are berthed at Portcemen terminal in year 2015, considered as the result of evaluating the total arrivals and the total time of the service which comes from the ship loader's performance for both cement and clinker.

Loading performance of clinker	1,100	tons/h
Loading performance of cement	500	tons/h

Due to the data provided was complete but not sufficient enough, for developing the simulation, they are assumed the following scenarios:

- Ship loaders work 24 hours/day
- No preparation time for the machines is considered
- All vessels arrive at 8:00 am

Once the sequence of arrivals is sorted out with their corresponding cargo and the volume of tons which have to be loaded, applying the loading performance of cement and clinker, the loading time for each service can be determined, and so the service time. The average loading time is 25.6 hours per service, in other words, 1 day per service approximately.

As it is mentioned above, every service lasts **25.6 hours in average**, meaning that the server is working **17% of the time** in a year.

With the arrival times and the service times determined, the simulation can proceed in order to acquire the departure times. Thus, it can be seen how many vessels might wait in queue for the service.

In the following table, all the values abovementioned for each call in Portcemen are shown. The results of the analysis reveal that in 4 different occasions during the year, vessels have to wait to be served. The average waiting time of these 4 vessels is **15 hours**.

In order to preserve the data confidentiality, the detailed information of the arrivals such as cargo (cement or clinker) and Tm have not been shown in the table below.

ORIGINAL DATA						ARRIVALS		LOADING	DEPARTURE		SIMULATION		
Sequence	**Cargo***	**tons/h***	**Tm***	**Day**	**IAT (days)**	**Arrival time**	**Hours**	**Loading time (h)**	**Departure time**	**Hours**	**ARRIVALS**	**WAITING TIME (h)**	**DEPARTURES**
1				8-gen	9	8/1/2015 8:00	176	16.8	9/1/2015 0:48	192.8	8/1/2015 8:00	0	9/1/2015 0:48
2				16-gen	8	16/1/2015 8:00	368	16.6	17/1/2015 0:36	384.6	16/1/2015 8:00	0	17/1/2015 0:36
3				21-gen	5	21/1/2015 8:00	488	33.3	23/1/2015 17:18	521.3	21/1/2015 8:00	0	23/1/2015 17:18
4				25-gen	4	25/1/2015 8:00	584	16.6	26/1/2015 0:36	600.6	25/1/2015 8:00	0	26/1/2015 0:36
5				30-gen	5	30/1/2015 8:00	704	22.7	31/1/2015 6:42	726.7	30/1/2015 8:00	0	31/1/2015 6:42
6				2-febr	3	2/2/2015 8:00	776	37.5	3/2/2015 21:30	813.5	2/2/2015 8:00	0	3/2/2015 21:30
7				19-febr	17	19/2/2015 8:00	1,184	16.8	20/2/2015 0:48	1,200.8	19/2/2015 8:00	0	20/2/2015 0:48
8				26-febr	7	26/2/2015 8:00	1,352	34.2	27/2/2015 18:12	1,386.2	26/2/2015 8:00	0	27/2/2015 18:12
9				1-març	3	1/3/2015 8:00	1,424	30.7	2/3/2015 14:42	1,454.7	1/3/2015 8:00	0	2/3/2015 14:42
10				5-març	4	5/3/2015 8:00	1,520	51.4	7/3/2015 19:24	1,571.4	5/3/2015 8:00	0	7/3/2015 19:24
11				6-març	1	6/3/2015 8:00	1,544	7.7	6/3/2015 15:42	1,551.7	6/3/2015 8:00	23.7	8/3/2015 3:06
12				8-març	2	8/3/2015 8:00	1,592	10.4	8/3/2015 18:24	1,602.4	8/3/2015 8:00	0	8/3/2015 18:24
13				22-març	14	2/3/2015 8:00	1,928	38.9	9/3/2015 22:54	1,966.9	2/3/2015 8:00	0	9/3/2015 22:54
14				25-març	3	25/3/2015 8:00	2,000	9.3	25/3/2015 17:18	2,009.3	25/3/2015 8:00	0	25/3/2015 17:18
15				3-abr	9	3/4/2015 8:00	2,216	44.6	5/4/2015 12:36	2,260.6	3/4/2015 8:00	0	5/4/2015 12:36
16				9-abr	6	9/4/2015 8:00	2,360	43.3	11/4/2015 11:18	2,403.3	9/4/2015 8:00	0	11/4/2015 11:18
17				14-abr	5	14/4/2015 8:00	2,480	10.1	14/4/2015 18:06	2,490.1	14/4/2015 8:00	0	14/4/2015 18:06
18				21-abr	7	21/4/2015 8:00	2,648	45.4	23/4/2015 13:24	2,693.4	21/4/2015 8:00	0	23/4/2015 13:24
19				30-abr	9	30/4/2015 8:00	2,864	8.0	30/4/2015 16:00	2,872.0	30/4/2015 8:00	0	30/4/2015 16:00
20				4-maig	4	4/5/2015 8:00	2,960	35.2	5/5/2015 19:12	2,995.2	4/5/2015 8:00	0	5/5/2015 19:12
21				19-maig	15	19/5/2015 8:00	3,320	37.5	20/5/2015 21:30	3,357.5	19/5/2015 8:00	0	20/5/2015 21:30
22				28-maig	9	28/5/2015 8:00	3,536	36.4	29/5/2015 20:24	3,572.4	28/5/2015 8:00	0	29/5/2015 20:24
23				29-maig	1	29/5/2015 8:00	3,560	11.4	29/5/2015 19:24	3,571.4	29/5/2015 8:00	12.4	30/5/2015 7:48
24				31-maig	2	31/5/2015 8:00	3,608	52.5	2/6/2015 20:30	3,660.5	31/5/2015 8:00	0	2/6/2015 20:30

25				8-juny	8	8/6/2015 8:00	3,800	44.2	10/6/2015 12:12	3,844.2	8/6/2015 8:00	0	10/6/2015 12:12
26				11-juny	3	11/6/2015 8:00	3,872	10.0	11/6/2015 18:00	3,882.0	11/6/2015 8:00	0	11/6/2015 18:00
27				12-juny	1	12/6/2015 8:00	3,896	7.1	12/6/2015 15:06	3,903.1	12/6/2015 8:00	0	12/6/2015 15:06
28				1-jul	19	1/7/2015 8:00	4,352	9.2	1/7/2015 17:12	4,361.2	1/7/2015 8:00	0	1/7/2015 17:12
29				7-jul	6	7/7/2015 8:00	4,496	18.2	8/7/2015 2:12	4,514.2	7/7/2015 8:00	0	8/7/2015 2:12
30				10-jul	3	10/7/2015 8:00	4,568	43.5	12/7/2015 11:30	4,611.5	10/7/2015 8:00	0	12/7/2015 11:30
31				12-jul	2	12/7/2015 8:00	4,616	10.1	12/7/2015 18:06	4,626.1	12/7/2015 8:00	0	12/7/2015 18:06
32				22-jul	10	22/7/2015 8:00	4,856	36.9	23/7/2015 20:54	4,892.9	22/7/2015 8:00	0	23/7/2015 20:54
33				27-jul	5	27/7/2015 8:00	4,976	16.6	8/7/2015 0:36	4,992.6	27/7/2015 8:00	0	8/7/2015 0:36
34				6-ag	10	6/8/2015 8:00	5,216	8.3	6/8/2015 16:18	5,224.3	6/8/2015 8:00	0	6/8/2015 16:18
35				19-ag	13	19/8/2015 8:00	5,528	9.1	19/8/2015 17:06	5,537.1	19/8/2015 8:00	0	19/8/2015 17:06
36				22-ag	3	22/8/2015 8:00	5,600	46.4	24/8/2015 14:24	5,646.4	22/8/2015 8:00	0	24/8/2015 14:24
37				29-ag	7	29/8/2015 8:00	5,768	7.0	29/8/2015 15:00	5,775.0	29/8/2015 8:00	0	29/8/2015 15:00
38				1-set	3	1/9/2015 8:00	5,840	24.8	10/9/2015 8:48	5,864.8	1/9/2015 8:00	0	10/9/2015 8:48
39				5-set	4	5/9/2015 8:00	5,936	9.3	5/9/2015 17:18	5,945.3	5/9/2015 8:00	0	5/9/2015 17:18
40				9-set	4	9/9/2015 8:00	6,032	33.5	10/9/2015 17:30	6,065.5	9/9/2015 8:00	0	10/9/2015 17:30
41				13-set	4	13/9/2015 8:00	6,128	10.1	13/9/2015 18:06	6,138.1	13/9/2015 8:00	0	13/9/2015 18:06
42				17-set	4	17/9/2015 8:00	6,224	7.1	17/9/2015 15:06	6,231.1	17/9/2015 8:00	0	17/9/2015 15:06
43				24-set	7	24/9/2015 8:00	6,392	44.6	26/9/2015 12:36	6,436.6	24/9/2015 8:00	0	26/9/2015 12:36
44				3-oct	9	3/10/2015 8:00	6,608	37.1	4/10/2015 21:06	6,645.1	3/10/2015 8:00	0	4/10/2015 21:06
45				9-oct	6	9/10/2015 8:00	6,752	10.3	9/10/2015 18:18	6,762.3	9/10/2015 8:00	0	9/10/2015 18:18
46				12-oct	3	12/10/2015 8:00	6,824	43.3	14/10/2015 11:18	6,867.3	12/10/2015 8:00	0	14/10/2015 11:18
47				13-oct	1	13/10/2015 8:00	6,848	30.1	14/10/2015 14:06	6,878.1	13/10/2015 8:00	15.3	15/10/2015 16:54
48				17-oct	4	17/10/2015 8:00	6,944	7.6	17/10/2015 15:36	6,951.6	17/10/2015 8:00	0	17/10/2015 15:36
49				12-nov	26	12/11/2015 8:00	7,568	55.0	14/11/2015 23:00	7,623.0	12/11/2015 8:00	0	14/11/2015 23:00
50				15-nov	3	15/11/2015 8:00	7,640	33.0	16/11/2015 17:00	7,673.0	15/11/2015 8:00	0	16/11/2015 17:00
51				19-nov	4	19/11/2015 8:00	7,736	10.1	19/11/2015 18:06	7,746.1	19/11/2015 8:00	0	19/11/2015 18:06

