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# Simulation Analysis for Integrated Container Terminal Activities

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Advisors:    Daria Battini                      Student:   Niccolò Pietrobon

             Allan Larsen

Co-advisor:  Cagatay Iris

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# *Introduction*

Containers or intermodal containers are a reusable transport and storage unit, designed to be moved between different mode of transport, such as ships, trains and trucks, without be unloaded or reloaded, for moving products and raw material among different countries. They can be shipped, stored and handled and for these reasons they are widely used for intermodal shipment all over the world. Their invention, dated after the end of the World War II, boosted the globalization of commerce in the second half of the 20$^{th}$ century, drastically reducing the cost of transporting goods and hence the long-distance trade. Containers are standardized in order to be moved between different modes of transportation. The cargo capacity is the twenty foot equivalent unit (TEU) and it is based on a volume of twenty feet of length and eight feet of width, which is equivalent to one TEU. Containers can also be of two TEUs, meaning that their length is the double of one TEU containers but with the same eight feet of width.

Due to the exponential growth of this market, many researches are published every year, dealing with the real possibility of improving ports performance by simulating container terminals activities both on the sea-side, meaning fastening ships loading and unloading, and on the land-side, referring to improve connections between companies and terminals. Next to those, also all the activities in terminals, that made the containers move from the sea-side to the land-side, have to be improved in order to avoid port congestion or slowdowns, aiming to higher efficiency and productivity. Terminals can be essentially thought as made of three areas: ships operation area, yard and trucks and trains operations area. The first one is the quay, usually split in berths, where ships interface with the land-side thanks to quay cranes which consent to load and unload containers. The yard is the area where containers are stored and park once they are unloaded, waiting to be moved back on ships or to leave the terminal. The trucks and trains operation area is the terminal zone where containers are loaded on trains or on trucks to be transferred outside ports to reach customers who requested the good transportation. Thus ports require the synergy of multiple activities which have to be coordinated to work together to achieve the highest efficiency possible. In ports are also required specific vehicles for moving container from the quay-side to yards or to trucks and trains operations area and vice versa. Those typical vehicles, as well as the trained staff who works next to them into terminals, are topics of deep researches, because they can affect heavily ports efficiency and productivity.

Among the big amount of studies published every year, most of them focus on simulating the quay side operations, which means coordinating the vessels arrival, forecasting the right productivity based on schedules, berthing ships in the right place and at the right time, avoiding port congestions or idleness, assigning the appropriate quay cranes to moored vessels, which need to be served, based again on schedule and availability of cranes, and, eventually, deciding which vehicles utilize to move containers and which routes use to minimize time and space. The primary objective of these simulations is to cut down services time, minimize costs and maximize profits and customers satisfaction, through a continuously increasing efficiency and throughput.

This research focuses on the sea-side operation of berthing vessels, in order to determine the most effective and convenient solutions that maximize efficacy and proficiency. The simulation models and studies a continuous quay side for the berthing process, in order to make a direct comparison with a discrete quay, modeled and simulated in the same way. A discrete scenario assumes that wharfs are divided in a precise number of berths, split with boundaries that do not allow overlapping between adjacent berths, in the mooring process. The continuous scenario allows berthing vessels all along the wharfs, overcoming the boundaries, limitations and constrains set in the discrete methodology. The continuous framework breaks down the bounds of berth and wharfs are considered as a single berth. The continuous berthing space enables a higher exploitation of the wharfs and then a higher efficiency of ports, in respect to the discrete one, as well as a more accurate and realistic analysis and evaluation of ports performance. Indeed the overestimations of the discrete berthing condition are overcome with the continuous berthing space and, at the same time, productivity of ports is increased. Due to the higher performance granted by the continuous solutions, the berthing process is afterward modeled and analyzed altering the speed of incoming vessels, according on a specific condition, focusing on minimization of the fuel consumption and emission of vessels, during the sailing as much as in the appropriate areas at ports where vessels are temporary moored before being berthed at wharfs for being served. Changing the speed of incoming vessels, more than one time, allows speeding up vessels, if wharfs resource utilization is too low, or to slow them down to avoid port congestions, saving on fuel consumption and reducing emissions. The objective of the second half of the research is to analyze and compare the continuous quay side with the discrete one, for validating the advantages on using the continuous scenarios also in a more dynamic case. Both simulations are analyzed with four different models which differ in the berthing process. Three out of four models assume the berthing space as continuous, instead the last consider the quay side as discrete, to enable the final comparison between the discrete situation and the continuous one. Despite the easiness and approximations assumed in the discrete scenario, the continuous quay is modeled, analyzed and studied to verify and support the advantages of using this

