Vasileios Ntriankos

Optimising the yard layout of Container Terminals

The Port of Thessaloniki case

Report for the course CIE5050-09
"Additional Graduation Work, Research Project"

TU Delft Delft University of Technology

Challenge the future

Optimising the yard layout of Container Terminals

The Port of Thessaloniki case

By

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Report for the course CIE 5050-09
"Additional Graduation Work, Research Project"

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Preface

This research project is performed as a part of my studies in the Master of Science in Hydraulic Engineering at Delft University of Technology, following the course CIE 5050-09 "Additional Graduation Work, Research Project", a ten-week project at the level of MSc-Thesis. The aim of the study is to understand the operation of a container terminal and to develop a simplified theory to optimise the layout of its stacking yard. The project uses the container terminal of the port of Thessaloniki as a case study and comes up with a proposition to optimise the seaside part of the yard considering the cycle time of straddle carriers when serving the quay cranes.

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Abstract

Over the last decades, containerisation became the major way to transport discrete goods replacing a part of general cargo trade and facing the increasing consumer demand of developed and developing world. As a result, container terminals became an important part of a lot of ports worldwide while new technology was developed to encounter the increasing requirements for the operation of container terminals.

A container terminal has a quite complicated operation as different kind of equipment and people need to cooperate under a strict timeline that does not tolerate mistakes. The optimisation of a container terminal can be achieved by adjusting different parameters concerning different areas or equipment of the terminal. In this project, the arrangement of the yard layout is analysed focusing on a straddle carrier operation. The comparison criterion is the mean maximum travelling distance that a straddle carrier needs to travel for a seaside job cycle, serving the quay cranes.

Considering a rectangular layout, making reasonable assumptions and using simple mathematical relations, the travelling distance of straddle carriers from stacking blocks to the quay is modelled and a proposition to minimise this distance is developed. Then, assuming the speed of straddle carriers for the different areas they move, the mean maximum travelling time for a job cycle is determined. The theory is applied for the container terminal of the port of Thessaloniki in Greece and a rearrangement for its layout is proposed.

Using simple mathematics, for a simple yard layout, it is possible to propose changes that, for the port of Thessaloniki, can decrease the travelling time of straddle carriers up to 10%. This result is very sensitive to the assumptions of the driving strategy that straddle carriers follow and to the pooling strategy that is applied for the stacking yard operation.

1 Introduction

Containerisation appeared over a century ago, but its great development started in late 1960s and continued rapidly because of the great advantages it offers in the commercial transportations. In 2018 the container world trade reached 148 million TEUs, 17.1% of total seaborne trade in tons [4]. The main advantages of containerisation are time saving, labour cost saving, safety of goods, security and damage reduction and the ability to create a larger scale of economy, with bigger vessels and larger terminals [1]. These advantages have as a result a much lower transport cost and a much lower handling time in port terminals compared to general cargo trade. This is why containers gain continuously a larger share in transportation trade and today they are the main way to transport discrete goods.

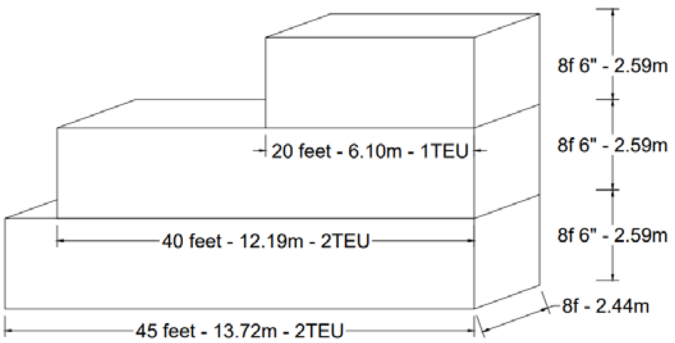


Figure 1 - Dimensions of typical containers

There are two main types of containers regarding their length: The 20feet and the 40feet standard type. However, there are also containers with different length like 30feet or 45feet. The width of the containers is standardized to 8feet. The height of the containers is not so standard and varies at around 8feet and 6inches. In addition to the standard "dry" containers, there are refrigerated containers (reefers), tank containers, open-top containers and other types of containers to serve special needs in transportation of goods. The most common unit to measure the number of containers is the Twenty-foot Equivalent Unit (TEU), corresponding to a 20feet long container.

The global container logistic chain follows a strict schedule on sailing and dwell time of the ships. Container terminals try to become more efficient and reliable by decreasing the waiting, unloading and loading time to attract more clients. Another aspect that terminals try to follow is the growing ships' size as shipping companies try to decrease the transportation cost and increase the speed of transporting goods. This trend makes container terminals consider the optimisation of their function by increasing the productivity of their different areas as well as the sufficient cooperation among them.

The container terminal of the port of Thessaloniki is a medium size container terminal with a throughput of almost 450.000 TEUs in 2019. It provides a gateway for containerised transportation from all over the world to Greece and to the whole Balkan Peninsula. The terminal already counts 31 years of full operation and it is currently planned an expansion to provide the available yard space and quay length to double its throughput.

The Thessaloniki's container terminal uses straddle carriers for the horizontal transportation of the containers from the apron area to the stacking yard, for the stacking yard arrangement and for loading and unloading trucks.

The research question of this report is what is the optimum location of a traffic lane in a rectangular part of a straddle carrier yard to minimise the distance (and thus travel time) that straddle carriers need to cover during a ship loading/unloading operation. After making some assumptions, the travelling distance from each block to each quay crane is described mathematically and then is minimised in terms of the position of the traffic lane. Finally, this theory is applied for the port of Thessaloniki and a layout rearrangement is proposed.

2 Container Terminals and yard operations

2.1 The layout of Container Terminals

The purpose of a container terminal is to transfer containerised cargo between ships and hinterland. Before berthing, an unloading and loading plan of the ship has already been agreed between the captain and the terminal operator. After berthing, containers are unloaded from the ship and then transferred by special equipment to be stored. Containers are recognised by their unique ID number and are located in a specific slot in the stacking yard. Then they are loaded to trucks, trains or inland vessels or even back to another sea vessel (for transhipment cargo) and continue their transportation till their last destination. The opposite procedure is followed for loading a ship as containers enter the terminal, stored in the stacking yard and then transferred to the quay and loaded on ships. An important stage in this procedure is the gate of the terminal, where containers are registered before entering or exiting the terminal [6].

In container handling there are a lot of different actors who need to collaborate for the efficient cargo transportation from one destination to another. Shipping companies, port authorities and terminal operators (sometimes they are the same), hauliers of the containers in hinterland and end clients set up the containers' logistic chain. Each actor has different interests and cares about different aspects. However, time and cost efficiency are the major leading factors of the container logistic chain. In some cases, to decrease the cost and increase the efficiency of this chain, big companies of alliances that handle several links of the chain together are formed, like APM-Maesk Group, MSC, COSCO, etc.

A container terminal consists of three basic areas which are schematised in figure 2 in the next page:

- The "apron area" or the seaside area where the quay is located together with the Ship-To-Shore (STS) cranes. In this area the loading and unloading of the ship takes place as well as the horizontal transport of containers. The apron area serves also the vehicles that support the ship, like provisioning supplies, bunkering if this is not offered by another ship, gangway for ship to shore connection, etc. In this area, right under the landside part of the cranes, there is the personnel who is responsible to handle the twistlocks of the containers, a procedure that is still difficult to be automated.
- The second area is the "storage area" or stacking yard of the terminal. This is the basic storage area for containers where they are stacked waiting for the loading and unloading procedures. This area needs to provide special facilities for reefers, the containers with an equipment to keep the temperature stable inside them, with electricity supply. It also provides space for "special" containers like dangerous cargo containers, containers that need to be checked by authorities, empties (empty containers), etc.
- The third basic area of the terminal is the landside area. In this area containers enter or exit via a specific gate and they are transported by trucks or railway to/from hinterland [1]. In this area there are all kinds of necessary facilities for the proper operation of the terminal, like gate facilities, workshop's buildings, offices, custom facilities, electricity station, etc.

The level of service provided by the terminal is a combination of the productivity of the terminal, mainly depended on quay productivity that defines the service time, the reliability of the terminal and the flexibility for last minutes changes [6]. There are different Key Performance Indicators of the service level, such as the berth productivity (TEU/hour), the annual throughput per meter quay (TEU/m/year), the yard density (TEU/ha), the annual throughput per equipment unit (moves/year). There are also financial indicators like the cost of operation (€/TEU) of the container terminal [8]. The overall performance of the terminal is based on the performance of every different procedure that takes place in it and on the level of connection and collaboration between them. Depending on the specific procedure of the terminal that is optimised, different performance indicators may be applied.

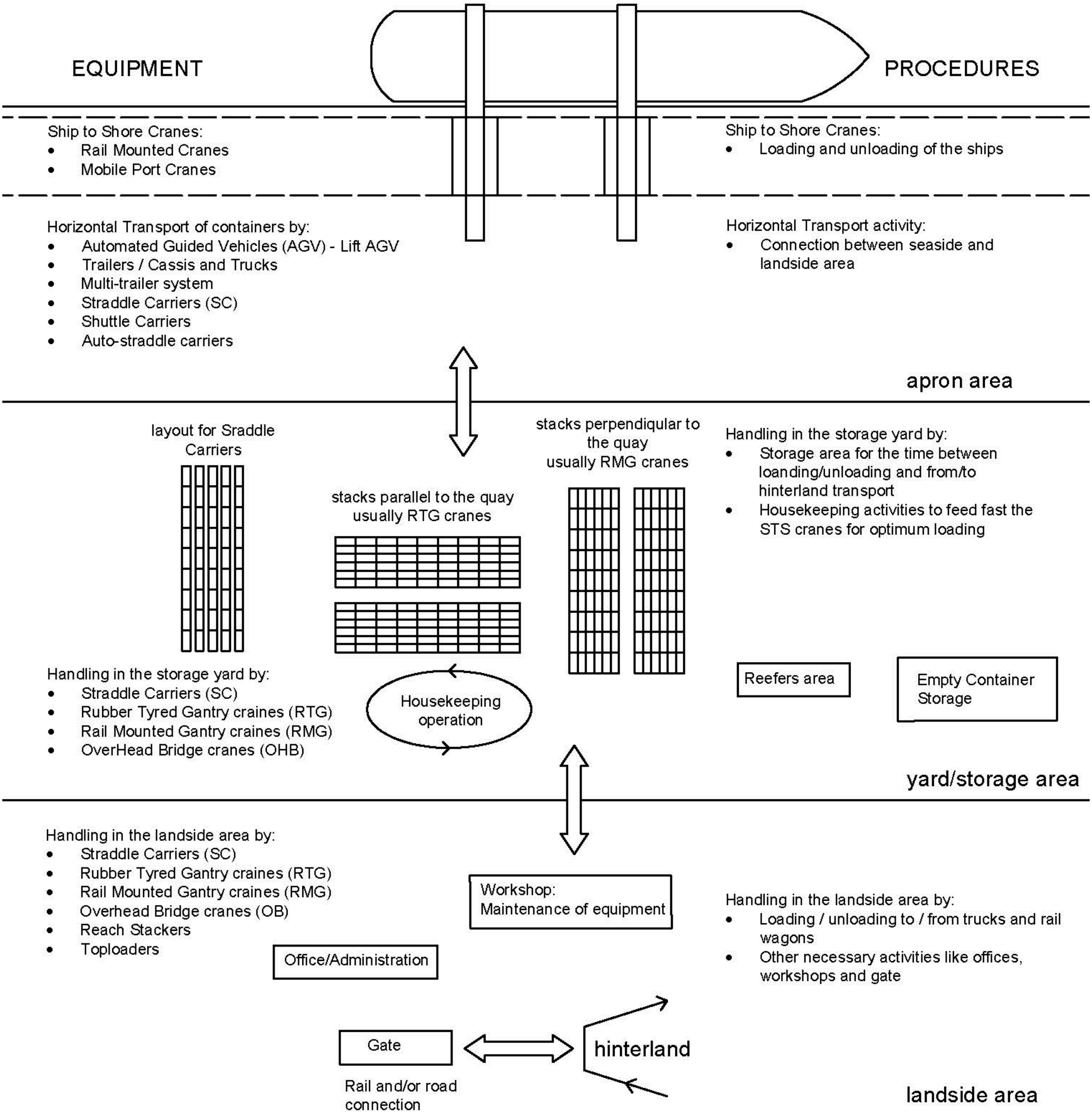


Figure 2 - General Plan of a Container Terminal with the purpose of different areas and equipment

2.2 The equipment of Container Terminals

Containerisation is a standardised way of transporting discrete cargo that gains more and more share in world transporting of goods. The increasing volumes together with the standardisation of containers led to the development of a variety of different kind of specialised equipment to handle containers through every procedure that takes place in the container terminal.