52				21-nov	2	21/11/2015 8:00	7,784	7.0	21/11/2015 15:00	7,791.0	21/11/2015 8:00	0	21/11/2015 15:00
53				27-nov	6	27/11/2015 8:00	7,928	36.4	28/11/2015 20:24	7,964.4	27/11/2015 8:00	0	28/11/2015 20:24
54				28-nov	1	28/11/2015 8:00	7,952	30.1	29/11/2015 14:06	7,982.1	28/11/2015 8:00	12.4	30/11/2015 1:54
55				17-des	19	17/12/2015 8:00	8,408	44.7	19/12/2015 12:42	8,452.7	17/12/2015 8:00	0	19/12/2015 12:42
56				22-des	5	22/12/2015 8:00	8,528	31.8	23/12/2015 15:48	8,559.8	22/12/2015 8:00	0	23/12/2015 15:48
57				24-des	2	24/12/2015 8:00	8,576	10.1	24/12/2015 18:06	8,586.1	24/12/2015 8:00	0	24/12/2015 18:06
58				30-des	6	30/12/2015 8:00	8,720	36.4	31/12/2015 20:24	8,756.4	30/12/2015 8:00	0	31/12/2015 20:24

Figure 54. Simulation analysis. Source: Elaborated by the author.

*Data omitted in the present document in order to preserve the data confidentiality.

The results of the analysis are summarized in the table below.

Average service time (h)	25.6
% of time the server is working	17%
% of time the server is empty	83%
Minimum service time (h)	7
Maximum service time (h)	55
Minimum number of vessels in terminal	0
Number of days a year when the terminal is empty	307
% of the total	84%
Maximum number of vessels in terminal	2
Number of days a year when the maximum number is produced	4
% of the total	1%
Number of days a year when a vessel is at terminal	54
% of the total	15%
Total waiting time of vessels in queue (h)	64
Average waiting time of vessels in queue (h)	15
Minimum inter-arrival time (days)	1
Maximum inter-arrival time (days)	26

Figure 55. Summary of the values calculated. Source: Elaborated by the author.

These ideas improve the knowledge about the behaviour of the traffic patterns at the terminal, and they will bolster the conclusions obtained from the queuing theory method results.

4.1.7. Levels of service

Terminal capacity calculations provide a link between the level of service achieved and the following factors: the demand placed, the capacity provided and the performance expected.

When planning facilities, it is necessary to try out different capacities with different traffic forecasts for different points of time. This calculation will be used for setting performance (productivity), proposed capacity (number of berths) and varying traffic demand to determine the effect on level of service (ship waiting time). Alternatively, for a proposed waiting time, traffic and number of berths for the required productivity can be determined.

All these calculations use liner equations except the ship waiting parameter or queuing times for berths. As it is previously mentioned in the queuing theory chapter, it is a complex mathematical expression which for different assumptions may not have a numerical solution. The use of theoretical queuing formulas and computer simulation models have been used to estimate ship waiting time. Results from queuing theory are dependent on the statistical distribution of ship arrivals and ship servicing time.

❖ Charts

For the above reasons, the use of planning charts[12] is recommended first to obtain a general vision and a clear understanding of the relationships and their sensitives, and then as a crosscheck on calculations. The charts are graphical statements of the linear equations but for greater precision is preferable to use equations. The relationship between berth utilization and ship waiting time is plotted by a curve based on queuing theory in the charts. As it is referenced in UNCTAD Manual "*Port development",* the charts only apply for dry bulk terminals.

Hereunder, both charts are shown. The first one, related to *berth time*, gives the following information to the planner: effective capacity of each ship-loader or unloader; through-ship gross loading or unloading rate: through-ship net loading or unloading rate (which is equivalent to the gross rate if the berth is worked 24 hours per day); and average berth time for individual ships. The through-ship net rate is a key figure in describing the productivity of a bulk berth.

The planning chart II, related to ship cost, is a similar method as planning chart I with the following turning points: number of ships per year; number of terminal commission days per year; number of berths; and the average daily ship cost while at port. The number of terminal commission days per year is the sum of the number of commission days for each berth. For each set of turning-points, the intersections of the trajectory and the axes give the planner the following information: annual berth-day requirement; berth utilization; ship time at port; and annual ship cost while at port.

Both charts are shown in Annex E of the present thesis.

❖ Waiting time/Service time ratio

According to Spanish Recommendations on Maritime Works (ROM 2.0-11), the service quality level (τ) is defined as relative waiting or average waiting time of ships in port before being assigned a berth due to the occupancy of all berths divided by the average total time of the vessels moored at the berth or time of service.

This ratio is widely used as a measure of the level of service provided by a terminal, as would seem logical, for ships that have less cargo to discharge cannot afford to wait as long as ships that have more.

Therefore, τ is the ratio between the waiting time at the queue and the services per unit time that the terminal provides:

$$\tau = \frac{W_q}{1/\mu}$$

Or, in other words: τ is the proportion of the service time that a vessel has to wait before being attended:

[12] Information extracted from *Port development: A handbook for planners in developing countries* prepared by the secretariat of UNCTAD in 1985. Completely referred in the Bibliography.

$$W_q(h) = \tau \cdot \frac{1}{\mu}$$

Regarding the waiting time ratio, the Port Management Manual developed by UNCTAD in 1985 establishes that *"It is usually considered that waiting time should be not more than* ***lo-50 per cent of working time****. But this ratio is also misleading since it can improve (i.e. decrease) as service time deteriorates (i.e. increases). As with berth occupancy, the ratio should be used only when the other factors are constant. When the plan has been based on investing for the economic optimum, the waiting-time/service-time ratio is bound to be an acceptable figure, generally less than* ***30 per cent****."*

For this minor thesis, the performance of the terminal will be evaluated considering the average waiting time in queue (Wq) and service time (μ) that have been defined previously and characterized analytically in section 4.1.5 in the calculations of the parameters for the selected queuing model.

On the other hand, regarding the "Recommendations for the project and execution of docking and mooring works" by the Spanish Recommendations on Maritime Works (ROM 2.0-11), it establishes that *"In general, relatives waiting times between* ***0.1 and 0.5*** *are considered admissible depending on the characteristics of the fleet expected at berthing. That is, average waiting times between 10% (for totally regular traffic) and 50% (for totally tramp traffic) of the average service time, with intermediate values for mixed traffic."*

According to the explained above, the value of the ratio (τ) will be obtained of the simulation scenarios previously defined. Once this value is obtained, it will be compared with the criteria of admissible waiting time defined by UNCTAD and with the one defined by ROM. The fulfilment or unfulfilment of these criteria will conform the core of the assessment of the Portcemen terminal performance in which is based this minor thesis.

Summarizing, the criteria evaluated are the following:

- From UNTAD: Admissible waiting time less than 30% (admissible τ less than 0.3)
- From ROM: Admissible τ between 0.1 and 0.5

4.2. Future situation

In normal circumstances, improving service levels and increasing the number of servers, can improve the service efficiency and reduce the waiting time. However, improving the level of service and increasing the number of servers will increase the service costs too. Therefore, to achieve the purpose of optimization, we must make the sum of service cost and waiting cost to be minimal.

Previously, the parameters for the queuing model applied in our case of study (M/M/1) in Portcemen terminal during 2015 have been calculated. A study of resilience has been carried out to analyze eventual scenarios that may occur in the future. For this, the parameters for other selected model have been calculated.

The proposed scenarios that have been analyzed are:

- Increasing the demand
- Increasing the servers

Aside from modifying the real data of 2015 by varying the demand and the servers, the rest of the parameters contemplated in the data of Portcemen terminal will be sustained such as the ship loaders performance or the average loading time.

Once these 2 situations outlined above are staged, they will be compared with the criteria of admissible waiting time defined by UNCTAD and with the one defined by ROM.

The criteria evaluated are the following:

- From UNTAD: Admissible waiting time less than 30% (admissible τ less than 0.3)
- From ROM: Admissible τ between 0.1 and 0.5

- **Increasing the demand:**

In this case, the demand will be increased to double and triple so it can be seen when the current system collapse. The original data from which the simulation of these scenarios is started is n=58 vessels. It has to be considered that the queuing model followed is M/M/1, so there is only 1 server. On the other hand, the average loading time is kept in 25.6h.

The parameters related to both of scenarios (double and triple the demand) are shown hereunder.