condition in real-life ports. The four models utilized in the simulation are called *Sub-berths*, *Fully Discretized, Hybrid Discretization* and *Desired Position*. They are named distinctively to underline their heterogeneous policies in the berthing process. The four models are also simulated imposing a further constrain on the queue where ships wait in the port before the berthing process, due to resources unavailability or space limitations. In fact the number and time of vessels, temporary moored in this appropriate area, affect significantly the port efficacy. Thus it is studied the correct order with which vessels have to be berthed, with the ultimate purpose of increasing ports performance and efficiency. The queue policies applied are the *first-come-first-served* (FCFS), *shortest processing time* (SPT), *earliest due date* (EDD) and *biggest load* (BL). Each policy creates a ranking to berth vessels, which is continuously updated, and the order depends either on when vessels arrive at the port or on their length and the time required to be served and processed. Those same models and queue policies are applied when the speed assignment is simulated with the berthing process and, in order to find the best condition of speeding up or slowing down vessels, another restrain is added. The speed of vessels is changed only after they are 500 nautical miles away from port and then it is repetitively changed while they sail to the port, two times more. The trigging condition for altering the speed of incoming vessels is the number of the already queued ships at the port, and this number is changed to assess possible benefits in terms of costs as well as in port performance. The comparison among models is accomplished thanks to the collection of some measures of performance, during the simulation, for each models and queue policy applied. The main indicators are the wharfs utilization, the average number and time vessels have to wait in the queue, total time required to complete the berthing process and the resulting costs of models utilization.

The simulation models which are used to evaluate the proposed modeling approach are developed in ARENA 14.50 Simulation Software. The results of the conducted computational experiments showed that in the pure berth allocation the proposed modeling approach provides more accurate and realistic estimates of performance measures, such as average wharf utilization, average ship waiting time in a queue, and the average number of ships in queuing up to get container terminals. While dealing with the possibility of change the speed of vessels, similar outcomes are recorded, reminding that in the second scenario cost are boosted due to the further addition, to previous factor, of the fuel consumption.

# Chapter 1

# Integrated Container Terminal

## 1.1   Terminal activities

A container terminal is a facility where cargo containers are moved between different transport vehicles, for the allowing the exchange of every kind of goods. The transshipment may be between container ship and land vehicles, usually trains or trucks, or, alternatively, can be between land vehicles: in the former case the terminal is described as a maritime container terminal; in the latter the terminal is described as an inland container terminal. Maritime container terminals often are a part of a larger port, and the biggest maritime container terminals can be located around major harbors. Inland container terminals tend to be located in or near major cities, with good rail connections to maritime container terminals. Both maritime and inland container terminals usually provide storage facilities for both loaded and empty containers. Loaded containers are stored for short periods, while waiting for moving on in transportation; unloaded containers may be stored for longer periods awaiting their next use.  Containers are normally stacked for storage, and the resulting stores are known as container stacks. In recent years methodological advances regarding container terminal operations have considerably improved and so container transportation grew considerably in worldwide and with it the necessity to optimize it, to let it grow more efficient and with lower costs. Indeed productivity, efficiency and performance have to increase drastically because the challenge ports are meant to satisfy is the demand, and then the handling, of mega-vessels capable of carrying 10000 – 12000 TEU, twenty foot equivalent unit, and beyond.