For the loading and unloading of the ship, special cranes have been developed to be used on the quay. The purpose of these cranes is to transfer the container from the ship to the apron area and vice versa. The most common cranes that can reach high productivity levels are STS cranes. STS cranes are rail mounted gantry cranes that can load and unload up to 4 TEUs in one movement depending on their design and may have the ability to separate the loading and unloading of the ship with the loading and unloading of the Horizontal Transport Vehicles (HTVs) by having two different trolleys. When the throughput volume is lower or when flexibility is necessary to handle peaks, Mobile Harbour Cranes (MHC) can also be used as quay cranes in a container terminal. These cranes do not need rails providing flexibility but they have in general lower productivity than STS cranes. In small terminals with very low throughput even ship's gear can be used for loading and unloading the ship [3].

Figure 3 - Ship To Shore gantry crane to the left and Mobile Harbor Crane to the right picture [19]

The stacking yard is the area where containers are temporarily stored waiting to be transported to the hinterland or to the ship. To handle this storage area different kind of equipment has been designed which requires a specific layout of the yard. Rail-Mounted Gantry cranes (RMGs) and Rubber-Tyred Gantry cranes (RTGs) are large cranes that can usually lift one container up to five high stacking and can span up to 6 to 8 containers wide. RMGs are more suitable than RTGs for automated operation because of their stable rail movement but are less flexible. Straddle Carriers (SC) are flexible vehicles moving on wheels that carry the container straddled between their legs. They can carry a container over two or three stacked containers and they usually combine the horizontal transportation of containers with the handling in the stacking yard. For small movements and local handling of containers, for supporting in case of high loads and for handling the empty containers, Reach Stackers, Top Loaders and Front Lifters are used completing the equipment of the stacking yard [3].

Figure 4 - Rail Mounted Gantry crane (RMG) to the left [21] and Rubber Tyred Gantry crane (RTG) to the right picture [20]

Figure 5 - Reach Stacker to the left and Front Lift equipment to the right picture [22]

For some of the stacking operations (RMG and RTG), the link between quay and stacking yard is carried out by Horizontal Transport Vehicles (HTVs) that transport containers from stacking yard to the quay to be loaded onboard or from the quay to the stacking yard to be temporarily stored. In some terminals Tractor-Trailer sets (TT) are used, which are specially designed trailers to carry containers, using a tractor to pull them. In automated terminals, a common HTV is the Automated Guided Vehicle (AGV) that can carry two TEUs and move autonomously. A more developed version of AGV is the lift-AGV that can load and unload a container in specially designed rafts by itself without the interference of quay or yard equipment, making its operation cycle independent from the operation cycle of quay cranes and yard equipment.

For other operations, the horizontal transportation is combined with the stacking procedure and reach stackers, straddle carriers or shuttle carriers (a smaller SC that cannot stack containers as it cannot lift the container high but it can be automated) are used.

Figure 6 - 1 over 3 and 1 over 2 straddle carriers operating together for horizontal transport and for stacking of containers

Figure 7 - Tractor - Trailer set for the horizontal transport of containers

Figure 8 - Automatic Guided Vehicle (AGV) to the left [23] and lift - AGV to the right picture [24]

2.3 The stacking yard of Container Terminals

The stacking yard provides the link between the seaside and the landside area of the terminal being a temporary storage area for containers. The performance of this link between seaside and landside is crucial for the final performance of the terminal as it needs to follow the productivity of quay cranes while serving simultaneously the different means of transportation to the hinterland [10].

Containers in the stacking yard are stored in Bays (the rows of containers placed end to end in their large dimension), Rows (the rows of containers placed side to side in their small dimension) and Tiers (the rows of containers placed one above the other). The yard is divided into storage blocks by traffic lanes which allow the free movement of the equipment through the yard:

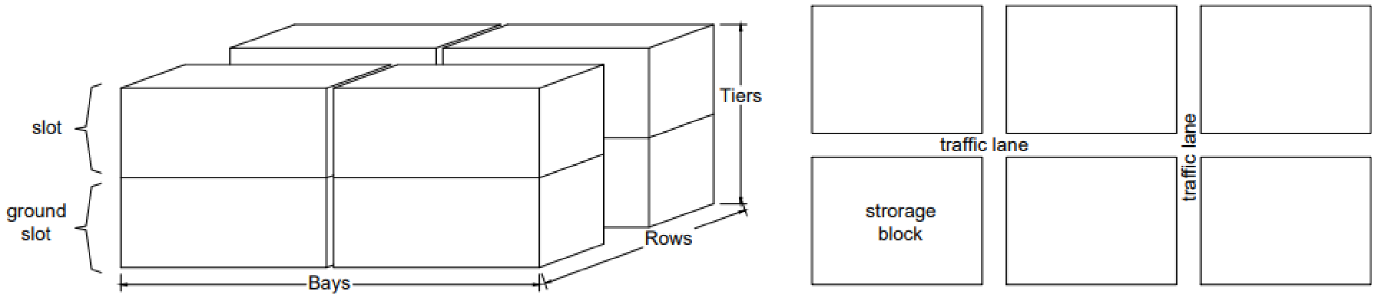


Figure 9 - Storage terminology

The storage capacity of the yard is determined by the storage density (as a result of the storage configuration of the yard), the storage area and the dwell time (the average time a container stays in the yard). Higher density and larger area result to a higher capacity, while longer dwell time results to a lower capacity of the yard [3].

There are several processes taking place in a container terminal's stacking yard:

- Stacking of inbound containers that are unloaded by Quay Cranes from ships
- Retrieval of inbound containers to be loaded on trucks, train or inland ships
- Stacking of outbound containers that are unloaded from trucks, train or inland ships
- Retrieval of outbound containers to be loaded on ships
- Reshuffling of a container to pick up another container that is located in a lower tier
- "Housekeeping" arrangement of the containers that are about to be loaded on a ship to reduce the retrieval and the horizontal transport time during loading operation

The layout is a main characteristic of a stacking yard and can be developed parallel or perpendicular to the quay, while mixed layout has also been developed in some terminals. The differences between the two types of layout depend on the yard equipment and on the general yard configuration.

For an RMG/RTG yard the perpendicular layout is typical for import/export terminals and its main advantage is that seaside and landside operations are completely separated. This has a positive impact on safety as the horizontal transport vehicles of the terminal, which may be automated and serve the seaside horizontal transport, are not in contact with manned equipment that usually serves the landside operation and external personnel, like trucks' drivers, have less contact with the operation of the terminal. The main disadvantage of this layout is that it cannot handle peaks in demand in either of the two sides. Parallel layout is typically used for transhipment terminals. Seaside and landside operations cannot be completely separated but the equipment can correspond better to peak demands as the equipment can serve either the waterside or the landside demand when necessary. In general, when transhipment ratio is larger than 65% a parallel layout is more efficient [10]. For a SC stacking yard, the different layout corresponds to different travelling distances for the equipment to serve the quay cranes and the landside means of transport. The efficiency of each layout depends on the general configuration of the yard.

2.4 The process strategies in a straddle carrier stacking yard

After the basic characteristics of a container terminal are determined and the layout of the stacking yard is finalised, there are a lot of different ways to define the jobs to be processed and to divide these jobs to SCs. Straddle carriers can work in different cycles in the yard, while the containers in the yard can be arranged or not with a particular way in the stacking yard depending on their final destination and on special characteristics that they may have [15].

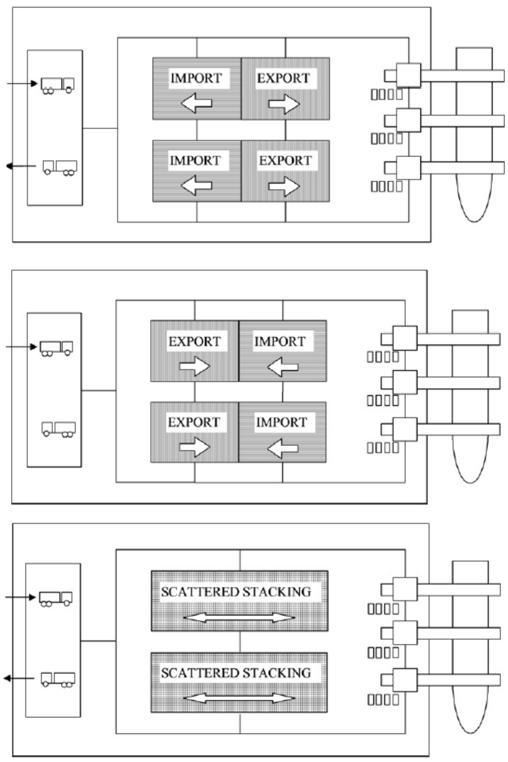
The different tasks for a SC can be defined as:

- Serving a quay crane which loads a ship in the seaside zone
- Serving a quay crane which unloads a ship in the seaside zone
- Unloading trucks in the landside zone
- Loading trucks in the landside zone

The different strategies for straddle carriers can be defined as:

- The single cycle strategy, which assigns only one task in every SC only in one zone. Following this strategy, each SC can perform only one of the above four tasks. Each SC is assigned to one quay crane if it operates in the seaside zone.
- The pooling quayside strategy: Each SC performs only one task but it can be assigned to more quay cranes, depending on the productivity of the crane. This strategy can increase the performance of the terminal, as it is essential for a QC not to wait for a container from the yard and to work continuously, while a truck in the landside area could have a small waiting time.
- The double cycle strategy in which SC can perform both loading and unloading in the seaside or in the landside zone.
- The quadruple cycle strategy in which SC performs all the above four different tasks in both seaside and landside zone.

When deciding on a strategy, the goal is to minimise the total service time for a SC. To do so, the empty travelling time between ending a job and starting the next one needs to be reduced.



To allocate the containers in the stacking yard, there are three different strategies:

1. To allocate the outbound containers to the seaside area. With this strategy, the loading of the ship is faster as containers are closer to the quay

In case of unbalanced flows, more slots need to be available for the higher flows.

2. To allocate the outbound (export) containers to the land side area. This option is preferable when there is an important transhipment ratio or when the unloading ration for gantry cranes is higher than the loading ratio.

3. To allocate the containers wherever in the stacking yard without any division.

The selected strategy depends on the characteristics of the terminal. Different physical configuration, different kind and quantity of equipment, different ways to arrange the operation can lead to different decisions on how to divide the jobs to SCs and on how to allocate the containers in the stacking yard [15].

2.5 The effectiveness of the stacking yard

The operation of the stacking yard is complicated as it needs to support effectively and simultaneously the quay cranes through the horizontal transport, the stacking procedure and the landside means of transportation that bring containers inside and outside the terminal. To optimise a complex operation in terms of time and cost effectiveness there are a lot of different options, depending on the different aspects of the yard.

Some main factors that can be optimised for the operation of the stacking yard are the followings:

- The layout rearrangement of the yard, which can reduce the maximum distance between a random container and a random quay crane or a random parking position of a truck. Depending on the equipment of the yard, a significant improvement of the cycle time of the equipment may be achieved.
- The fuel and electricity consumption by the equipment, which can be reduced by renewing the equipment or adjusting its operation and its speed.
- The maintenance cost, which can be reduced by changing the maintenance cycle of the machinery or by renewing or changing its type
- The stacking strategy which determines the areas for different kind of containers, like import, export, transhipment containers, empties, reefers, etc.
- The stacking philosophy that determines which container goes to which stacking slot. This is prescribed by an Information System, the Terminal Operation System that emulates (simulation with real data in real time) the operation in the yard and gives the instructions to the machinery.

A different perspective that can change entirely the operation of the stacking yard is the possibility for a container terminal to switch to automation:

The development of technology and of Information Systems has led to the modernisation of port operations and cargo handling. More and more information is managed by computes and is possible to be shared simultaneously to different receivers applying a first level of automation in port operation. Sophisticated software and equipment is used to handle cargo in different steps of operations making possible the application of a higher level of automation in the whole performance of terminals. The first robotised container handling equipment was applied in 1993 in Rotterdam ECT Delta Terminal and since then more than 50 terminals in the world have already applied a higher level of automation in their operation while a lot more terminals are using automation in a more preliminary level [7].

Automation in container terminal operation has many advantages that make it attractive for application in existing terminals and even more in new designed terminals. The excluding of human factor for the different stages of cargo handling make it possible to increase safety in terminal operation and to reduce the possibility of human errors. This can result in a more stable productivity independent of different human attitudes and of restrictions due to human pressure like the limited working hours. Furthermore, the use of robotised equipment and decision making systems can result in less operational expenditures by reducing the labour cost and to higher land utilisation. Finally, automated equipment is friendlier for the environment as it usually uses electricity instead of conventional fuel for its operation [8].

However, automation has some inconveniences that can postpone or even reject the application plans in some terminals depending on their characteristics. The most important fact is that automated equipment and relevant operational systems are quite expensive, and a high initial expenditure is necessary for the investment. Also, automated operation is sensitive to volume variation and to specificities that can make operation run in an unstable manner. Automated equipment cannot handle exceptions as it is not programmed for that so human interference is necessary in specific cases. Furthermore, it is less flexible in changes of the layout and of future expansion than conventional operation and presupposes special training of terminal personnel. Last but not least, automated application faces union resistance that makes it even more difficult to apply it in an existing terminal [8].