M/M/1	Demand n=58 ORIGINAL DATA	Demand n=116 DOUBLE	Demand n= 174 TRIPLE
λ	0.160 arrivals/day	0.318 arrivals/day	0.477 arrivals/day
μ	0.938 services/day	0.938 services/day	0.938 services/day
ρ	0.167	0.339	0.508
P_0	83%	66%	49%
P_1	14%	22%	25%
P_2	2.3%	7.6%	13%
L	0.20 vessels	0.51 vessels	1.03 vessels
L_q	0.03 vessels	0.17 vessels	0.53 vessels
W	30.7 hours	38.7 hours	52.1 hours
W_q	5.1 hours	13.1 hours	26.5 hours
η	0.2	0.5	1.1

Figure 56. Values of the parameters by increasing the demand. Source: Elaborated by the author

As can be seen from the table above, the probability of the system being empty decreases as the demand increases whereas the probability of having *n* vessels in the system increases exponentially as the demand increases. Moreover, both number of clients and average waiting time raise along with the demand.

Considering the criteria of admissible waiting time defined by UNCTAD and ROM, the results obtained by increasing the demand are presented below.

M/M/1	Demand n=58 ORIGINAL DATA	Demand n=116 DOUBLE	Demand n= 174 TRIPLE	Demand n=343 CONGESTION
λ	0.160 arrivals/day	0.318 arrivals/day	0.477 arrivals/day	0.940 arrivals/day
μ	0.938 services/day			
Utilization factor (%) ρ	17%	34%	51%	100%
P_0	83%	66%	49%	0%
W	30.7 hours	38.7 hours	52.1 hours	-10,782 hours
W_q	5.1 hours	13.1 hours	26.5 hours	-10,807 hours
τ ratio	0.2	0.5	1	-422
Waiting time (%)	20%	50%	100%	-
Congestion?	NO	NO	NO	YES
Fulfils UNCTAD Criteria?	YES	NO	NO	NO
Fulfils ROM Criteria?	YES	YES	NO	NO

Figure 57. Performance of the terminal if the demand increases. Source: Elaborated by the author

As can be seen from the table above, the waiting time increases as the demand increases. There is none congestion for any of these cases despite several hours of waiting. Congestion makes its approach with a demand of **n=343 vessels/year**. It is considered that exist congestion when ρ>1, that is to say, when the arrival rate (λ) is bigger than the service rate (μ).

While the congestion factor determined through Queuing Theory Method implies a fully inoperative state of the terminal, the lack of fulfilment of the waiting time criteria imply an inadequate performance of the terminal, but not necessarily that the terminal is not operative or congested.

In this sense, it is observed how the different levels of restriction of the different criteria for waiting time, (being UNCTAD criteria more restrictive), lead to scenarios when one of the waiting time criteria (ROM) is fulfilled and other (UNCTAD) is not, as it is the case of n=116 for M/M/1 model. For this case, it should be recommended to improve the conditions of it so as to ensure the availability of a higher number of service channels, which at the same time would require further research, due to the variability of the traffic.

In the case of tripling the demand, no longer fulfil the requirements of waiting time of both criteria.

❖ **Increasing the servers: M/M/2**

In this case, the server will be increased to double so it can be seen the performance of the terminal with a queuing model M/M/2. The original data from which the simulation of these scenarios is started is n=58 vessels. Simultaneously, the demand will be multiplied by 2, 3 and 6 times. On the other hand, the average loading time is kept in 25.6h.

The parameters related to the abovementioned scenarios are shown hereunder.

M/M/2	Demand n=58 ORIGINAL DATA	Demand n=116 DOUBLE	Demand n= 174 TRIPLE	Demand n=348 BY SIX TIMES
λ	0.160 arrivals/day	0.318 arrivals/day	0.477 arrivals/day	0.953 arrivals/day
μ	0.938 services/day	0.938 services/day	0.938 services/day	0.938 services/day
ρ	0.085	0.169	0.254	0.508
P_0	85%	72%	62%	44%
P_1	14%	24%	32%	45%
P_2	2.4%	8%	16%	46%
L	0.17 vessels	0.35 vessels	0.54 vessels	1.5 vessels
L_q	0.01 vessels	0.01 vessels	0.04 vessels	0.479 vessels
W	25.8 hours	26.4 hours	27.5 hours	37.7 hours
W_q	0.1 hours	0.8 hours	1.9 hours	12 hours
η	0.1	0.2	0.3	1

Figure 58. Values of the parameters by increasing the servers and the demand. Source: Elaborated by the author

As can be seen from the table above, the probability of the system being empty decreases as the demand increases whereas the probability of having *n* vessels in the system increases exponentially as the demand increases. Moreover, both number of clients and average waiting time raise along with the demand.

By looking more carefully to the probability of the system being empty and the probability of having *n* vessels in the system in the case of having 2 servers compared to 1 server, both of them are practically identical having a demand of n=58 vessels. It makes sense since in case of having only 1 server, with a demand of 58 vessels, the system operates well below its maximum capacity before congestion. So with 2 servers only one of them will work most of the time because it is capable to absorb all the demand whereas the other one will remain empty the most of the time.

Considering the criteria of admissible waiting time defined by UNCTAD and ROM, the results obtained by simulating a M/M/2 queuing model are presented below.

M/M/2	Demand n=58 ORIGINAL DATA	Demand n=116 DOUBLE	Demand n= 174 TRIPLE	Demand n=348 BY SIX TIMES
λ	0.160 arrivals/day	0.318 arrivals/day	0.477 arrivals/day	0.953 arrivals/day
μ	0.938 services/day			
Utilization factor (%) ρ	0.085	0.169	0.254	0.508
P_0	85%	72%	62%	44%
W	25.8 hours	26.4 hours	27.5 hours	37.7 hours
W_q	0.1 hours	0.8 hours	1.9 hours	12 hours
τ ratio	0.007	0.03	0.07	0.47
Waiting time (%)	1%	3%	7%	47%
Congestion?	NO	NO	NO	NO
Fulfils UNCTAD Criteria?	YES	YES	YES	NO
Fulfils ROM Criteria?	YES	YES	YES	YES

Figure 59. Performance of the terminal if the servers increase. Source: Elaborated by the author

As can be seen from the table above, the waiting time increases as the demand increases. There is none congestion for any of these cases despite several hours of waiting. Congestion makes its approach with a demand of **n=1200 vessels/year**. In the case of M/M/1, congestion makes its approach with a demand of n=343 vessels/year. Thus, servers have been doubled but the demand has been tripled before congestion makes its approach. In the case of n=360 vessels/year, no longer fulfil the requirements of waiting time of both criteria.

Regarding the M/M/2 queuing model, as it is mentioned above, congestion makes its approach at n=1200 vessels per year, or in other words, 100 vessels/month or 25 vessels/week. This fact will never be done in Portcemen terminal in Barcelona. This is an unrealistic situation that never will achieve dry bulk terminals in Port of Barcelona.

5. DISCUSSION AND CONCLUSIONS

This minor thesis has provided an analysis on the performance of the Portcemen Terminal in Port of Barcelona. The main objective of this thesis was to characterize and analyze the fulfilment of Portcemen terminal in Barcelona Port applying the queuing theory in order to investigate the service levels using standard design parameters of ROM and UNCTAD. Moreover, the sub-goal of the thesis was to carry out a resilience study of the cement terminal in Barcelona Port through performance indicators and raising various scenarios. The conclusions obtained are presented below.

- **Terminal performance:**

It was assumed that the population size is unlimited and so it is the capacity of the service. Thus, there is no restriction on the capacity of the system and it can be an infinite waiting line. So we could assert that the notation of the Queuing Theory Model assumed in this cement terminal is M/M/1/infinite/FIFO (M/M/1).

With the calculations of the parameters for this queuing model for the demand in 2015, it can be asserted that it is an over dimensioned system. With a demand of 58 vessels per year in 2015, the probability of the system being empty is extremely high (83%) and the probability of having one vessel in the system is only 14%. The terminal receives on average 1.10 arrivals/week, or in other words 4.75 arrivals/month. With only 1 loading and unloading equipment, the number of services if the server is occupied is 1 service/day approximately with an average duration of 25.6 hours/service.

Nevertheless, it has to be borne in mind that the traffic in 2015 was only the 60% approximately of the traffic before the financial crisis of 2008 in Spain that represented one of the most significant setback in global trade. Yet, maritime shipping is subject to fluctuations as commercial opportunities change. This is an added difficulty of predicting traffic to dimensioning maritime terminals. Although Portcemen terminal is not one of the biggest cement terminals in the world, for sure it has had and it will have greater volume of dry bulk traffic than it has now.

Through the manual simulation of the terminal based on the data provided by Portcemen that simulates the dynamics of the terminal during year 2015, it could be analysed the performance of such terminal. With the arrival times and the service times determined, the simulation could proceed in order to acquire the departure times. Thus, it can be seen how many vessels might wait in queue for the service. The results obtained, considering some assumptions which have to be done due to the lack of information, show that the maximum number of vessels that overlap in the same day is 2. This fact only happens in 4 different occasions during this year, where these vessels have to wait on average 15 hours to be served. All year round, there are 307 days in which no vessels arrived, 54 days that served 1 vessel and 4 days that overlap 2 vessels in the same day.

Every service lasts 25.6 hours in average, meaning that the server is working 17% of the time in a year. This fact reflects again that most time of the year the terminal is empty.

Moreover, on the basis of data compiled, inter-arrivals time have been calculated. The minimum inter-arrival time is 1 day whereas the maximum inter-arrival time is 26 days. As can be seen, the arrivals are totally stochastic and extremely variables. Although the larger vessels have real scheduled arrivals, the smaller ones do not. It was necessary in this minor thesis to assume the random nature of the arrivals in case of non-programmed calls. Accordingly, the minimum service time is 7 hours whereas the maximum service time is 55 hours.