Within the international supply chain and logistics system, ports have become more and more important in the basic transport activities. Thus, any shortage in or lack of well-planned orders encountered in the port operation processes is most likely to affect the whole logistic system, which eventually will cause undesirable delays in deliveries and then relative cost penalties. A supply chain is essentially a business process that links manufacturers, customers and suppliers in the form of a 'chain' to develop and deliver as one 'virtual' organization of resources (Lee, Park, and Lee 2003). As one of the most important transportation infrastructure, ports are the noticeable rings of the international supply chain.

Ports are very important to the transport logistics networks, but the main problem is to optimize all the operations which take place in a port. Apart from their role as the traditional sea/land interface, ports are a good location for value-added logistics, in which members of different channels can meet and interact. Thus, the port system not only serves as an integral component of the transport system, but is also a major subsystem of the broader production and logistics systems (Bichou and Gray 2004). Due to a great deal of advantages it offers and thus its attracting an immense variety of goods with a steadily increasing rate, containerized shipping has recently and increasingly used as preferred means of transport. This constantly increasing business bring a continuous improved and research for optimization, leading to the creation, in the recent years, of a container ships over 13000 twenty-foot equivalent unit (TEU) utilized on routes between ports. The primary cause for such rapid increases in tonnages and terminal handling capacities lies in the rapid improvement in containerized shipping enabling to reach vital hub for the transportation and movement of containers. Container terminals play a fundamental and important role in the worldwide trade, aiming to improve operational efficiency, such as transport operations within the port area, warehouse operations, loading and unloading processes and certain gate operations comprising check in and check out.



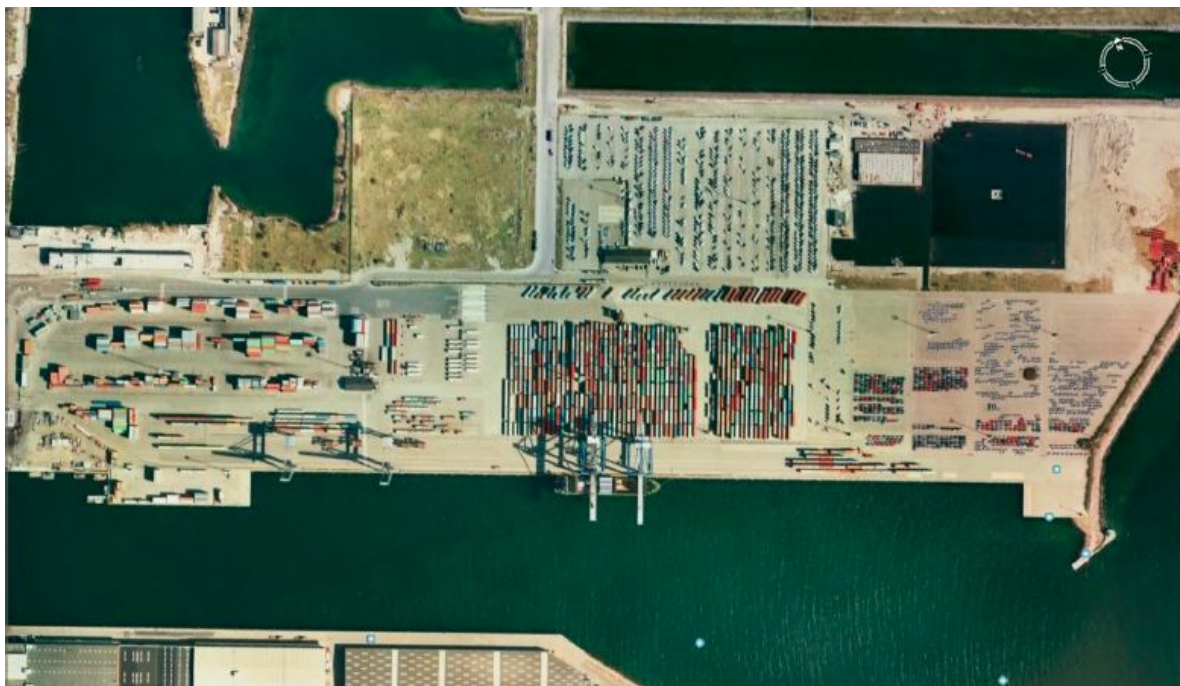**Figure 1.** Copenhagen port seen from the satellites