Because of the above advantages and inconveniences of automation, there is not a general rule on how and in which level it is optimal. Every terminal has a different concept that requires specific consideration. Different levels of automation are possible to be applied and especially for a brownfield port this is a way to switch in automation in gradual steps. Generally, the levels of automation are the followings [6]:

- Automation in information sharing between the terminal and the shipping companies, the hauliers and the carriers. The information is spread simultaneously to all necessary actors inside and outside the terminal.
- Use of automation in decision making, control and plan of the processes of the terminal through an information system.
- Automation in container handling by robotised equipment. The equipment can be fully robotised working without human interference or partly robotised by remote controlled operation. This can be applied in parts of a terminal, such as:
    - Gate automation
    - Yard automation
    - Quay automation
    - Horizontal transport automation

Automation in information by the use of sophisticated IT systems gains more and more field in world terminals as it is a first step that can save time and increase the efficiency of terminal operation in a more conventional way without high investments. Then, automation in decision making and control of the processes usually depends on the terminal layout and on automation in container handling equipment as it is part of the Terminal Operation System that handles the whole operation of the container terminal. The first part of the equipment that is robotised is the stacking yard, sometimes combined with automated horizontal transport vehicles. Fully automated quay cranes are still difficult to be applied but there are already in operation partly automated quay cranes by remote control [7].

An example of a container terminal that recently (partly) switched to automation is the terminal of port of Auckland in New Zeeland. This terminal uses straddle carriers for the horizontal transport, the stacking operation and for serving the trucks in the landside area. Since April 2020, the handling of the stacking yard and the loading and unloading operation of trucks is performed by automated straddle carriers, while the horizontal transport is still performed by manned straddle carriers, as it was computed that by creating this hybrid automated terminal, it will be achieved a higher level of productivity. The innovation of this terminal is that manned and unmanned straddle carriers interact each other for the operation of the same yard [18].

Figure 10 – The new 1 over 3 automated straddle carrier at the port of Auckland [18]

3 The Container Terminal of Thessaloniki

3.1 The Port of Thessaloniki

Thessaloniki was founded by king Kassandros, uncle of Alexander the Great in 315 B.C. and from the very beginning was developed as a port - city. The city was developed during Roman times (148 B.C. - 325 A.C.) and later on during the ages of Byzantine Empire (325 A.C. - 1430 A.C.) it was the second most important city of the Empire being a main trade node for Balkan Peninsula.

The port of the city with its modern form was established in 1896 when it was given for 40 years to the French company "Société Anonyme Ottomane de construction et d' exploitation du port de Salonique". This company constructed the first piers of the port and its breakwater as well as the first modern storage areas and the emblematic building of customs, which is now used also as passenger terminal. Because of its geographical position and because of its early connection with the main railway network of Balkans the port was developed very fast and every one or two decades a new pier was constructed, and new land infrastructures were available for port usage.

Today the port has 6 piers and 26 quays, and it accommodates almost all kind of terminals: Passenger terminal, general cargo terminal, dry bulk terminal and a container terminal. Right next to the port there is a separated cement terminal and a liquid bulk terminal. These two terminals are not operated by the Port Authority of Thessaloniki but by other private companies. In the port area there are also a lot of logistic centres and other trade companies which are housed in the old warehouses of the port. Inside the port territory, there are numerous old buildings with special architectural value, which are protected by the law. The first and older pier of the port was given for use to the city of Thessaloniki in 1997, hosting cultural and entertainment activities.

The "Thessaloniki Port Authority" was founded in 1970 and in 1999 the port became a public company named "Thessaloniki Port Authority S.A". In 2001 was listed on the Athens's Stock Exchange and in March 2018 the use of the infrastructure of the port was sold in the consortium "South Europe Gateway Thessaloniki (SEGT) Limited" until 2051. The owner of all the infrastructures of the port is the Greek Public State. In the concession agreement they are described numerous investments that need to take place in the coming years based on a new Master Plan which is still under study.

The total throughput of the area of Thessaloniki Port Authority in 2018 was 7,298,218 tons. The container share of this throughput was 2,187,133 tons (424,000 TEUs), while dry bulk has the largest share of cargo handling. The trend of conventional cargo is stable the last 10 years and varies in around 4,000,000 tons per year [13].

Figure 11 - General Port layout in 2018 [17]

3.2 The Container Terminal of the Port of Thessaloniki

The container terminal of the port of Thessaloniki is developed in the 6th pier, at the western part of the port. The construction of the 6th pier started in 1974 with the construction of the quay walls. The embankment and the gantry cranes pedestal completed in 1986. The container terminal started its operation in 1989 and since then it has a continuous development with more equipment and more space added to the existing every couple of years. This development is shown in the following graph, in which the drop due to financial crisis in Greece is also obvious.

Figure 12 - The Container Terminal of the port of Thessaloniki in early '90s [25]

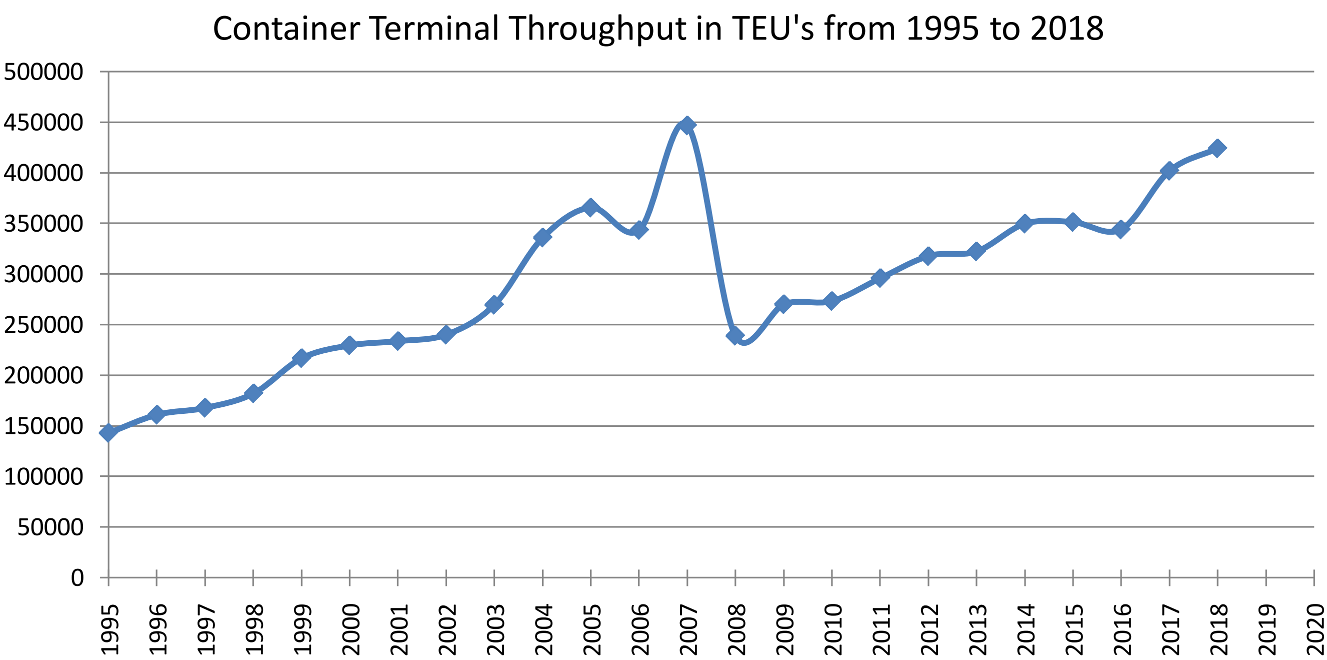


Figure 13 - The total throughput of Container Terminal through years

The container terminal has two berths with total quay length of 550m and can host ships with draught up to 12m. It has 4 quay cranes from which the 2 are post panamax type. The horizontal transport of the containers as well as the operation of the stacking yard is handled by straddle carriers. The current equipment is consisted of 1 over 2 SCs and recently the port was equipped with larger, 1 over 3 SCs. Currently, the stacking in the yard is in some blocks in 2 tiers and in some others (the export blocks near the quay) in 3 tiers.

The pooling strategy of the terminal is the division of the fleet of straddle carriers into two teams. One team serves the landside cycle of loading and unloading trucks. The other team serves the seaside cycle of transferring containers from/to the quay cranes to load and unload ships. Usually two SCs are designated for one QC. The SC's operator receives the instructions for its job from the Terminal Operation System (TOS) through an automated procedure. The instructions to the SCs' operators refer to which container needs to be transported to which place/slot of the yard. The operator decides which is the shortest route in the yard to carry out his job.

The total ground slots of the yard are about 5,800 TEUs and the total area of the terminal is about 325,000m^2. Recently trucks with trailers became part of the horizontal transport fleet of the terminal but they are not in complete use yet, while reach stackers and front lifts are used for handling the empties. There are designated areas with electricity supply for reefers, areas for containers with dangerous cargo and containers that need to be controlled by authorities.

The terminal is connected with the national road network as well as with the national railway network, but the majority of containers is transported to and from the terminal by trucks. The terminal has currently about 120 parking places for trucks and a double railway connection served by a Rail Mounted Gantry Crane.

Origin / Destination	number of 20 feet containers		number of 40 feet containers	
	Laden	Empties	Laden	Empties
Unloading				
From abroad	30,480	32,961	38,296	15,565
Transit	12,955	0	14,501	0
Transshipment	85	4	134	3
From Greece	29	0	0	0
Total	43,549	32,965	52,931	15,568
Loading				
To abroad	67,235	3,647	13,759	13,759
Transit	6,828	0	0	0
Transshipment	86	4	3	3
To Greece	0	0	0	0
Total	74,149	3,651	13,762	13,762
General Total	117,698	36,616	66,693	29,330
TEU factor	1.38			

Figure 14 - Container analysis for 2018 in number of pieces

3.3 The layout arrangement of the port of Thessaloniki

The container terminal of the port was developed gradually since 1989, when the construction of the 6th pier and the necessary infrastructure was completed. Initially, the pier was divided into two terminals almost equally, to the dry bulk terminal (Quay 24) to the east and to the container terminal (Quay 26) to the west. The southern part of the pier (Quay 25) is still unfinished, waiting for the extension of the pier to the south.

During the 90's, the western part of the basement of the pier was embanked initially for serving Ro-Ro vessels, but it finally became part of the container terminal. The terminal also expanded inside the pier, taking part of the dry bulk terminal and forming a stacking yard with nearly 5,800 TGS (Twenty foot container Ground Slots) in total. The stacking height of 3 containers in the seaside part of the yard and of 2 containers in the rest of the yard provides a yard capacity of around 14,500 TEUs. The current allocation strategy is that export containers are located to the seaside part of the yard. The steps of the development of the stacking yard are shown below:

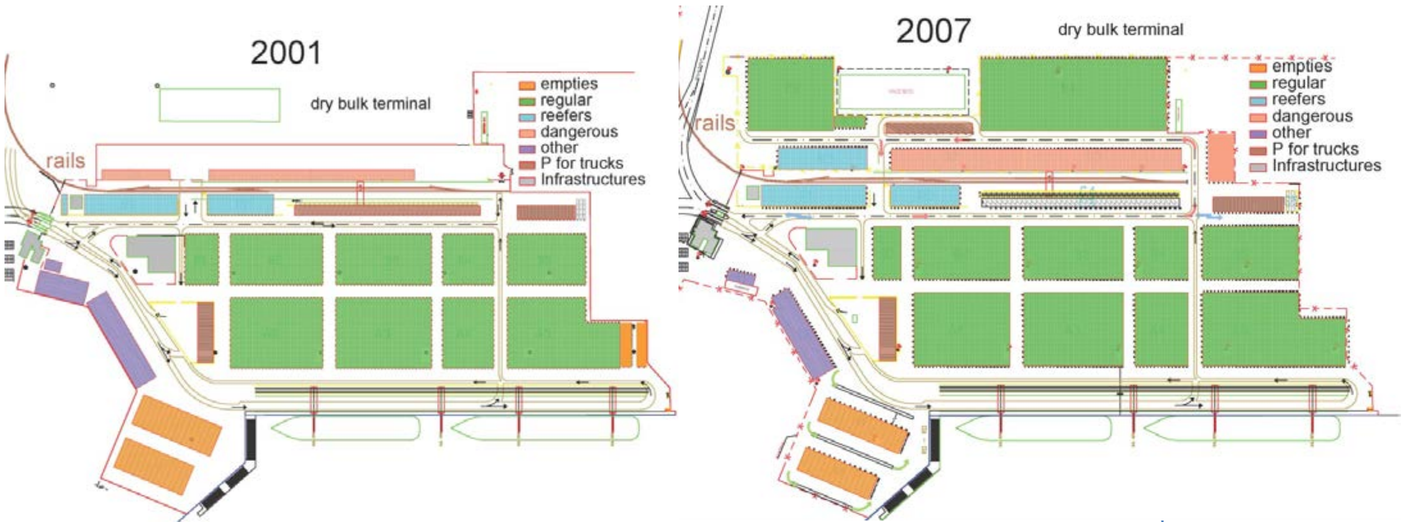


Figure 15 – Older terminal layouts. Between 2001 and 2007 the terminal expanded inside the 6^{th} pier