❖ **Levels of service:**

Terminal capacity calculations provide a link between the level of service achieved and the demand placed, the capacity provided and the performance expected. When planning facilities, it is necessary to try out different capacities with different traffic forecasts for different points of time. This calculation will be used for setting performance (productivity), proposed capacity (number of berths) and varying traffic demand to determine the effect on level of service (ship waiting time).

According to Spanish Recommendations on Maritime Works (ROM 2.0-11), the service quality level (τ) is defined as relative waiting or average waiting time of ships in port before being assigned a berth due to the occupancy of all berths divided by the average total time of the vessels moored at the berth or time of service. This ratio is widely used as a measure of the level of service provided by a terminal. For this reason, it has been applied in the present thesis in order to analyze the performance of the terminal considering the average waiting time in queue (Wq) and service time (μ). Once the value of the ratio (τ) is obtained, it has been be compared with the criteria of admissible waiting time defined by UNCTAD and with the one defined by ROM.

In year 2015, with a demand of n=58 vessels/year, such ratio (τ) is 0.2 so there is no congestion and both criteria of admissible waiting time are fulfilled. It can be asserted that the terminal in 2015 works in a low level of capacity.

A study of resilience has been carried out to analyze eventual scenarios that may occur in the future. For this, the parameters for other selected model have been calculated. The proposed scenarios that have been analyzed in the thesis are increasing the demand and increasing the number of servers.

- Increasing the demand

In this case, the demand has been increased to double and triple so it can be seen when the current system collapse. The results obtained are summarized in the table below.

M/M/1	Demand n=58 ORIGINAL DATA	Demand n=116 DOUBLE	Demand n= 174 TRIPLE	Demand n=343 CONGESTION
Utilization factor (%) ρ	17%	34%	51%	100%
τ ratio	0.2	0.5	1	-422
Congestion?	NO	NO	NO	YES
Fulfils UNCTAD Criteria?	YES	NO	NO	NO
Fulfils ROM Criteria?	YES	YES	NO	NO

Figure 60. Summary of the performance of the terminal if the demand increases. Source: Elaborated by the author

Predictably, the probability of the system being empty decreases as the demand increases whereas the probability of having *n* vessels in the system increases exponentially as the demand increases. Moreover, both number of clients and average waiting time raise along with the demand. As can be seen, there is none congestion for any of these cases despite several hours of waiting. Congestion makes its approach with a demand of n=343 vessels/year. It is almost a vessel per day served when the system collapses.

While the congestion factor determined through Queuing Theory Method implies a fully inoperative state of the terminal, the lack of fulfilment of the waiting time criteria imply an inadequate performance of the terminal, but not necessarily that the terminal is not operative or congested.

In this sense, it is observed how the different levels of restriction of the different criteria for waiting time, (being UNCTAD criteria more restrictive), lead to scenarios when one of the waiting time criteria (ROM) is fulfilled and other (UNCTAD) is not, as it is the case of n=116 for M/M/1 model. For this case, it should be recommended to improve the conditions of it so as to ensure the availability of a higher number of service channels, which at the same time would require further research, due to the variability of the traffic.

In the case of tripling the demand, no longer fulfil the requirements of waiting time of both criteria. However, the system is not congested yet.

- Increasing the servers

In this case, the server has been increased to double so it can be seen the performance of the terminal with a queuing model M/M/2. Simultaneously, the demand will be multiplied by 2, 3 and 6 times. The results obtained are summarized in the table below.

M/M/2	Demand n=58 ORIGINAL DATA	Demand n=116 DOUBLE	Demand n= 174 TRIPLE	Demand n=348 BY SIX TIMES
Utilization factor (%) ρ	9%	17%	25%	51%
τ ratio	0.007	0.03	0.07	0.47
Congestion?	NO	NO	NO	NO
Fulfils UNCTAD Criteria?	YES	YES	YES	NO
Fulfils ROM Criteria?	YES	YES	YES	YES

Figure 61. Summary of the performance of the terminal if the servers increase. Source: Elaborated by the author

By analysing the probability of the system being empty and the probability of having *n* vessels in the system in the case of having 2 servers compared to 1 server, both of them are practically identical having a demand of n=58 vessels. It makes sense since in case of having only 1 server, with a demand of 58 vessels, the system operates well below its maximum capacity before congestion. So with 2 servers only one of them will work most of the time because it is capable to absorb all the demand whereas the other one will remain empty the most of the time.

There is none congestion for any of these cases despite several hours of waiting. Congestion makes its approach with a demand of n=1200 vessels/year, or in other words, 100 vessels/month or 25 vessels/week. This fact will never be done in Portcemen terminal in Barcelona. This is an unrealistic situation that never will achieve dry bulk terminals in Port of Barcelona. In the case of M/M/1, congestion makes its approach with a demand of n=343 vessels/year. Thus, servers have been doubled but the demand has been tripled before congestion makes its approach. In the case of n=360 vessels/year, no longer fulfil the requirements of waiting time of both criteria.

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ANNEX

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A. EVOLUTION OF SOLID BULK CARGO BY AUTHORITY PORT IN TONS

Port Authority	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	TOTAL BY AAPP
A CORUÑA	4.437.796	4.095.639	4.140.677	3.289.608	3.215.589	3.191.581	3.470.995	4.179.771	3.688.168	4.310.507	4.912.338	4.345.101	5.057.024	52.334.794
ALICANTE	1.667.536	1.642.514	1.569.601	1.086.515	1.111.169	723.273	720.512	717.061	940.343	1.109.761	1.244.009	1.904.456	1.877.179	16.313.929
ALMERIA	6.306.756	5.964.929	6.065.259	4.906.958	3.291.672	3.213.116	3.930.994	4.703.570	4.151.806	4.406.405	5.762.813	4.695.167	5.622.006	63.021.451
AVILES	3.082.731	3.615.486	3.451.464	3.114.668	2.293.135	2.746.802	3.297.196	3.393.152	2.797.247	3.012.751	3.260.161	2.920.900	2.874.981	39.860.675
BAHIA DE ALGECIRAS	2.652.263	2.708.226	2.679.852	1.588.521	1.743.479	1.475.224	1.563.349	1.955.220	1.597.565	1.603.174	2.130.519	1.778.840	1.942.451	25.418.683
BAHIA DE CADIZ	2.557.442	2.699.354	4.405.625	2.117.801	1.636.990	1.687.143	1.851.089	1.815.381	1.867.533	1.776.315	1.623.696	1.763.516	1.747.593	27.549.478
BALEARES	2.318.339	2.188.436	2.314.781	2.130.632	1.689.471	1.859.831	1.643.380	1.623.778	1.309.549	1.319.455	1.215.735	1.550.899	1.610.653	22.774.939
BARCELONA	4.051.927	4.107.582	3.870.253	3.506.472	3.921.099	3.542.218	3.544.297	4.685.744	4.373.720	4.764.706	4.426.087	4.430.798	4.465.644	53.690.547
BILBAO	4.261.127	5.524.178	5.832.384	5.266.459	3.827.983	4.451.915	4.000.342	4.261.691	4.421.587	4.593.976	4.528.219	4.362.064	4.543.171	59.875.096
CARTAGENA	5.082.060	5.173.022	5.371.083	4.628.556	3.615.556	3.114.236	3.653.775	4.880.341	4.519.222	5.308.274	5.554.193	5.304.817	5.820.153	62.025.288
CASTELLON	3.293.591	3.590.891	3.902.855	4.017.009	1.865.858	2.941.178	3.244.831	3.114.303	3.102.799	4.192.762	4.636.911	5.198.982	6.463.715	49.565.685
CEUTA	71.229	66.793	75.637	71.772	68.226	141.410	142.108	150.350	63.426	32.645	25.625	22.249	21.900	953.370
FERROL-SAN CIBRAO	8.289.621	8.709.257	8.726.704	9.781.089	9.268.088	7.435.083	8.685.748	10.505.475	8.999.195	9.498.616	9.839.879	9.406.039	10.455.814	119.600.608
GIJON	19.658.167	18.298.185	18.305.091	16.869.645	12.456.055	13.401.423	12.573.625	14.482.418	14.947.162	16.218.571	18.905.283	16.023.647	19.192.104	211.331.376
HUELVA	7.512.508	7.394.282	7.603.640	6.525.092	4.180.685	5.394.260	4.502.005	4.830.967	4.145.909	4.662.814	5.137.350	5.759.383	6.487.394	74.136.289
LAS PALMAS	1.772.615	1.678.836	1.615.745	1.139.545	753.111	738.740	524.432	375.490	364.102	477.533	483.909	534.113	500.380	10.958.551
MALAGA	2.100.473	1.953.430	1.603.906	1.342.750	766.796	772.746	893.662	782.253	868.836	1.095.103	1.370.093	1.748.149	1.675.098	16.973.295
MARIN	1.016.241	891.966	937.575	847.406	879.867	960.542	853.558	805.966	826.305	853.972	998.817	1.047.281	915.820	11.835.315
MELILLA	84.427	45.826	51.655	34.112	32.782	43.257	33.395	20.779	9.000	6.815	3.425	5.825	7.372	378.670
MOTRIL	1.246.697	1.172.380	973.264	756.864	453.149	473.242	608.379	547.036	479.197	430.807	452.358	451.149	404.311	8.448.833
PASAIA	3.281.138	3.248.288	2.778.170	2.351.378	1.649.664	1.655.965	1.246.600	1.419.971	1.212.240	1.509.001	1.694.292	1.099.170	834.439	23.980.316
STA. CRUZ DE TENERIFE	1.892.082	1.986.964	1.716.058	1.352.468	848.311	818.565	782.167	567.440	488.158	437.559	406.750	414.999	413.555	12.125.076
SANTANDER	5.139.652	4.164.897	4.374.837	3.732.466	2.919.749	2.879.604	3.060.049	3.236.676	2.988.773	3.189.256	3.518.578	2.823.113	3.428.750	45.456.400
SEVILLA	2.788.885	2.827.598	2.343.706	2.344.193	2.421.146	2.133.427	1.997.898	1.813.175	1.824.074	1.739.610	2.073.690	2.250.277	2.201.621	28.759.300
TARRAGONA	11.903.296	11.237.751	13.626.199	12.420.882	9.830.390	9.452.166	9.279.089	10.888.789	7.375.070	9.708.015	8.391.029	9.065.474	9.515.688	132.693.838
VALENCIA	6.360.690	7.148.231	7.322.671	5.165.374	3.523.706	2.591.139	2.374.045	2.177.058	2.444.573	2.680.192	2.684.864	2.531.577	2.278.857	49.282.977
VIGO	692.535	701.899	632.226	458.180	381.302	459.139	433.320	303.132	289.478	299.331	287.939	234.910	261.609	5.435.000
VILAGARCIA	578.235	613.257	570.068	506.221	488.175	409.144	339.355	346.675	202.966	323.047	403.439	320.553	421.100	5.522.236
TOTAL TONS OF SOLID BULK	**114.100.059**	**113.450.097**	**116.860.986**	**101.352.636**	**79.133.203**	**78.706.369**	**79.250.195**	**88.583.662**	**80.298.003**	**89.560.973**	**95.972.002**	**91.993.448**	**101.040.382**	**1.230.302.015**