The objective of the port management is to monitor all the processes and find a way to measure their performance in order to promote the quality of the service provided. In fact the demand of

transport service for terminals has increased, and it will increase more, thank to the growth of new seaborne container routes. This market has started a fierce competition among different ports to get as much as possible customers: improvements, and then investments, are absolutely needful to optimize all the problems within the container terminals. These problems are highly dependent and connected, from loading and unloading to storage containers: the goal is to constantly improve utilization of resources, such as berths, container yards, quay cranes, yard cranes and all the vehicles used in ports, to improve efficiency and productivity. Despite the interconnection between port activities a unified approach does not exist, because the problem is too large, and so simpler problem are model, analyzed and optimize. Approximate solutions are sought but there is room for improved solution methods and better, finer and more accurate models.  It has to keep in mind that no two terminals are the same but the optimization objectives are the same. The main ones are the minimization of costs, maximization of profits and customer satisfaction. These goals can be reached if ports have a high efficiency in transporting and stacking a considerable number of containers from and to the quay-side and a high productivity and containers throughput from quay-side to land-side and vice versa with the lowest possible cost. Moreover ports must kept adherence to delivery dates and promised handling times.  Thus container terminals have to provide an efficient and cost-effective service, investing a lot to meet the demand for faster and higher quality. In order to study the effects of the determinants of port competitiveness, the indicators of port competitiveness should first justify. Since the environment in which ports operate continuously changes, ports are affected by different and various factors driving global competition, including the far reaching unitization of general cargo, the rise of mega-vessels, the use of software of logistics integrators, the creation of network linkages among port operators, the development of inland transport networks and so on.

In this context, J. Tongzon and W. Heng (2005) propose eight key determinant factors of port competitiveness, which should always be taken in consideration by the port management. The first one is the *port operation efficiency level*. In container terminals the speed of container handling and accordingly the vessel turnaround time, the total time needed to serve completely vessels, is a crucial issue in term of competitiveness. Then increasing the productivity is extremely necessary to enable ports to meet the service requirements of their customers and to get competitive advantages. Productivity can be considered a measure of the efficiency of the port and measured by the number of resources utilized for a given task in a given time. The level of efficiency can be represented how quickly containers are handled and how quickly vessels are turned around ports. The second one is the *port cargo handling charges*, an important factor that is always considered before the selection of the port or the shipping line. Since the competitiveness is high in this environment, reducing the

total shipping cost can get important advantages. In fact ports with lower service charges are usually preferred. The third key factor which can affect the competitiveness of a port is the *reliability*. Indeed the price is an important factor but reliability influences also the choice of shipping line and shippers. Reliability means a steady performance adapted to shipping lines schedules, ensuring to cut down, as much as possible, strikes, equipments breakdown or other situations that can delay operation processes and impact with huge losses for shippers. The geographical aspect of ports choice is more important than the price, because *port selection is a preference of carriers and shipper* and it makes boost the competitiveness of a port. In fact there is the possibility of losing clients not because of high cost or deficiencies but because customers rearrange new partnerships. The fifth factor is the *depth of the navigation channel*, because insufficient water depths in access channel and port basins prevent some ports from being a transshipment center. In fact many shipping companies intend to increase the size of their container ships, especially of vessels deployed in the container shipping market, and this consideration has significant effects on port competition. The *adaptability to the changing market environment* is the sixth factor that affects port competitiveness. The market environment in which ports operate changes continuously, and a successful port must constantly be prepared to adopt new roles in order to understand the customer needs. The *land-side accessibility* is the second last factor, because efficiency of inland transport prevent from congestions, delays and loss of money. These are the reasons why ports are strategically located close to the main global trade lanes becoming a node in integrated logistics chains with quick and safe accesses from inland transport system satisfying a basic requirement and influencing the port selection. The last factor that a port has to get to grant competitiveness is the *product differentiation*, differentiating from other ports and offering a greater value to port users. A differentiation strategy aims to provide specific port service to create market niches and be the first to exploit them, considering the increasing number of containers and the terminal expansion.