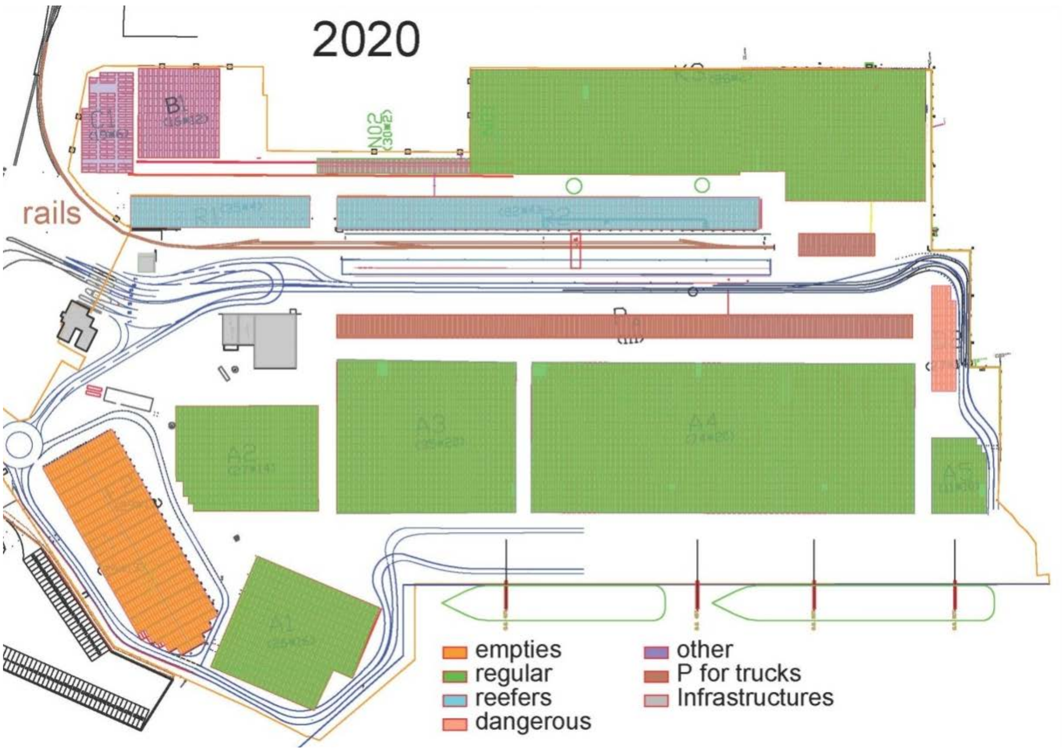


Figure 16 – The terminal layout today

3.4 The development plan of the container terminal of Thessaloniki

Future development is a main goal for every commercial company. The concession agreement requires by the new manager of the port facilities to develop the port of Thessaloniki having specific targets for the throughput and for the financial activity of the port. One of these main targets is the extension of the 6^{th} pier and the expansion of the container terminal and the dry bulk terminal of the port. This extension is under consideration and planning by the port and the city of Thessaloniki for more than 10 years and now the circumstances seem to be mature enough to proceed to the next stage.

The obligation of the concession agreement is for an extension of at least 440m. At least 400m of them need to be able to host a ship with a maximum draught of 16.5m. The minimum width of the expanded container terminal will be 300m. By this expansion of the terminal it is expected to double its annual throughput and reach at least 1,000,000 TEUs per year. The exact way this is going to be achieved is part of the new Master Plan of the port which is still under development.

The minimum service level of the container terminal is defined by 18 productive moves per gantry crane per gross operating hour in monthly average and 45min per truck calculated as total time spent on terminal from gate-in to gate-out. The minimum operating hours for the gate need to be 16hours per working day and 8 hours on Saturday. The quayside operating time is 24/7 [17].

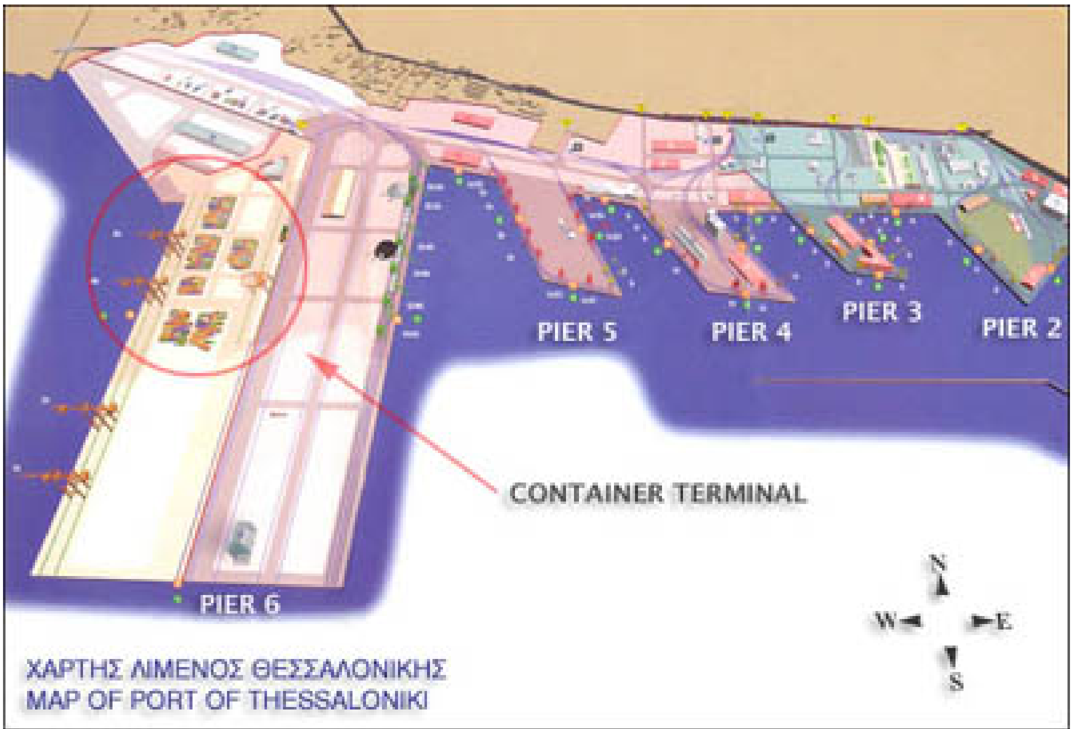


Figure 17 - Graphical plan of the extension of the 6^{th} pier [25]

4 Optimising the layout of the stacking yard

4.1 The layout arrangement problem in an SC yard and optimisation approach

The yard layout problem of container terminals considered in this research project, is to determine the number and the position of traffic lanes and to design the stacking blocks to minimise the cycle time of yard equipment and consequently to increase the productivity of the stacking yard. The first step is to set the boundaries of the yard according to space restrictions and according to the general layout of the terminal which includes the apron area, the landside area, various buildings and other necessary infrastructure (rail connection) all to be designed in a constrained by the land availability space for the terminal. Secondly, inside the yard, it is important to pre-define areas for containers which need special treatment. The two common special categories are the reefers that need power supply and containers of dangerous goods that have to be stored in special areas of the yard separately [14]. Thirdly, it is important to predict some area for containers that need to be opened for control by the authorities and for containers that have blocked twist-locks and they need special treatment by specific technicians. Finally, the remaining area is to be separated into blocks by traffic lanes for the storage of regular containers. The more complicated a terminal layout, the more difficult it becomes to optimize the arrangement of the yard layout. In the picture below, an example of a quite complicated terminal layout is presented.

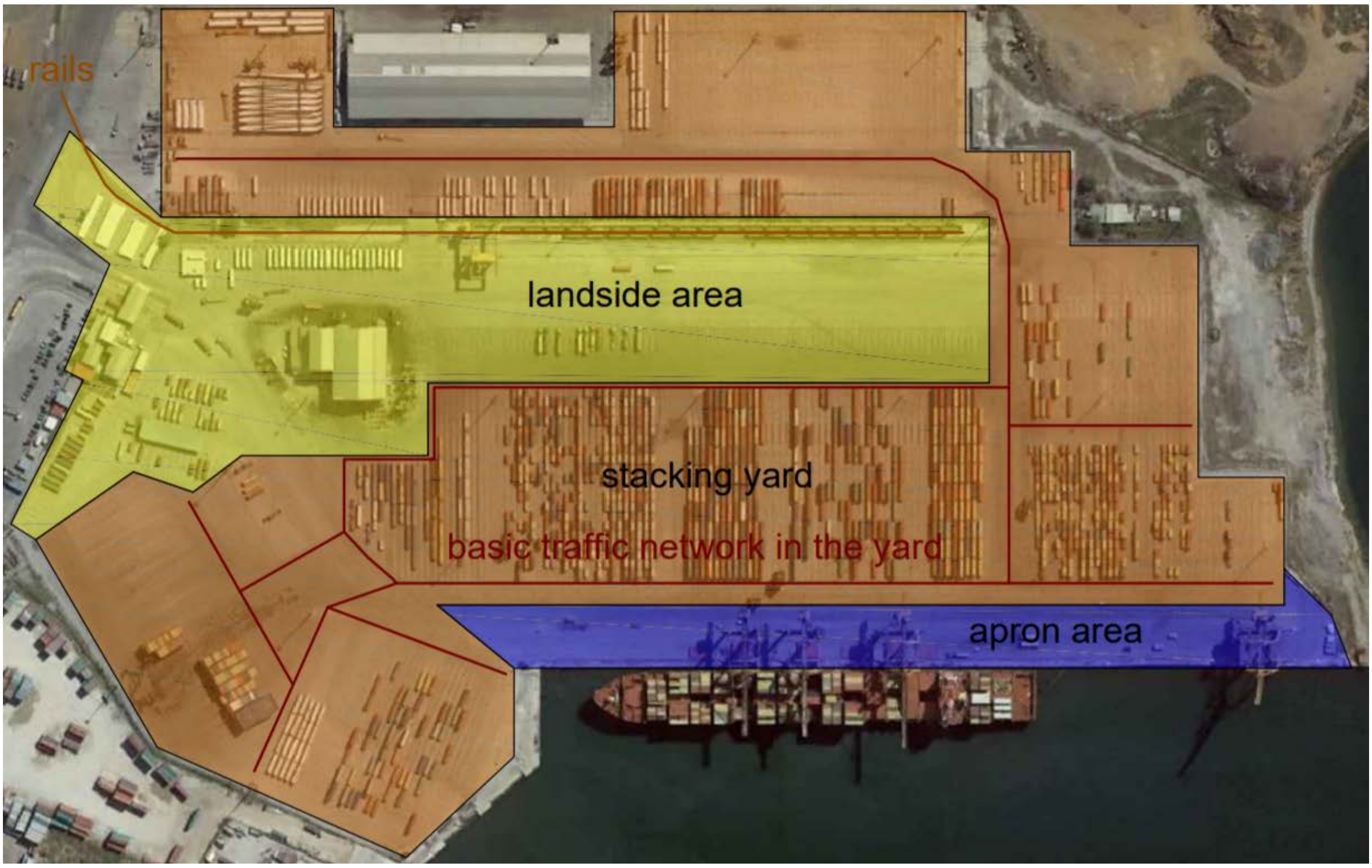


Figure 18 – General layout of the container terminal of port of Thessaloniki some years ago

More traffic lanes in the stacking yard can give the ability to straddle carrier operator to choose a shorter route and can reduce the traffic inside the lanes and possible waiting time for entering a row. However, more lanes need more space so there is less space available for container storage (i.e. this reduces the number of ground slots). To keep the capacity of the yard the same, it is necessary either to increase the average stacking height or to increase the yard area. By increasing the stacking height, the probability of reshuffles is also increased and the mean reshuffling time is longer, while by increasing the yard area, there is higher demand for land and straddle carriers need to travel longer distances in the yard. Because of all the above issues, a well-designed layout, taking all these issues into consideration, is necessary for the stacking yard to succeed the optimum capacity with the minimum cycle time for the equipment.

In this report, the scope is limited to the seaside cycle time (the time for straddle carriers to serve quay cranes), as it is considered to be more important for the final operation of the stacking yard and for the total performance of the terminal. The reasoning process is analysed as follows:

4.2 The simplified problem and key assumptions. Before analysing the problem, all the necessary assumptions are analysed. Then, the simplest case with one traffic lane in a rectangular yard layout is considered and the optimum position of this lane for perpendicular and for parallel layout is determined.

4.3 Verification of the model. Using the port of Thessaloniki as a case study, a model verification is applied by considering another reasonable location for the traffic lane, rather than the one computed by the model.