Annual evolution of solid bulk cargo in Spain by Authority Port in tons (2005-2017). Source: Puertos del Estado

B. QUEUING THEORY FORMULAS

M/M/1 Queuing System Formulas

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

$$P_n = (1-\rho) \cdot \rho^n$$

$$P_0 = 1 - \rho$$

$$L = \frac{\rho}{1-\rho} = \frac{\lambda}{\mu - \lambda}$$

$$L_q = \frac{\lambda^2}{\mu \cdot (\mu - \lambda)} = \frac{\rho^2}{1-\rho}$$

$$W = \frac{L}{\lambda} = \frac{1}{\mu - \lambda}$$

$$W_q = \frac{\rho}{\mu - \lambda}$$

$$\eta = \frac{\rho}{1-\rho}$$

$$P(n \geq X) = \rho^X$$

$$P(W > t) = e^{-\mu(1-\rho)t}$$

$$P(W_q > t) = \rho \cdot e^{-\mu(1-\rho)t}$$

$$P(X = x) = \frac{\lambda^X}{x!} \cdot e^{-\lambda}$$

$$P(X = x) = \mu \cdot e^{-\mu x}$$

M/M/c Queuing System Formulas

$$r = \frac{\lambda}{\mu}$$

$$\rho = \frac{\lambda}{c \cdot \mu}$$

$$P_n = \begin{cases} \frac{\lambda^n}{n!\,\mu^n} \cdot P_0, & l \leq n < c \\ \frac{\lambda^n}{c^{n-c} \cdot c! \cdot \mu^n} \cdot P_0, & n \geq c \end{cases}$$

$$P_0 = \left(\sum_{n=0}^{c-1} \frac{r^n}{n!} + \frac{r^c}{c!\,(1-p)}\right)^{-1} = \frac{1}{\sum_{n=0}^{c-1} \frac{(\frac{\lambda}{\mu})^n}{n!} + \frac{(\frac{\lambda}{\mu})^c}{c!} \cdot \left(\frac{1}{1-(\frac{\lambda}{c\mu})}\right)}, \rho < 1$$

$$L = r + \left(\frac{r^c \cdot \rho}{c! \cdot (1-\rho)^2}\right) \cdot P_0$$

$$L_q = \frac{r^c \cdot \rho}{c! \cdot (1-\rho)^2} \cdot P_0 = \frac{\left(\frac{\lambda}{\mu}\right)^{c+1}}{(c-1)! \cdot (c-\frac{\lambda}{\mu})^2} \cdot P_0$$

$$W = W_q + \frac{1}{\mu} = \frac{1}{\mu} + \left(\frac{r^c}{c!\,(c\mu)(1-\rho)^2}\right) \cdot P_0$$

$$W_q = \frac{L_q}{\lambda} = \left(\frac{r^c}{c!\,(c\mu)(1-\rho)^2}\right) \cdot P_0$$

$$C(c,r) = \frac{r^c}{c!\,(1-\rho)} \cdot P_0 = \frac{\frac{r^c}{c!\,(1-\rho)}}{\sum_{n=0}^{c-1} \frac{r^n}{n!} + \frac{r^c}{c!\,(1-\rho)}}$$

M/D/1 Queuing System Formulas

$$L = \rho + \frac{1}{2}\left(\frac{\rho^2}{1-\rho}\right)$$

$$Lq = \frac{1}{2}\left(\frac{\rho^2}{1-\rho}\right)$$

$$W = \frac{1}{\mu} + \frac{\rho}{2\mu(1-\rho)}$$

$$W_q = \frac{\rho}{2\mu(1-\rho)}$$

Relationships between random variables

$$L = \lambda \cdot W$$

$$Lq = \lambda \cdot Wq$$

$$W = Wq + \frac{1}{\mu}$$

$$r = L - Lq = \lambda \cdot (W - Wq) = \frac{\lambda}{\mu}$$

$$Lq = L - (1 - P_0)$$

C. CHARACTERISTICS OF THE VESSELS SERVED IN PORTCEMEN TERMINAL IN 2015

IMO	Name_of_Ship	Built	Ship_Type	Deadweight (dwt)	Bale (m^3)	Grain (m^3)	Depth (m)	Draught (m)	Holds (units)	Length (m)	Beam (m)
9397652	ALBIZ	2008-11	General Cargo Ship	5750	0	7249	8	6,2	1	99,9	16
9460514	AMSTEL FALCON	2013-06	Bulk Carrier	56108	69924	71657	17,87	12,569	5	189,99	32
9406805	AN PING	2009-02	Bulk Carrier	55259	66966	69452	17,8	12,522	5	189,9	32
9362669	ANJA C	2006-07	General Cargo Ship	8099	10140	10251	9	6,99	3	108,16	18
9087673	APOLLO LYNUX	1994-02	General Cargo Ship	8189	12972	14288	13,4	7,809	2	100,72	19
9169330	AQUATA	1999-01	Bulk Carrier	46685	58135	59830	16,1	11,36	5	187,3	32
9638783	ARKLOW BEACH	2014-07	General Cargo Ship	8660	9003	9903	0	7,186	2	119,49	15
9494747	ATLANTIC LAUREL	2012-03	Bulk Carrier	33271	40638	41897	13,9	9,77	5	178,41	29
9346689	BLUE ANTARES	2008-04	General Cargo Ship	4450	0	5818	7,85	5,85	1	89,95	15
9274575	CARDINAL	2004-07	Bulk Carrier	55408	68798	69872	17,62	12,486	5	189,99	32
9423530	COLUMBIA	2009-04	Bulk Carrier	58701	70557	72360	18	12,828	5	189,99	32
9216602	DIMITRIOS K	2001-09	General Cargo Ship	24765	29590	30552	13,65	9,6	5	175,64	23
9394222	DON JUAN	2007-04	Bulk Carrier	21057	0	26631	12,5	8,6	4	157,9	23
9230763	DORIC SPIRIT	2001-10	Bulk Carrier	52428	65600	67756	17	12,02	5	190	32
9577446	ELINA B	2011-01	Bulk Carrier	58551	70734	75531	18,6	13	5	196	32
9229697	EQUINOX SEAS	2003-04	Bulk Carrier	52009	63249	64935	17	12,27	5	189,99	32
9697844	FEDERAL BRISTOL	2015-10	Bulk Carrier	34564	41498	41651	14,85	10,857	6	199,98	23
9566447	FUTURE LILY	2012-06	Bulk Carrier	56128	68733	71345	18,1	12,715	5	189,99	32
9490832	GENCO RHONE	2011-03	Bulk Carrier	57970	69760	71549	18	12,95	5	189,99	32
9116448	GLORY OCEAN	1996-04	Cement Carrier	16061	0	13600	12,2	9,16	8	138,79	22
9312717	GOMERA	2006-06	General Cargo Ship	5698	0	7563	8,1	6,14	0	106,15	15
9325099	GRIKOS	2006-06	Bulk Carrier	29828	38422	40031	13,8	9,716	5	170,7	27
9224673	HALIL SAHIN	2001-06	Bulk Carrier	48377	60053	61782	16,55	11,69	5	187,3	32
9514200	IONIC SPIRIT	2010-04	Bulk Carrier	56108	68733	71345	18,1	12,715	5	189,99	32