Due to the fact that ports have become intensively operating plants providing a great wealth of services to a member of parties and that the quality of the services provided has increasingly been raised, their structure has eventually become so sophisticated and complex that each port has begun to act as a source of various activities all together. In the literature (Hassan, Saber, and Ragheb, 1993) is suggested that complicated and interconnected port operations are divided into four main categories: *ship operations*, *cargo handling operations* and *warehousing* and *inland transportation*. The *ship operations* are all the processes related to the sea side and regarding the ship. The *handling operations* can be considered the activities required to load or unload containers and then move them around the port. The *warehousing* deals with the storage and stacking of the container in the opposite yard where they are hold to be moved or to be utilized. Finally the *inland transportations*

gathers all the operations necessary to transport containers outside or inside ports, and then other transportation system are required, such as trains and trucks.

According to Koh et al. (1994), the main activities in container port operation can be subdivided into the following types:

• *Berth operation*: The berth operation concerns the schedules of arriving vessels and the allocation of wharf space and quay crane resources to service the vessels.
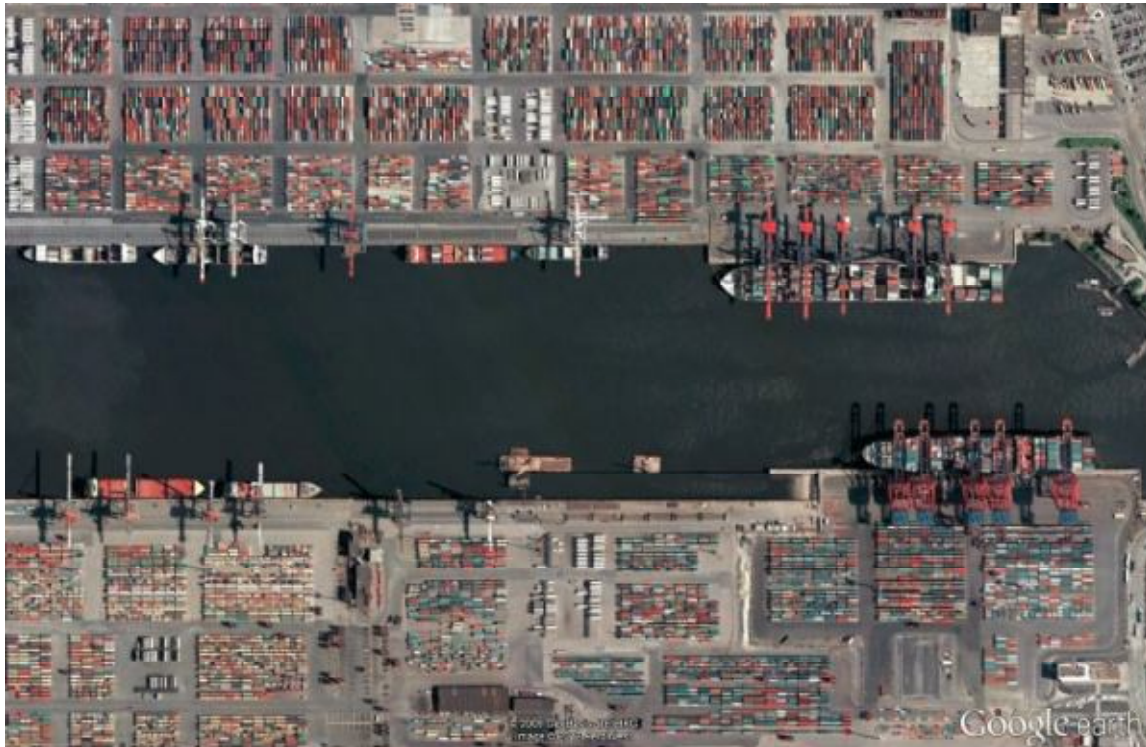