4.4 Optimisation test case: Considering more traffic lanes. For the case study of the port of Thessaloniki, the option of two traffic lanes is analysed and compared with the one with one traffic lane.

4.5 Calculation of the current performance of the yard and proposition of an optimisation. Using the model that is developed in the previous chapters, an analysis of the current performance of the yard is approached and an optimisation of a certain part of the yard is proposed.

4.2 The simplified problem and key assumptions

The case study for the problem assumes a container terminal with a straight quay with two berths and a rectangular yard layout, as shown in figure 19. The horizontal transport of containers and the stacking/retrieval to/from the yard is handled by straddle carriers. Straddle carriers are divided into two teams: One serving the landside area and the other the seaside. In this study only the seaside cycle will be considered. The necessary assumptions for this case are listed below:

- The processes of straddle carriers taken into account are:
  - The stacking or inbound containers that are unloaded by quay cranes from ships
  - The retrieval of outbound containers to be loaded on ships
- The velocity of straddle carriers in the block is reduced compared to the free distance velocity. Turning time is not considered, as this is not impacted by travel distances.
- There is no influence of traffic density in straddle carriers' travelling time.
- Straddle carriers enter a block only if they need to perform an operation inside this block. They do not cross a block to reach another block.
- No special import or export storage area is considered. The storage position is selected randomly.
- No cost consideration for the different terminal sizes is considered.
- Straddle carriers enters the yard from the seaside area and exit the yard from the landside area for a perpendicular layout. No backward movement is considered. Straddle carriers are allowed to move only forward.
- Each ship is represented by one point on the quay, which is the mean position of quay cranes when serving this ship.

The research question that is going to be answered, as introduced in the beginning, is what is the optimum location of a traffic lane in a rectangular part of a straddle carrier yard to minimise the distance (and thus travel time) that straddle carriers need to cover during a ship loading/unloading operation.

For this first simplified problem, to find the optimum location for one traffic lane, the in-block travelling distance is not considered. The reason is because the in-block distance is the same wherever the traffic lane is located, so it does not affect the effort to minimise the travelling distance. The measurement starts from the landside exit of the row of the block.

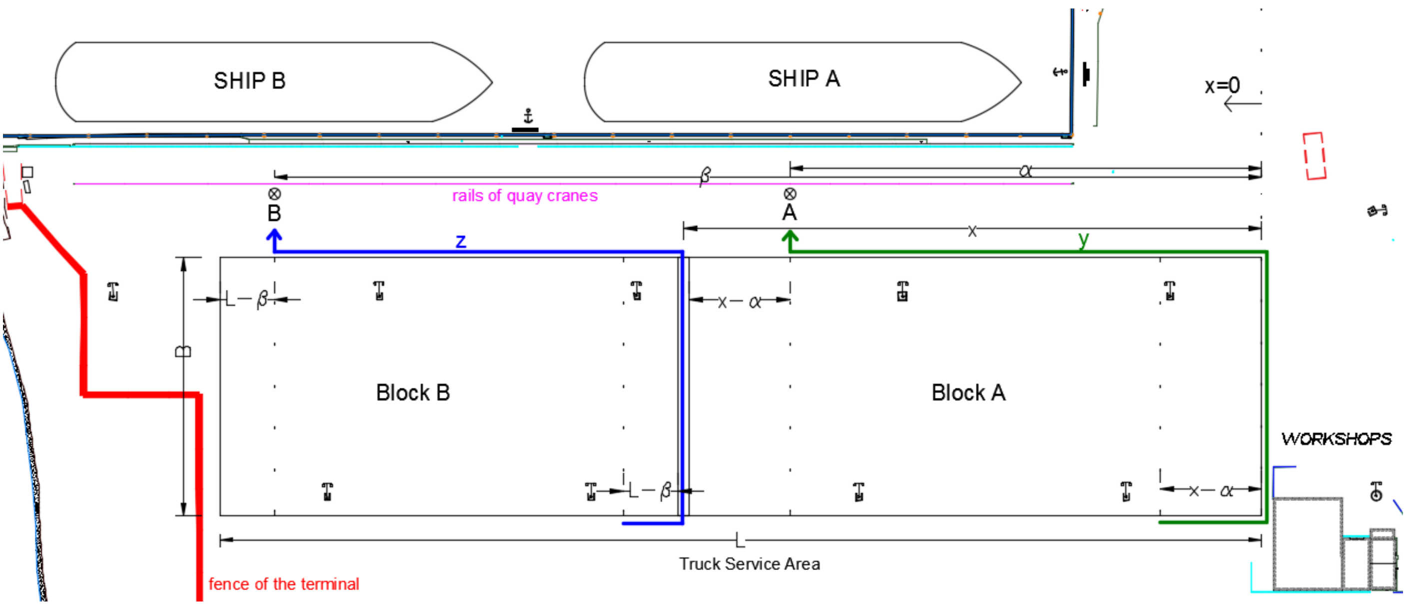


Figure 19 – Arrangement for a perpendicular layout

With the blue colour is indicated the route of a straddle carrier to the ship B and with green the route to the ship A. Based on the geometry, the following results are derived with the following sequence:

1. The traffic lane needs to be between points A and B (α<x<β) to serve the reduction of travelling time for both of the ships simultaneously. Let “x” be the position of the traffic lane.

2. Taking into account the above, if a container from the Block A located at x' needs to be transferred to the ship B, then the horizontal travelling distance is β-x' no matter where the lane is located. Similarly, if a container from the Block B located at x' needs to be transferred to the ship A, the travelling distance is x'-α, no matter where the lane is located. So, to proceed with the determination of the optimum location of the traffic lane, it is assumed that containers from Block A are transferred to ship A and containers from Block B to ship B.

3. Taking into account the above, the longest distance that a container will need to travel to reach ship A is $y = x - \alpha + B + \alpha$, shown on the above diagram with the green line, so $y = x + B$.

4. The longest distance that a container will need to travel to reach ship B is $z = L - \beta + B + \beta - x$, shown on the above diagram with the blue line, so $z = L - x + B$

5. To minimise the distances, considering that the possibility of a container to be transported from a row is equal for all the rows, it is sufficient to minimise the distance for the longest route.

6. Let W be the width of a row. Then, $\frac{L}{W}$ is the total amount of rows in the whole Block. $\frac{x}{W}$ is the amount of rows in Block A and $\frac{L-x}{W}$ is the amount of rows in Block B. The possibility that a container will need to be transported from Block A is then $\frac{\frac{x}{W}}{\frac{L}{W}} = \frac{x}{L}$ and the possibility that a container will need to be transported from Block B is $\frac{\frac{L-x}{W}}{\frac{L}{W}} = \frac{L-x}{L}$

So, to optimise the travelling distance for both of the ships, it is necessary to minimise both $\frac{x}{L} \cdot (x + B)$ and $\frac{L-x}{L} \cdot (L - x + B)$.

To achieve this, the sum S is minimised, as an expression of the added maximum distance for serving both of the ships:

$$S = \frac{x}{L} \cdot (x + B) + \frac{L - x}{L} \cdot (L - x + B) \Leftrightarrow$$

$$S = \frac{2}{L} \cdot x^2 - 2 \cdot x + L + B$$

The above is a parabolic equation and has a minimum at $x = \frac{L}{2}$.

The result of the above analysis is that it doesn't matter where the ships are located or where the yard is located compared to the quay (there is an eccentricity of the yard on the above layout). The minimum travelling distance is achieved when the lane is located in the middle of the rectangular yard, i.e. when the blocks have the same dimensions.

The similar procedure can be followed for a parallel to the quay layout:

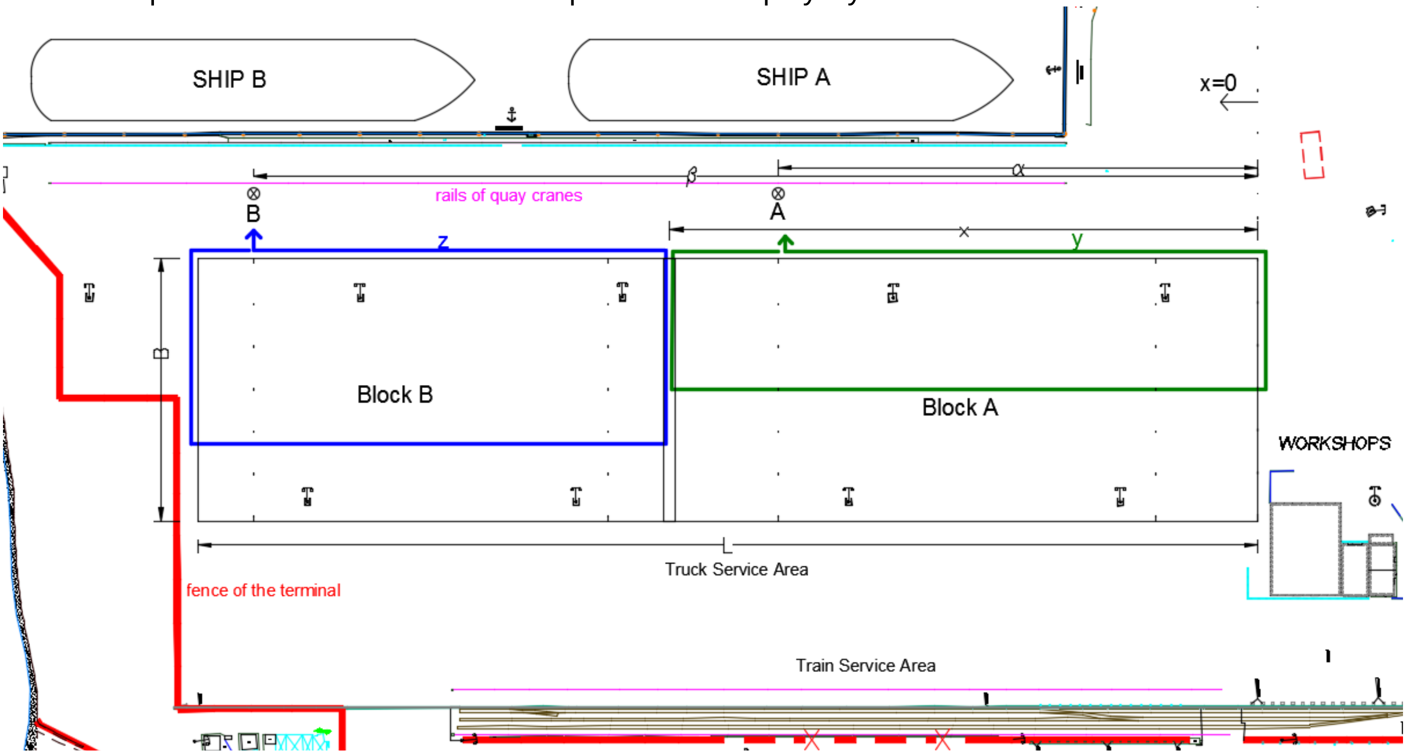


Figure 20 – Arrangement for a parallel layout

In this case, simulating the whole cycle of the straddle carrier, assuming that the container is placed in the middle row (B/2), the travel distance for Ship A is described as: $S_A = 2 \cdot x + 2 \cdot \frac{B}{2} = 2 \cdot x + B$ and for Ship B as: $S_B = 2 \cdot (L - x) + 2 \cdot \frac{B}{2} = -2 \cdot x + 2 \cdot L + B$.

Let “l” be the length of each bay of the yard. Then, all the bays of the yard are L/l, in Block A there are x/l bays and in Block B (L-x)/l bays.

Considering the probability that a container needs to transferred from a bay is equal for each bay, then the probability that a container from Block A needs to be transferred is $\frac{\frac{x}{l}}{\frac{L}{l}} = \frac{x}{L}$ and the probability that a container from Block B needs to be transferred is $\frac{\frac{L-x}{l}}{\frac{L}{l}} = \frac{L-x}{L}$

Similarly, the sum of the total distance for the straddle carriers for ship A and ship B is:

$$S = (2 \cdot x + B) \cdot \frac{x}{L} + (-2 \cdot x + 2 \cdot L + B) \cdot \frac{L - x}{L} \Leftrightarrow$$

$$S = (2 \cdot x + B) \cdot \frac{x}{L} + (-2 \cdot x + 2 \cdot L + B) \cdot \frac{L - x}{L} \Leftrightarrow$$

$$S = \frac{4}{L} \cdot x^2 - 4 \cdot x + 2 \cdot L + B$$

This is also a parabolic equation with its minimum for $x = \frac{L}{2}$.

So, for both parallel and perpendicular layout, no matter the exact position of the berths, the vertical lane should be located in the middle of the yard.

The next question is if a vertical or a parallel layout is more suitable for the terminal. For this case, it is assumed that the lane will be located in the above optimum location, in the middle of the yard, so $x = \frac{L}{2}$.

From this point, since the optimum position of the lane is defined, it is considered that all the containers of the yard have the same probability to be loaded to ship A and to ship B. So containers from Block A can be loaded to ship B and from Block B to ship A. This assumption makes the problem more realistic without affecting the analysis above.