9420277	KACEY	2009-06	Bulk Carrier	55522	66368	69450	17,8	12,53	5	189,9	32
9236822	KANG FU	2002-04	Bulk Carrier	51069	64000	65252	16,67	11,89	5	189,99	32
9558048	KITTY C	2011-08	General Cargo Ship	6798	0	8450	8,14	6,63	2	106,07	16
9214733	LAIDA	2003-02	General Cargo Ship	5604	0	7249	8	6,196	2	99,9	16
9397640	MUROS	2008-05	General Cargo Ship	4950	6074	6074	7,35	6,27	1	89,9	14
9064281	NACC VALBELLA	1992-12	Cement Carrier	9146	0	8068	10	7,712	2	113,5	18
9454814	NARWA	2009-01	General Cargo Ship	6050	0	8500	8,1	6,04	2	114,4	14
9237137	NAVIOS MERIDIAN	2002-08	Bulk Carrier	50316	60713	63198	16,9	11,93	5	189,8	32
9454802	ODER	2008-08	General Cargo Ship	6050	0	8501	8,1	6,04	2	114,4	14
9196395	PAGONA	1999-07	Bulk Carrier	27797	34926	36255	13,8	9,67	5	169,03	27
9460320	PANOCEANIS	2007-11	Bulk Carrier	53562	65526	68927	17,3	12,303	5	189,9	32
9117313	PARASKEVI	1996-05	Bulk Carrier	45950	54621	57600	15,8	11,103	5	189,95	32
9588536	PATMOS JOHN	2011-11	Bulk Carrier	56633	68200	71634	18	12,8	5	189,96	32
9223174	PRETTY LADY	2001-03	Bulk Carrier	50169	60713	63216	16,907	11,925	5	189,8	32
9338125	SDS WIND	2005-10	General Cargo Ship	7600	10255	10255	9	7,01	3	108,2	18
9525821	SFL HUDSON	2009-08	Bulk Carrier	56836	68200	71634	18	12,8	5	189,94	32
9485930	SHELDUCK	2012-03	Bulk Carrier	34467	46815	48766	14,7	9,9	5	180	30
9539444	SKALA	2012-06	Bulk Carrier	33628	43164	44039	14,3	10,101	5	179,99	29
9375147	SOMERS ISLES	2012-05	General Cargo Ship	4800	0	6480	8,85	5,85	0	99,97	16
9436276	SUA	2009-09	General Cargo Ship	6797	0	0	8,3	6,28	2	119,27	16
9213739	VARNEBANK	2000-10	General Cargo Ship	8727	0	12855	9,65	7,05	2	132,23	16
9483279	VENTURE PEARL	2012-08	Bulk Carrier	55639	69550	70733	18,3	12,868	5	187,88	32
9454838	WARNOW	2009-06	General Cargo Ship	6050	0	8501	8,1	6,04	2	114,4	14
9566423	XIN RUI HAI	2012-10	Bulk Carrier	56092	68000	70811	18,1	12,73	5	189,99	32

Characteristics of the vessels served in Portcemen Terminal in 2015. Source: Sea-Web and Marinetraffic

D. IMAGES OF THE VESSELS SERVED IN PORTCEMEN TERMINAL IN 2015

In this Appendix details of bulk ships are presented. Several ship registers classify bulk ships in several classes. To give an idea about the sizes of the bulk ships per class, for each class a picture of a bulk ship is presented. The values of their characteristics were determined using the data base of Sea-web (http://www.sea-web.com). Vessels are sorted alphabetically.