**Figure 2.** A port with two wharfs where vessels are berthed according on their length in precise spot of the quay

• *Ship operation*: The core competence of a container terminal in a seaport is to serve container vessels by discharging and charging containers. Vessel operators expect this service to be as fast as possible. Fast service operations require a careful disposition of the seaside resources, namely the quay space and the quay cranes.
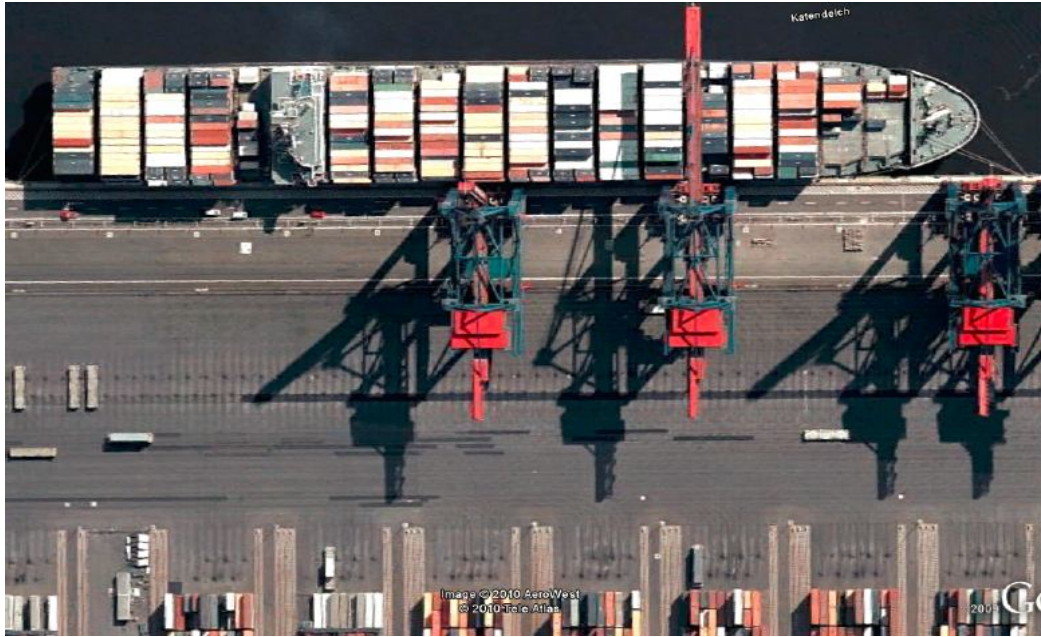
**Figure 3.** The vessel is served by the quay cranes that allow the loading and unloading of containers

• *Yard operation*: The operation involves discharging containers from the vessels, loading containers onto vessels, shuffling containers that are out of sequence in the yard block, redistribution of containers to other blocks, known also as yard shifting, for more efficient loading into the second vessels and inter-terminal haulage where containers are moved to other yards in another terminal.



**Figure 4.** A typical yard of a port where container are stocked and moved with appropriate cranes and vehicles

• *Gate operation*: The gate operation deals with external freight forwarders. Two activities are involved, namely export delivery where the freight forwarders bring in export containers to the yard or wharf to be loaded onto the vessels, and import receiving, where the freight forwarders receive containers from the yard or wharf to bring into the country.