Another necessary reasonable assumption already discussed above is that straddle carriers travel with a lower speed (almost the half) inside the block compared to the "free speed" outside of the block. The reason is both the confined space in the block, the extra attention the driver needs to pay and that the container is not located in the lower position of the carrier but higher, resulting in a reduced stability of the vehicle. In modern straddle carriers, this speed reduction is automated by the operation system of the carrier.

In the perpendicular case, the total maximum travelling distance from Block A to ship A is
$\mathrm{S}_{\mathrm{A-A}} = a - \left(\frac{L}{2} - a\right) + \tilde{B} + \frac{L}{2} - a + B + a = 2 \cdot a + \tilde{B} + B$, with $\tilde{B}$ the distance travelled in the block.

From Block B to ship A, $\mathrm{S}_{\mathrm{B-A}} = 2 \cdot (\mathrm{L} - \alpha) + \mathrm{B} + \tilde{\mathrm{B}}$.

So, the mean maximum distance for ship A is

$$\mathrm{S}_{\mathrm{mean\ -A}} = \frac{2 \cdot \alpha + B + \tilde{B} + 2 \cdot (L - \alpha) B + \tilde{B}}{2} = L + B + \tilde{B}$$

From Block A to ship B, $\mathrm{S}_{\mathrm{A-B}} = 2 \cdot \beta + \mathrm{B} + \tilde{\mathrm{B}}$

From Block B to ship B, $\mathrm{S}_{\mathrm{B-B}} = 2 \cdot \left(\beta - \frac{L}{2}\right) + B + \tilde{B}$

Then, the mean maximum distance for ship B is

$$\mathrm{S}_{\mathrm{mean\ -B}} = \frac{2 \cdot \beta + B + \tilde{B} + 2 \cdot \left(\beta - \frac{L}{2}\right) + B + \tilde{B}}{2} = 2 \cdot \beta - \frac{L}{2} + B + \tilde{B}$$

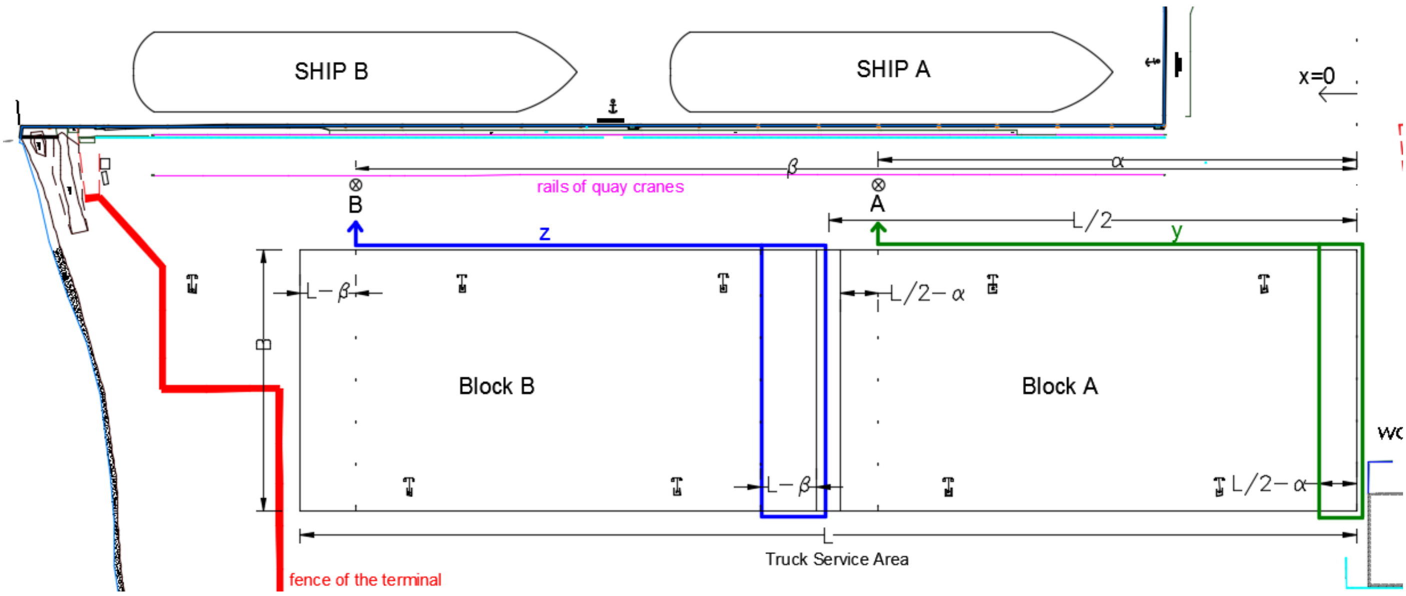


Figure 21 – The whole travelling distance for SCs in a perpendicular layout

The similar distance for parallel layout and for a container in the middle row of the block is:

From Block A to ship A:
$S_{A-A} = \frac{L}{2} + \frac{B}{2} + \frac{\tilde{L}}{2} + \frac{B}{2} = \frac{L}{2} + B + \frac{\tilde{L}}{2}$, with $\frac{\tilde{L}}{2}$ the in-block travelled distance.

From Block B to ship A: $S_{B-A} = 2 \cdot \frac{L}{2} + \frac{L}{2} + B + \frac{\tilde{L}}{2} = \frac{3 \cdot L}{2} + B + \frac{\tilde{L}}{2}$

So, the mean maximum distance for ship A is $S_{mean-A} = \frac{\frac{L}{2} + B + \frac{\tilde{L}}{2} + \frac{3 \cdot L}{2} + B + \frac{\tilde{L}}{2}}{2} = L + B + \frac{\tilde{L}}{2}$

From Block A to ship B: $S_{A-B} = 2 \cdot \frac{L}{2} + \frac{L}{2} + B + \frac{\tilde{L}}{2} = \frac{3 \cdot L}{2} + B + \frac{\tilde{L}}{2}$

From Block B to ship B: $S_{B-B} = \frac{L}{2} + \frac{B}{2} + \frac{\tilde{L}}{2} + \frac{B}{2} = \frac{L}{2} + B + \frac{\tilde{L}}{2}$

So, the mean maximum distance for ship B is $S_{mean-B} = \frac{\frac{L}{2} + B + \frac{\tilde{L}}{2} + \frac{3 \cdot L}{2} + B + \frac{\tilde{L}}{2}}{2} = L + B + \frac{\tilde{L}}{2}$

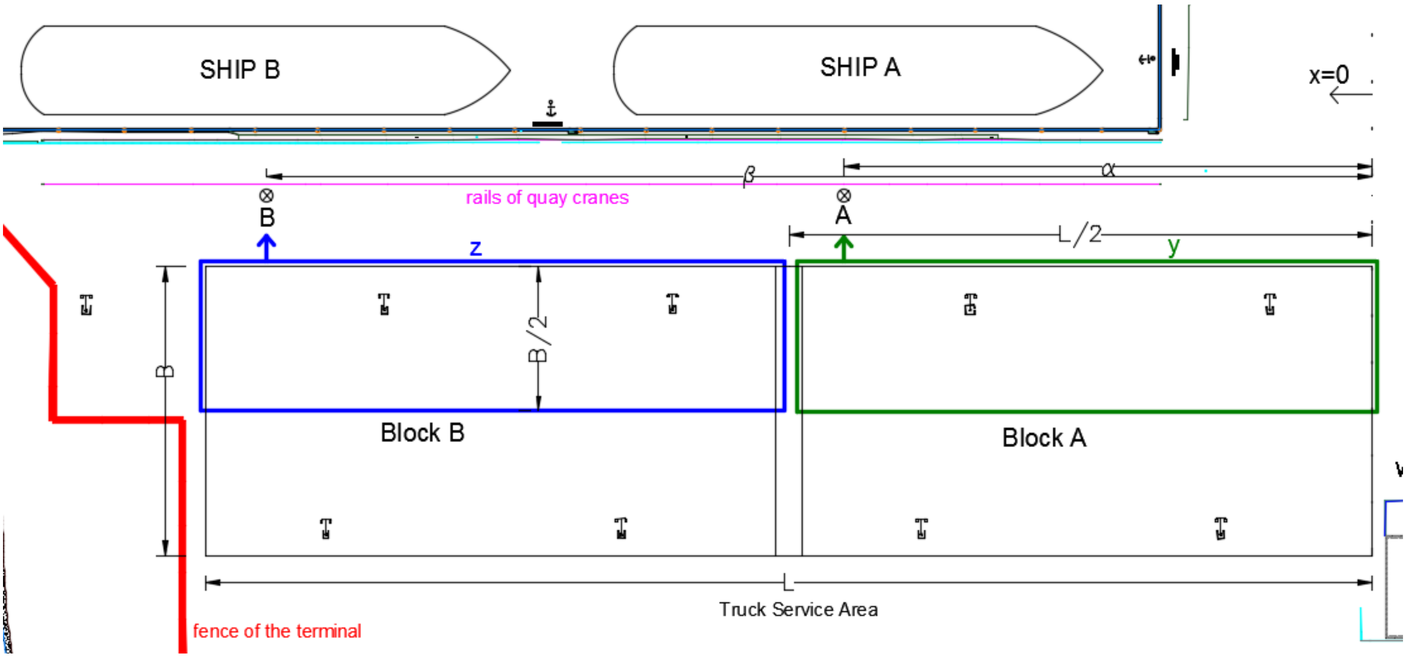


Figure 22 – The whole travelling distance for SCs in a parallel layout

It is remarkable that for the parallel layout the travelling distance for ship A and for ship B is the same and it is independent of the position of the ships.
For perpendicular layout, the travelling distance for ship A is independent of the position of ship A but for ship B the position of the ship is important.

Comparing the two distances for the perpendicular and for the parallel case, it is then important the specific characteristics of each terminal: If $L \gg B$, then the distance travelled inside the block for the parallel case is much larger than for the perpendicular case, so the total cycle time for the parallel case will be longer. For the perpendicular case, it is also important the position of the berths compared to the yard. If the berths are centered, then the distances are shorter. Thus, a generalised conclusion is not possible to be extracted. For each terminal, depending on the geometry and on the available space for the block, a different layout may be the optimum.

4.3 Verification of the model

The model will be verified by making a comparison of the travelling time of straddle carriers between the case described by section 4.2, locating the lane in the middle of the yard, and another reasonable location for the traffic lane.

<u>The characteristics of the terminal of Thessaloniki:</u>

The layout dimensions and the position of the berths are the followings:
$B \cong 130m$, L$\cong 525m$, $\alpha \cong 240m$, $\beta \cong 495m$.
The travelling free velocity of the new Konecranes straddle carriers is 19km/h and the in-block velocity is 11km/h. The turning velocity is approximately 15km/h but it is not taken into account. The lifting and lowering time are not taken into account for this comparison as they are not depended on the yard layout but on the equipment, the probable reshuffling needed and the experience of the driver.

<u>The case for one lane located in the middle of the yard (x=262,5m) – figure 21:</u>

The probability that a container from Block A will be loaded to ship A is the same with the probability that a container from Block B will be loaded to ship B as Block A and Block B are equal (have the same number of containers). So, assuming this kind of layout and using the formulas from section 4.2 for the traveling distances, the travelling time is calculated as follow:

- For ship A:

The travelling distance calculated at section 4.2 is: $S_{\text{mean }-A} = \frac{2\cdot\alpha+B+\tilde{B}+2\cdot(L-\alpha)B+\tilde{B}}{2} = L + B + \tilde{B}$

So, using the above travelling velocities, the travelling time is calculated as:

$$\frac{525+130}{19\cdot 1000} + \frac{130}{11000} = 0.046h = 2.78min$$

- For ship B:

The travelling distance calculated at section 4.2 is: $S_{\text{mean }-B} = \frac{2\cdot\beta+B+\tilde{B}+2\cdot\left(\beta-\frac{L}{2}\right)+B+\tilde{B}}{2} = 2\cdot\beta - \frac{L}{2} + B + \tilde{B}$

So, using the above travelling velocities, the travelling time is calculated as:

$$\frac{2\cdot 495 - 525/2 + 130}{19\cdot 1000} + \frac{130}{11000} = 0.057h = 3.42min$$

<u>The case for one lane located in the middle of the two berths (x=370,0m) – figure 23:</u>

For this case, using the reasoning procedure described at section 4.2, the distances for each Block to each Ship are calculated below:

From Block A to ship A: $S_{A-A} = 2\cdot 240 + 130 + \widetilde{130} = 610 + \widetilde{130}$

From Block B to ship A: $S_{B-A} = 2\cdot(525-240) + 130 + \widetilde{130} = 700 + \widetilde{130}$

So, the mean maximum distance for Ship A (considering the different dimensions of Block A and Block B) is

$$S_{\text{mean }-A} = \frac{S_{A-A}\cdot\frac{370}{525} + S_{B-A}\cdot\frac{525-370}{525}}{525} = 636 + \widetilde{130}$$