Picture 1. ALBIZ - 9397652

Picture 2. AMSTEL FALCON - 9460514

Picture 3. AN PING - 9406805

Picture 4. ANJA C - 9362669

Picture 5. APOLLO LYNUX - 9087673

Picture 6. AQUATA - 9169330

Picture 7. ARKLOW BEACH - 9638783

Picture 8. ATLANTIC LAUREL - 9494747

Picture 9. BLUE ANTARES - 9346689

Picture 10. CARDINAL - 9274575

Picture 11. COLUMBIA - 9423530

Picture 12. DIMITRIOS K - 9216602

Picture 13. DON JUAN - 9394222

Picture 14. DORIC SPIRIT - 9230763

Picture 15. ELINA B - 9577446

Picture 16. EQUINOX SEAS - 9229697

Picture 17. FEDERAL BRISTOL - 9697844

Picture 18. FIORIANO – SOMERS ISLES - 9375147

Picture 19. FORCE RANGER – PARASKEVI - 9117313

Picture 20. FUTURE LILY - 9566447

Picture 21. GENCO RHONE - 9490832

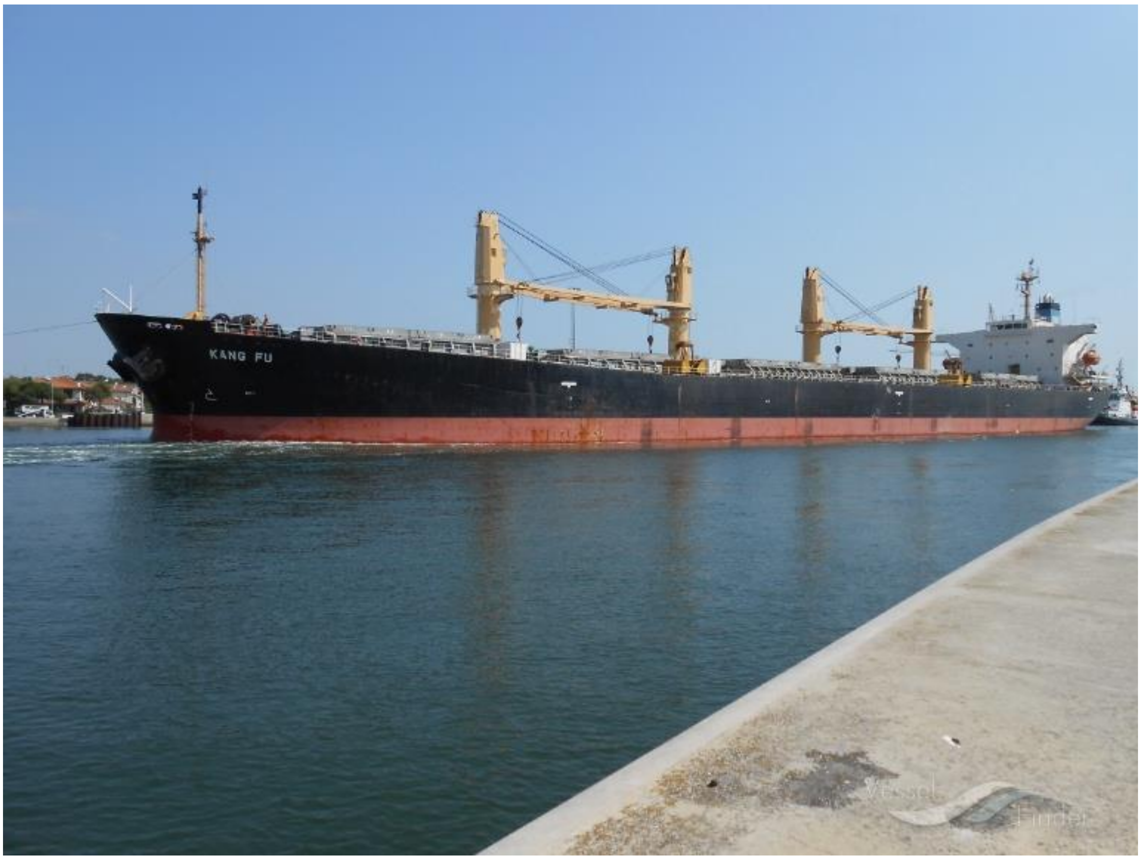
Picture 22. GLORY OCEAN - 9116448

Picture 23. GOMERA - 9312717

Picture 24. GRIKOS - 9325099

Picture 25. HALIL SAHIN - 9224673

Picture 26. KACEY - 9420277



Picture 27. KANG FU - 9236822

Picture 28. KITTY C - 9558048

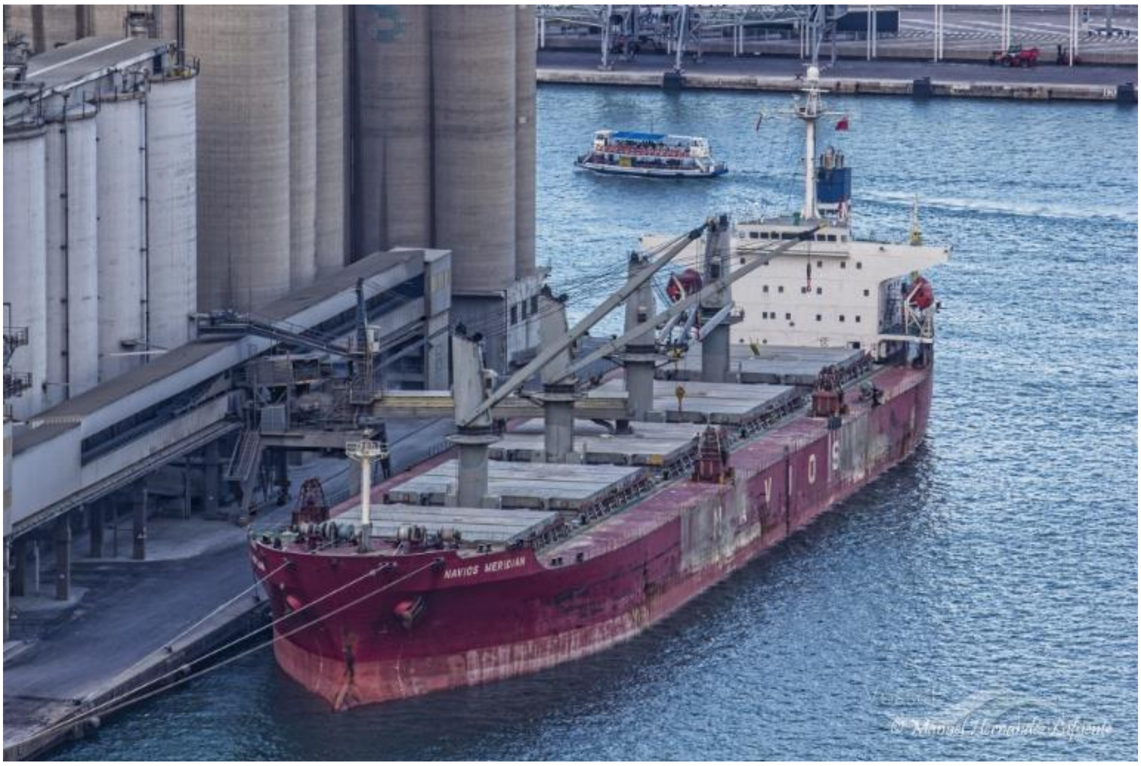
Picture 29. LAIDA - 9214733

Picture 30. MARLOWE - 8626379

Picture 31. MUROS - 9397640

Picture 32. MV IONIC SPIRIT - 9514200

Picture 33. NARWA - 9454814



Picture 34. NAVIOS MERIDIAN - 9237137

Picture 35. ODER - 9454802

Picture 36. PAGONA - 9196395

Picture 37. PANOCEANIS - 9460320

Picture 38. PORTOROZ – PATMOS JOHN - 9588536

Picture 39. PRETTY LADY - 9223174

Picture 40. SDS WIND - 9338125

Picture 41. SFL HUDSON - 9525821

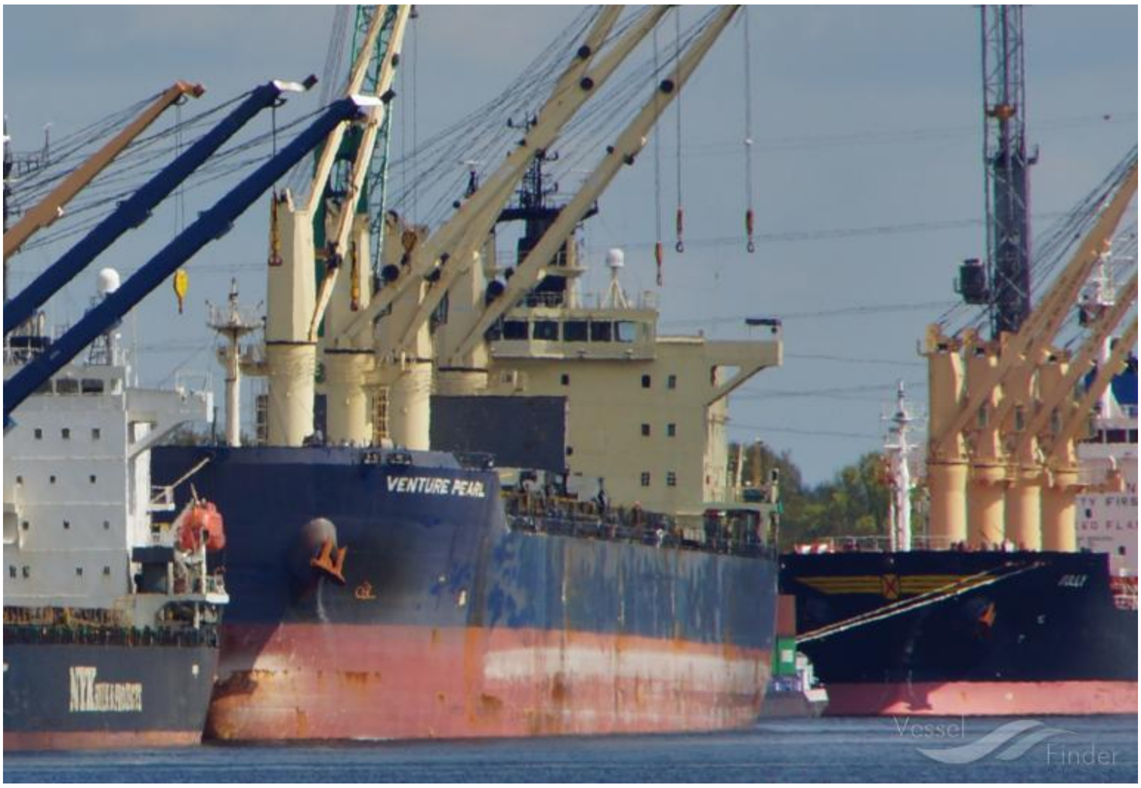
Picture 42. SHELDUCK - 9485930

Picture 43. SKALA - 9538444

Picture 44. SUA - 9436276

Picture 45. VALBELLA - 9064281

Picture 46. VARNEBANK - 9213739



Picture 47. VENTURE PEARL - 9483279

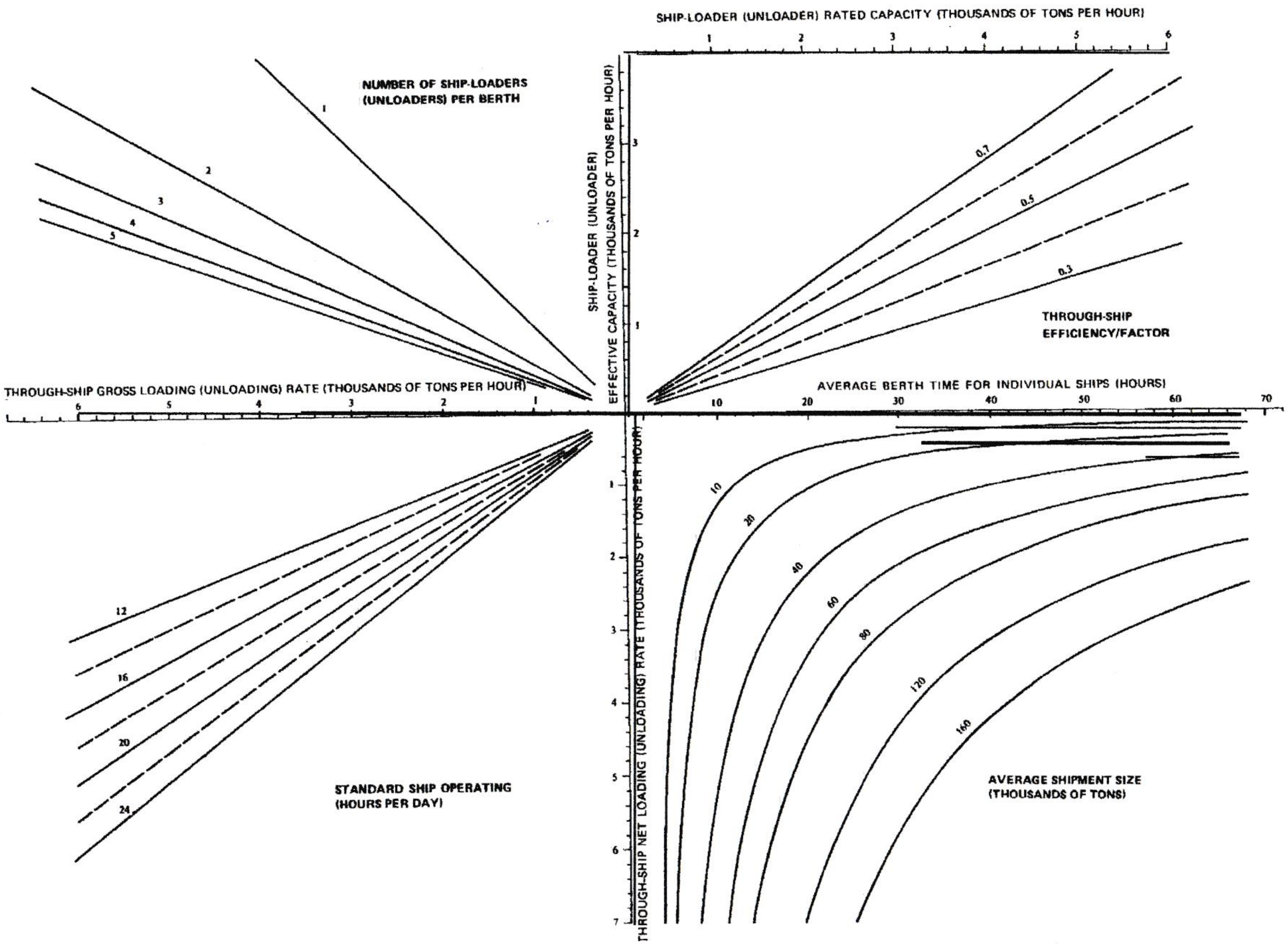
Picture 48. WARNOW - 9454838

Picture 49. XIN RUI HAI - 9566423

E. DRY BULK CARGO TERMINAL, PLANNING CHARTS

FIGURE 48

Dry bulk cargo terminal, planning chart I: berth time



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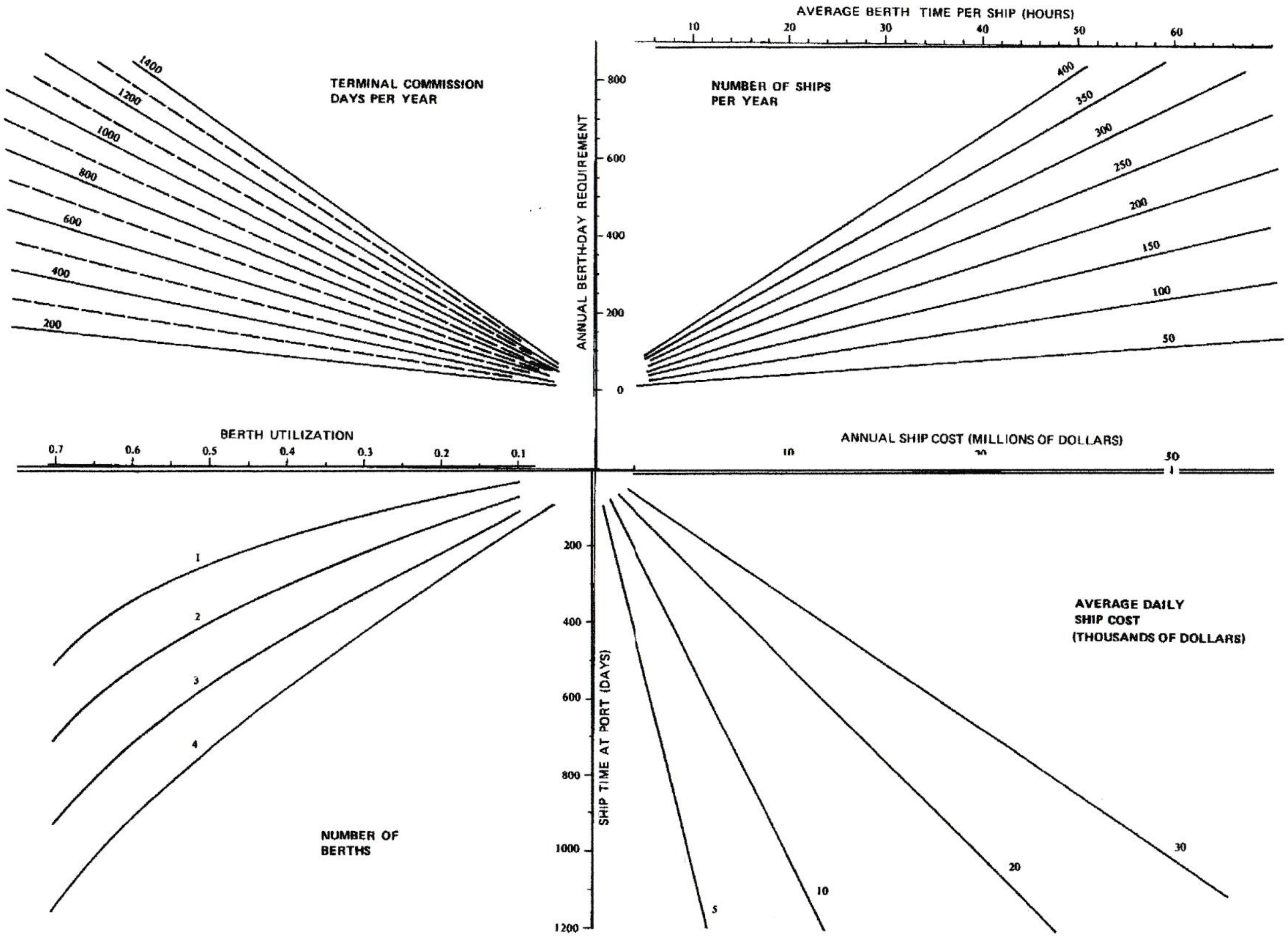
Dry bulk cargo terminal, planning chart I: berth time. Source: Port development by UNCTAD

FIGURE 49

Dry bulk cargo terminal, planning chart II: ship cost



Dry bulk cargo terminal, planning chart II: ship cost. Source: Port development by UNCTAD

F. TABLES OF SMIRNOV-KOLMOGOROV TEST

ESTADÍSTICA II 28.

Tabla 8

Test de Kolmogorov-Smirnov sobre Bondad de Ajuste

	Nivel de significación α							
n	**0.20**	**0.10**	**0.05**	**0.02**	**0.01**	**0.005**	**0.002**	**0.001**
1	0.90000	0.95000	0.97500	0.99000	0.99500	0.99750	0.99900	0.99950
2	0.68337	0.77639	0.84189	0.90000	0.92929	0.95000	0.96838	0.97764
3	0.56481	0.63604	0.70760	0.78456	0.82900	0.86428	0.90000	0.92065
4	0.49265	0.56522	0.62394	0.68887	0.73424	0.77639	0.82217	0.85047
5	0.44698	0.50945	0.56328	0.62718	0.66853	0.70543	0.75000	0.78137
6	0.41037	0.46799	0.51926	0.57741	0.61661	0.65287	0.69571	0.72479
7	0.38148	0.43607	0.48342	0.53844	0.57581	0.60975	0.65071	0.67930
8	0.35831	0.40962	0.45427	0.50654	0.54179	0.57429	0.61368	0.64098
9	0.33910	0.38746	0.43001	0.47960	0.51332	0.54443	0.58210	0.60846