Using the above travelling velocities, the travelling time for ship A is calculated as:

$$\frac{636+130}{19\cdot 1000}+\frac{130}{11000}=0.052h=3.12min$$

The same procedure is followed for ship B:

From Block A to ship B: $S_{A-B} = 2\cdot 495+130+\widetilde{130} = 1120+\widetilde{130}$

From Block B to ship B: $S_{B-B} = 2\cdot(495-370)+130+\widetilde{130} = 380+\widetilde{130}$

So, the mean maximum distance for ship B is $S_{mean\,-B} = \frac{S_{A-B}\cdot\frac{370}{525}+S_{B-B}\cdot\frac{525-370}{525}}{525} = 900+\widetilde{130}$

Using the above travelling velocities, the travelling time for ship B is calculated as:

$$\frac{900+130}{19\cdot 1000}+\frac{130}{11000}=0.066h=3.96min$$

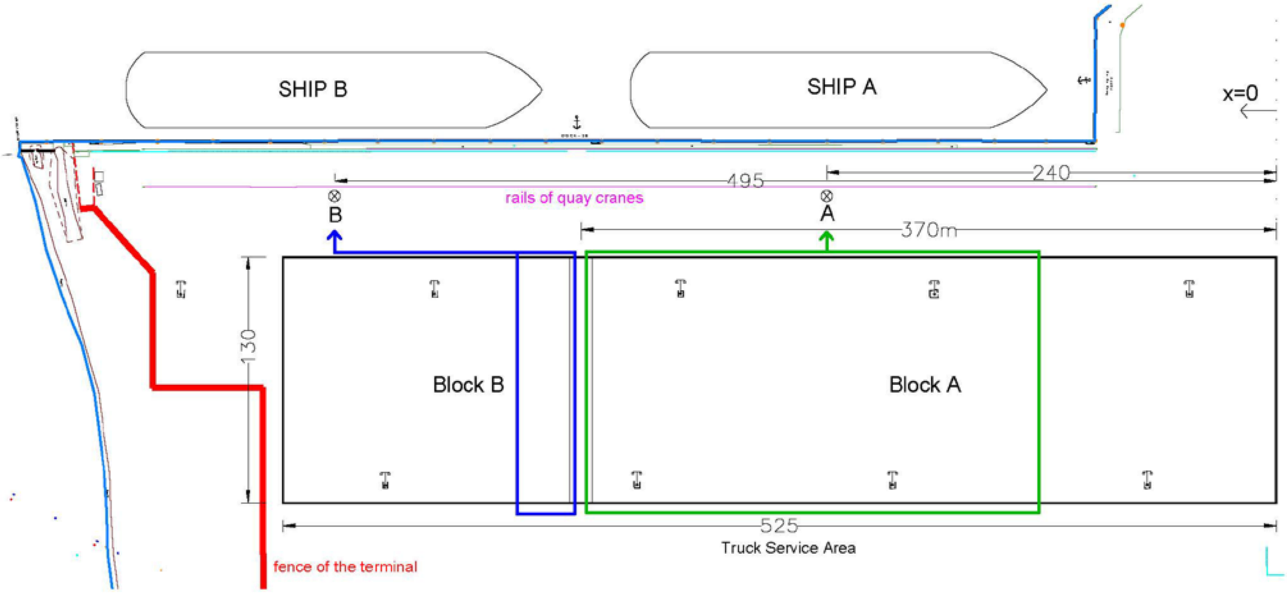


Figure 23 - The position of the traffic lane in the middle of the berthing positions

Making a comparison between the two cases, it is confirmed that the lane in the middle of the layout is the optimum and the theory works:

Time in min for straddle carrier cycle		
Ship	Lane in the middle of the layout	Lane in the middle of the ships
A	2.78	3.12
B	3.42	3.96

4.4 Optimisation test case: Considering more traffic lanes

The case for one traffic lane could probably work for a short stacking yard, but for a yard with a longer length it would be interesting to examine the case using more traffic lanes and the consequences of this choice for the travelling time and for the stacking capacity of the yard.

Considering more traffic lanes in random positions, the determination of the optimum position of the lanes becomes a more complicated mathematical problem, using the above theory. However, considering that the block dimensions are the same, so the lanes are located in L/3 and 2L/3 locations, a common consideration made by literature [14], the travelling distances for straddle carriers can be determined and compared with the results for one traffic lane.

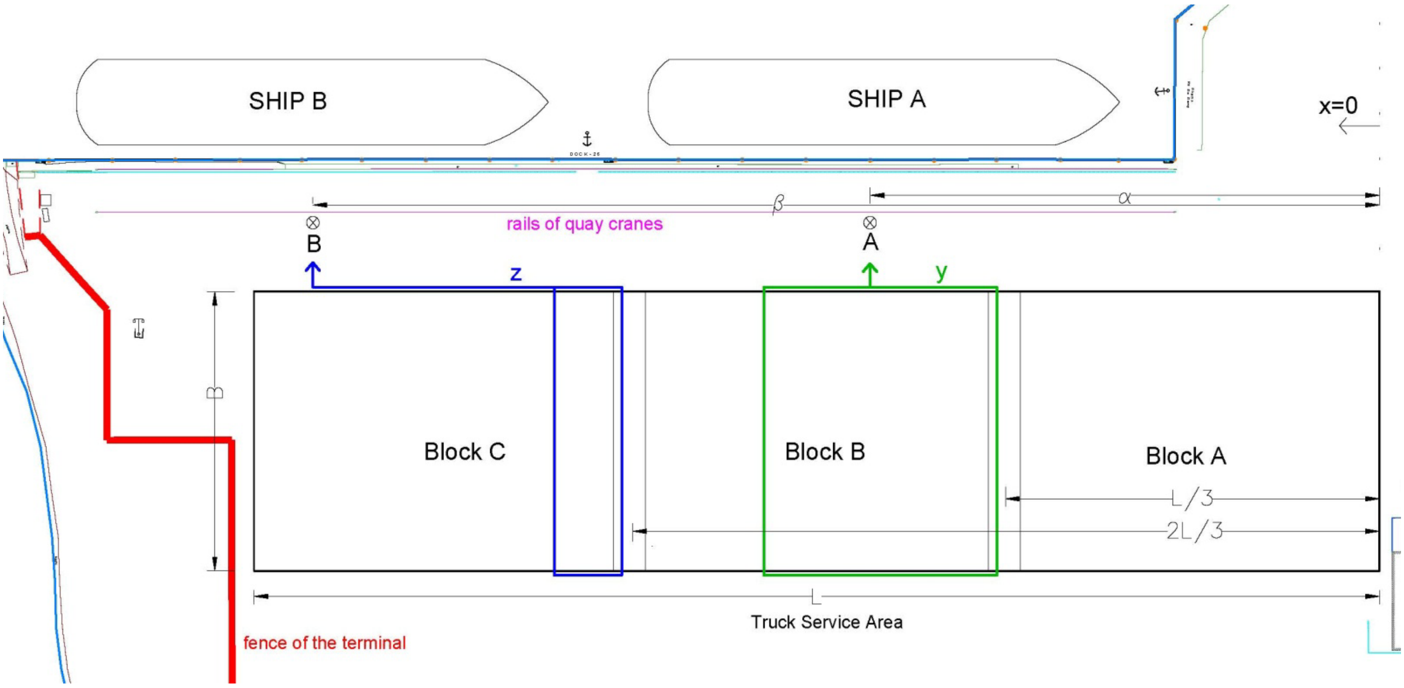


Figure 24 – The whole travelling distance for SCs in a perpendicular layout with two traffic lanes

The maximum travelling distances from each block to each ship are calculated as follow:

From Block A to ship A: $S_{A-A} = 2 \cdot \alpha + B + \tilde{B}$

From Block B to ship A: $S_{B-A} = 2 \cdot \left(\frac{2 \cdot L}{3} - a\right) + B + \tilde{B}$

From Block C to ship A: $S_{C-A} = 2 \cdot (L - \alpha) + B + \tilde{B}$

The mean maximum distance considering that each block has the same length (L/3) is then:

$$S_{m-A} = 2 \cdot \frac{L-a}{3} + B + \tilde{B}$$

This distance, using the velocities of straddle carries for the port of Thessaloniki mentioned before, results in a travelling time of 1.72min

With the same thinking, for ship B, the procedure is as follows:

From Block A to ship B: $S_{A-B} = 2 \cdot \beta + B + \tilde{B}$

From Block B to ship B: $S_{B-B} = 2 \cdot \left(\beta - \frac{L}{3}\right) + B + \tilde{B}$

From Block C to ship B: $S_{C-B} = 2 \cdot (\beta - \frac{2 \cdot L}{3}) + B + \tilde{B}$

The mean maximum distance considering that each block has the same length (L/3) is then:
$S_{m-B} = 2 \cdot \left(\beta - \frac{L}{3}\right) + B + \tilde{B}$

This distance results in a travelling time of 3.14min

In the following table, there are the results for the cycle time of Straddle Carriers in a layout with one traffic lane and with two traffic lanes:

Time in min for Straddle Carrier cycle			Difference
Ship	One lane	Two lanes	
A	2,78	1,72	-38,13%
B	3,42	3,14	-8,19%

It is obvious that the reduction of the travelling time for ship A is large, over one minute and for ship B shorter but still important.

The consequences in the storage capacity of the yard can be calculated as below:

The typical width of a traffic lane measured in the Port of Thessaloniki is 13.50m.

The required width for a straddle carrier's row is the width of the ground slot plus the width of the lane between the ground slots for the movement of the wheels of the carrier. The width of a ground slot is 2.70m and the width of the lane between the rows is 1.70m measured in the port of Thessaloniki.

So, an extra row needs 2.70+1.70 = 4.40m

Then, an extra traffic lane takes the place of 3 rows.

In the width of B=130m, there are 20 bays so an extra traffic lane costs $3 \cdot 20 = 60\text{TGS}$

Considering a 3-tier stacking, this lane costs 180 less TEU slots for the terminal.

4.5 Calculation of the current performance of the yard and proposition of an optimisation

The part of the stacking yard of Thessaloniki's container terminal which has been studied is the seaside part of the yard which is currently used for outbound (export) containers and is handled by 1 over 3 straddle carriers, so the containers are stacked in 3 tiers. This is one of the most important parts of the yard as it is directly connected with the loading time of the ships.

Before proceeding to calculations, it is important to set up again the assumptions of this case study:

- Straddle carriers enter the block from the seaside and exit the block from the landside.
- Straddle carriers do not move backwards.
- Straddle carriers cross a row only in case they need to pick-up or stack a container. Otherwise, they move around the block through traffic lanes.
- Point A and B represent the mean positions of quay cranes when operating on ship A and ship B respectively.
- All containers have the same possibility to be picked-up for loading and all the ground slots have the same possibility to be chosen for stacking an unloaded container from each ship.
- The free-moving velocity of a straddle carrier is 19km/h and the in-block velocity is 11km/h. The reduction of the velocity during turning has a negligible effect in the total travelling time of a cycle.
- Only travelling time is considered for the optimisation of the yard. Picking-up, stacking and reshuffling time is not taken into account as it is not affected by the position of the traffic lanes.

Currently, in the studied part of the yard there are 3 blocks, as presented in figure 25: The A2 block with 378 TGS, the A3 block with 700 TGS and the A4 block with 1480 TGS.

Using simple mathematical thinking and measuring on the plan, the following maximum travelling distances can be calculated for each block to each ship: (distance under ~ is the in-block distance)

$$S_{A2\rightarrow A} = 2\cdot 320 + 89 + \widetilde{89}m$$

$$S_{A3\rightarrow A} = 2\cdot 200 + 130 + \widetilde{130}m$$

$$S_{A4\rightarrow A} = 2\cdot 325 + 130 + \widetilde{130}m$$

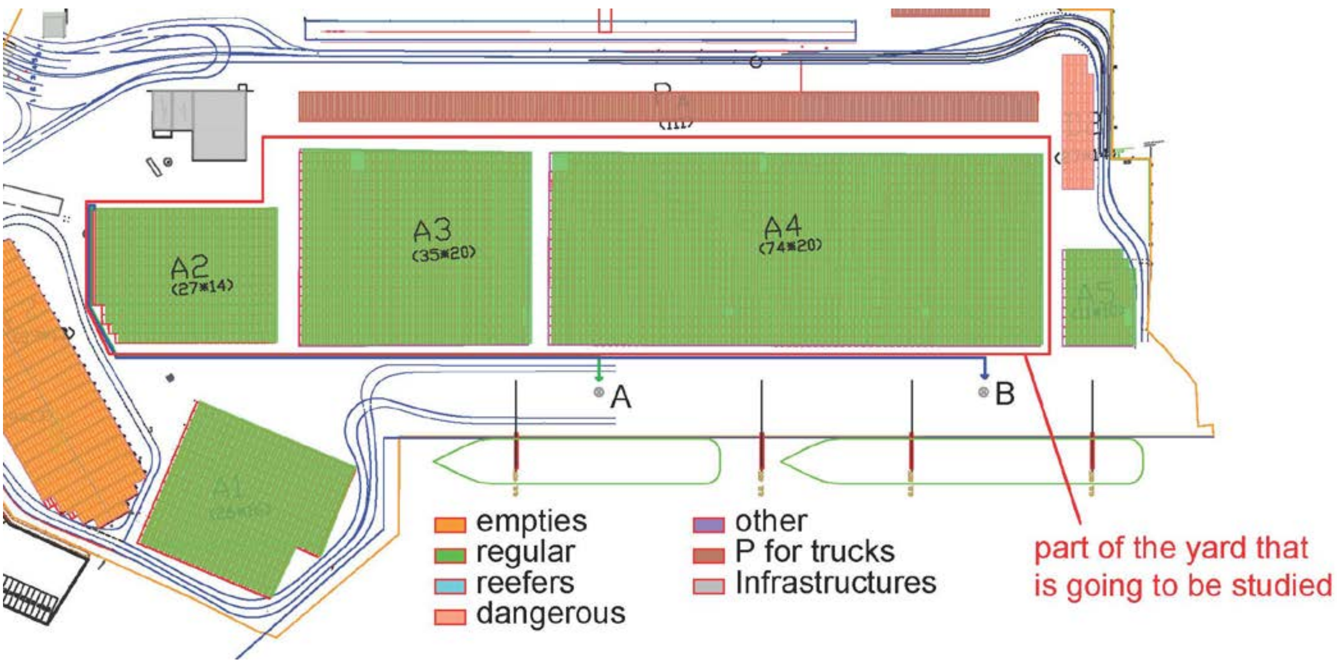


Figure 25 – Part of the current layout of the port which is going to be optimised

The weighed mean distance considering the number of TGS in each block for ship A is:

$$S_{mean \to A} = \frac{378 \cdot S_{A2\to A} + 700 \cdot S_{A3\to A} + 1480 \cdot S_{A4\to A}}{378 + 700 + 1480} = 580 + 124 + \widetilde{124}$$

So, the mean maximum travelling time is calculated as:

$$t_{mean \to A} = \frac{580+124}{19000} + \frac{124}{11000} = 0.0483h = 2.90min$$

The same procedure for ship B gives the following results:

$$S_{A2\to B} = 2 \cdot 590 + 89 + \widetilde{89}m$$

$$S_{A3\to B} = 2 \cdot 455 + 130 + \widetilde{130}m$$

$$S_{A4\to B} = 2 \cdot 325 + 130 + \widetilde{130}m$$

The weighed mean distance considering the number of TGS in each block for ship B is:

$$S_{mean \to A} = \frac{378 \cdot S_{A2\to B} + 700 \cdot S_{A3\to B} + 1480 \cdot S_{A4\to B}}{378 + 700 + 1480} = 800 + 124 + \widetilde{124}$$

So, the mean maximum travelling time is calculated as:

$$t_{mean \to B} = \frac{800 + 124}{19000} + \frac{124}{11000} = 0.0600h = 3.59min$$

The proposition for the new layout is to split in three equal parts the distance between the left edge of block A2 and the right edge of block A4. By doing this, the new layout is as shown in the figure below:

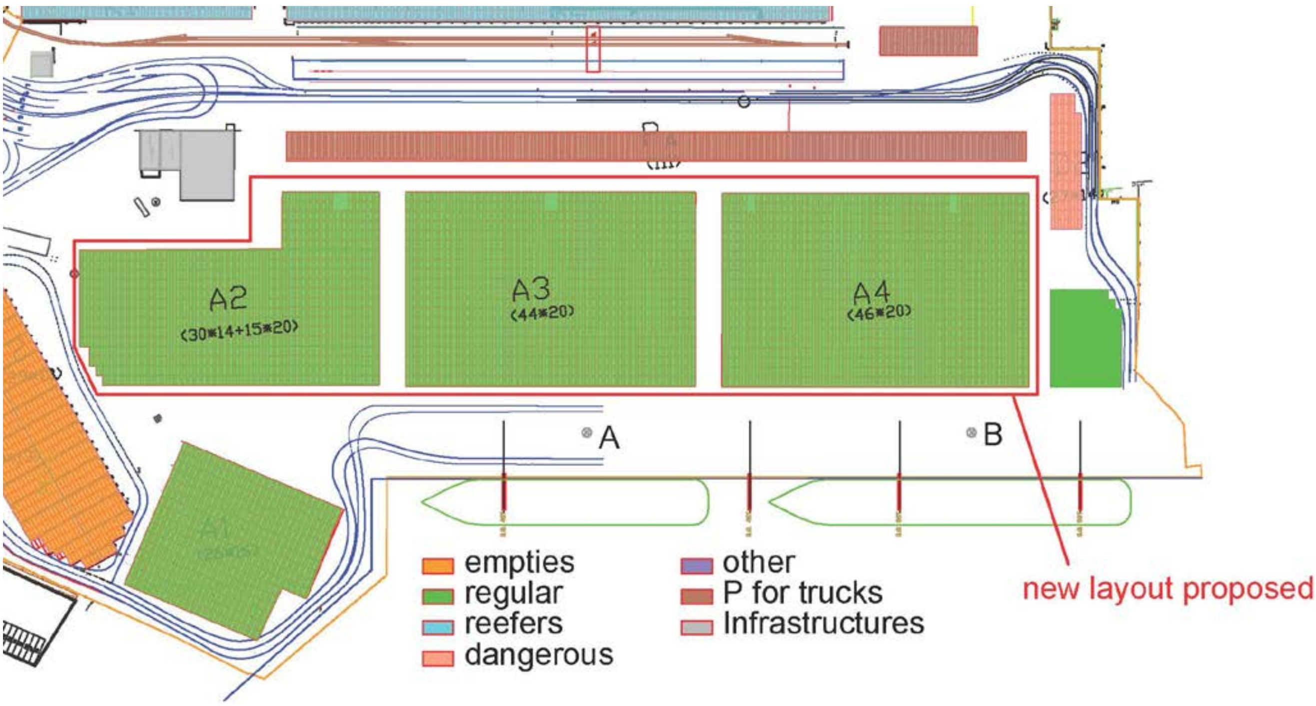


Figure 26 – Proposition for layout re-arrangement

By applying this rearrangement, there are created the following 3 new blocks: The A2 block with 720 TGS, the A3 block with 880 TGS and the A4 block with 920 TGS. The total TGS are 2520 instead of 2558 that were before the rearrangement.

Using the same simple mathematical thinking, the following maximum travelling distances can be calculated for each block to each ship: (distance under ~ is the in-block distance)

$$S_{A2\to A} = 2 \cdot 330 + 89 + \widetilde{89}m$$

$$S_{A3\to A} = 2 \cdot 190 + 130 + \widetilde{130}m$$

$$S_{A4\to A} = 2 \cdot 290 + 130 + \widetilde{130}m$$

The weighed mean distance considering the number of TGS in each block for ship A is:

$$S_{mean\to A} = \frac{720 \cdot S_{A2\to A} + 880 \cdot S_{A3\to A} + 920 \cdot S_{A4\to A}}{720 + 880 + 920} = 533 + 106 + \widetilde{106}$$

So, the mean maximum travelling time is calculated as:

$$t_{mean\to A} = \frac{533 + 106}{19000} + \frac{106}{11000} = 0.043h = 2.60min$$

The same procedure for ship B gives the following results:

$$S_{A2\to B} = 2 \cdot 590 + 89 + \widetilde{89}m$$

$$S_{A3\to B} = 2 \cdot 375 + 130 + \widetilde{130}m$$

$$S_{A4\to B} = 2 \cdot 202 + 130 + \widetilde{130}m$$

The weighed mean distance considering the number of TGS in each block for ship B is:

$$S_{mean\to A} = \frac{720 \cdot S_{A2\to B} + 880 \cdot S_{A3\to B} + 920 \cdot S_{A4\to B}}{720 + 880 + 920} = 745 + 106 + \widetilde{106}$$

So, the mean maximum travelling time is calculated as:

$$t_{mean\to B} = \frac{800 + 124}{19000} + \frac{124}{11000} = 0.0544h = 3.27min$$

Applying the above re-arrangement in the seaside part of the stacking yard of the port, the results are summarised below:

	Time in min		TGS			
	Ship A	Ship B	A2	A3	A4	Total
current	2.900	3.594	378	700	1480	2558
proposed	2.596	3.266	720	880	920	2520
difference	0.303	0.329	342	180	-560	-38
% improvement	10.47%	9.15%	90.48%	25.71%	-37.84%	-1.49%

Following this analysis, it can be conclude that an operational adjustment to the storage arrangement of the container terminal in an SC yard can result in significant benefits in the reduction of travel time for each seaside cycle of a straddle carrier. For the port of Thessaloniki case, a 10% reduction in travel time can be achieved at a cost of only 1.5% reduction in ground slots.

5 Discussion

Throughout this research project, various assumptions and considerations have been made. These are discussed below, considering their impact on the conclusion and recommendations.

- Different types of equipment

The yard layout arrangement is a common problem for a container terminal, not only in the beginning, when the initial plans of the terminal are studied, but also during its operation, when various characteristics of the terminal can change. The optimum arrangement of the yard is different for different kind of equipment and in the case of straddle carriers, this problem is treated analytically by Jörg Wiesse, 2012, "Quantitative Decision Support for the Layout Design of Container Terminals" [14].

- Pooling strategy

A very important step before proceeding to the analysis of the yard layout is to set up the assumptions of the problem. Pooling strategy and the straddle carrier traffic scheme are very important parameters in determining the arrangement of the layout. For this report, a single cycle strategy for straddle carriers is considered, for which each straddle carrier performs only one task (loading or unloading of a ship) and it is assigned to one quay crane. The traffic scheme is that it can move only forward in the yard during operation. This is considered a reasonable assumption, as this is the general way of operation. Backward movements are limited due to safety issues, as the visibility of the driver is more restricted.

The analysis above is very sensitive to these two assumptions, as by changing them, the whole consideration of travelling distances of straddle carrier is different so the probable solution of the yard layout problem could be different. These two assumptions do not influence only the values of travelling speed, but also the consideration of the routes that straddle carriers follow. It would be interesting in a future research case to test this theory with a different traffic scheme, for example by comparing different pooling strategies.

- Shape of the yard

The assumptions for the shape of the yard and the location relative to the quay (rectangular yard and straight quay wall) are important because they also affect the consideration of routes and travelling distances. More complicated shapes for the layout (like trapezoidal) are generally not applied, but a quay wall in an angle or with a corner can be applied depending on the topographical characteristics of the terminal and the available space. So, more research on this field could be useful in case of terminals with more complicated topography.

- Straddle carrier characteristics

The characteristics of straddle carriers, like the travelling speed inside and outside the blocks or the consideration of no speed reduction when turning seem to be of less importance, as they can affect the cycle time but this affect is the same no matter where the traffic lane is considered to be located. The lifting characteristics (1 over 2 or 1 over 3) are also not important for the position of traffic lanes. They could be important for the amount of traffic lanes as a new lane in a layout with more tiers takes the place of more stacking slots.

Finally, it is important to be mentioned again that every terminal is a different case that needs special study. Any generalisation of the theory needs to be done with great care, and should consider the validity of the assumptions and simplifications.

6 Conclusions

The container terminal of a port consists of three main areas: The quayside, the yard and the landside area. Each area has different kind of equipment, personnel with different skills and background, different procedures and its own characteristics for an effective operation. The productivity of the terminal depends not only on the capacity of each area separately but also on the effective collaboration among the different areas. In case of a modification that is going to improve the operation of an area of the terminal, it is necessary to check also the influence of this modification to the interaction between this area and the rest of the terminal.

The modelling of a general layout of container terminals is a quite complicated procedure. For greenfield ports, this procedure is valuable because there is a large freedom of arranging the layout by locating the infrastructures wherever is more convenient for the most effective operation of the whole terminal from the beginning. For brownfield ports, where infrastructures like buildings, electricity supply, railways are already in position, a layout rearrangement of the terminal is more difficult with less degrees of freedom. Every terminal is a different case which needs different treatment and the general theory may be not applicable.

However, for a given terminal, by using simple mathematical relations and by making reasonable assumptions related to the operation of this specific terminal, it is possible to come up with valuable results and be able to make an effective proposition for the layout rearrangement. Using this simple theory for a perpendicular layout, a rectangular part of the yard and assuming only forward move for straddle carriers, the optimum positions of traffic lanes are located if the layout is split into equal parts. The position of the blocks compared with the quay crane is not important (there can be an eccentricity of the quay) at least in case of one traffic lane.

Applying the above model for the seaside part of the layout in the port of Thessaloniki, a reduction of 10% can be achieved for the travelling time of straddle carriers. This reduction not only provides a good recommendation for the terminal operator, but also gives a first verification of the model in a real case.

Figure 27 – Artistic photo of the port of Thessaloniki, from the city side, 2017 [26]

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