10	0.32260	0.36866	0.40925	0.45562	0.48893	0.51872	0.55500	0.58042
11	0.30829	0.35242	0.39122	0.43670	0.46770	0.49539	0.53135	0-55588
12	0.29577	0.33815	0.37543	0.41918	0.44905	0.47672	0.51047	0.53422
13	0.28470	0.32549	0.36143	0.40362	0.43247	0.45921	0.49189	0.51490
14	0.27481	0.31417	0.34890	0.38970	0.41762	0.44352	0.47520	0.49753
15	0.26589	0.30397	0.33750	0.37713	0.40420	0.42934	0.45611	0.48182
16	0.25778	0.29472	0.32733	0.36571	0.39201	0.41644	0.44637	0.46750
17	0.25039	0.28627	0.31796	0.35528	0.38086	0.40464	0.43380	0.45540
18	0.24360	0.27851	0.30936	0.34569	0.37062	0.39380	0.42224	0.44234
19	0.23735	0.27136	0..30143	0.33685	0.36117	0.38379	0.41156	0.43119
20	0.23156	0.26473	0.29408	0.32866	0.35241	0.37451	0.40165	0.42085
21	0.22517	0.25858	0.28724	0.32104	0.34426	0.36588	0.39243	0.41122
22	0.221I5	0.25283	0.28087	0.31394	0.33666	0.35782	0.38382	0.40223
23	0.21646	0.24746	0.2749tl	0.30728	0.32954	0.35027	0.37575	0.39380
24	0.21205	0.24242	0.26931	0.30104	0.32286	0.34318	0.36787	0.38588
25	0.20790	0.23768	0.26404	0.29518	0.31657	0.33651	0.36104	0.37743
26	0.20399	0.23320	0.25908	0.28962	0.30963	0.33022	0.35431	0.37139
27	0.20030	0.22898	0.25438	0.28438	0.30502	0.32425	0.34794	0.36473
28	0.19680	0.22497	0.24993	0.27942	0.29971	0.31862	0.34190	0.35842
29	0.19348	0.22117	0.24571	0.27471	0.29466	0.31327	0.33617	0.35242
30	0.19032	0.21756	0.24170	0.27023	0.28986	0.30818	0.33072	0.34672
31	0.18732	0.21412	0.23788	0.26596	0.28529	0.30333	0.32553	0.34129
32	0.18445	0.21085	0.23424	0.26189	0.28094	0.29870	0.32058	0.33611
33	0.18171	0.20771	0.23076	0.25801	0.27577	0.29428	0.31584	0.33115
34	0.17909	0.21472	0.22743	0.25429	0.27271	0.29005	0.31131	0.32641
35	0.17659	0.20185	0.22425	0.25073	0.26897	0.28600	0.30597	0.32187
36	0.17418	0.19910	0.22119	0.24732	0.26532	0.28211	0.30281	0.31751
37	0.17188	0.19646	0.21826	0.24404	0.26180	0.27838	0.29882	0.31333
38	0.16966	0.19392	0.21544	0.24089	0.25843	0.27483	0.29498	0.30931
39	0.16753	0.19148	0.21273	0.23785	0.25518	0.27135	0.29125	0.30544

	Nivel de significación α							
n	**0.20**	**0.10**	**0.05**	**0.02**	**0.01**	**0.005**	**0.002**	**0.001**
40	0.16547	0.18913	0.21012	0.23494	0.25205	0.26803	0.28772	0.30171
41	0.16349	0.18687	0.20760	0.23213	0.24904	0.26482	0.28429	0.29811
42	0.16158	0.18468	0.20517	0.22941	0.24613	0.26173	0.28097	0.29465
43	0.15974	0.18257	0.20283	0.22679	0.24332	0.25875	0.27778	0.29130
44	0.15795	0.18051	0.20056	0.22426	0.24060	0.25587	0.27468	0.28806
45	0.15623	0.17856	0.19837	0.22181	0.23798	0.25308	0.27169	0.28493
46	0.15457	0.17665	0.19625	0.21944	0.23544	0.25038	0.26880	0.28190
47	0.15295	0.17481	0.19420	0.21715	0.23298	0.24776	0.26600	0.27896
48	0.15139	0.17301	0.19221	0.21493	0.23059	0.24523	0.26328	0.27611
49	0.14987	0.17128	0.19028	0.21281	0.22832	0.24281	0.26069	0.27339
50	0.14840	0.16959	0.18841	0.21068	0.22604	0.24039	0.25809	0.27067
***n* > 50**	$\frac{1.07}{\sqrt{n}}$	$\frac{1.22}{\sqrt{n}}$	$\frac{1.36}{\sqrt{n}}$	$\frac{1.52}{\sqrt{n}}$	$\frac{1.63}{\sqrt{n}}$	$\frac{1.73}{\sqrt{n}}$	$\frac{1.85}{\sqrt{n}}$	$\frac{1.95}{\sqrt{n}}$