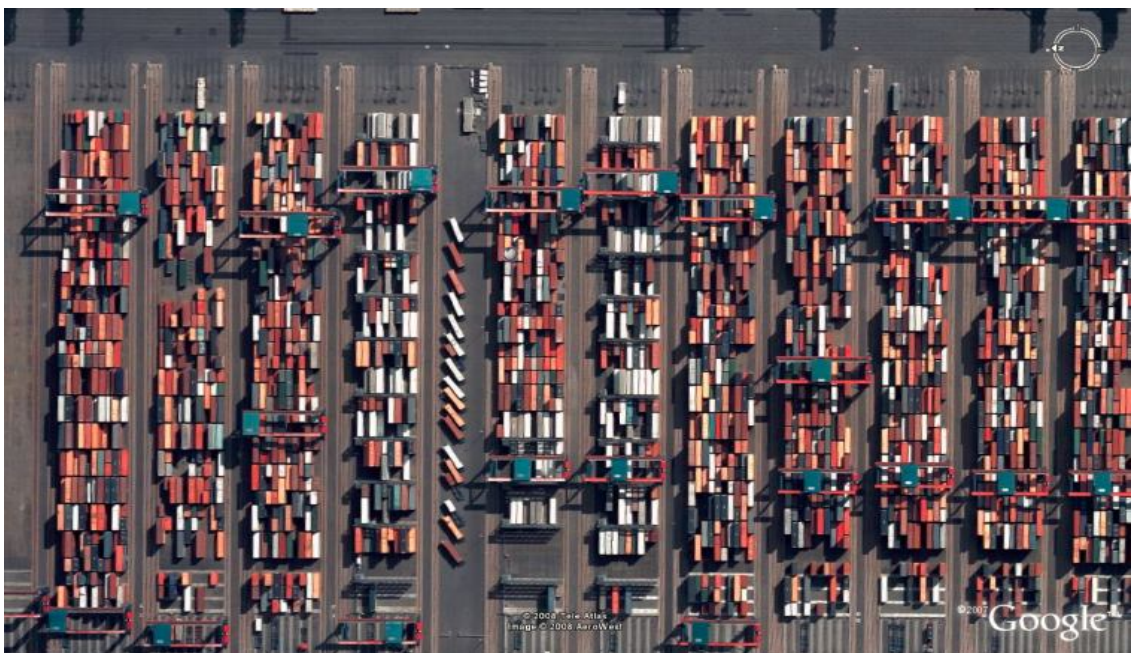• *Scheduling*: This is the function that ensures various resource pools, such as the prime mover, yard crane and other container handling equipment pools, which are utilized. These classification approaches can be used to evaluate different performance indicators, to make port improvement analysis, to study port expansion possibilities and to estimate future view of the port.

In container terminals all the processes and activities have to be coordinate and work in unison to enable the maximum efficiency and productivity in ports. Indeed if only one activity, even if marginal, stops, because of a failure or a breakdown, all the other activities are influenced by it and then accordingly ports performance drastically decrease.

Competition has increased due to the increasing number of seaborne containers route and so terminals are forced to handle more and more containers in short time and low cost. At the same time they have to enlarge their handling capabilities and strive to increase their productivity. Different concepts for satisfying the customers and future demand are utilized: some re-design an advanced layout of the terminal: indented berths, new infrastructures as automation in region with high labor cost, replacement of older equipment with more efficient one, aiming to a better efficiency saving and minor cost and higher profits, helped by powerful information technology and logistics control software including optimization. The exponential growth in worldwide trade makes ports operations topic of deep researches and analysis which have the purpose of optimizing all processes for enable the port to serve and handle more vessels, meaning moving more containers, for increasing the benefits, and at the same time cut down timing and costs as much as possible.

Simulation problems within container terminals can be classified in three main categories, with each of them some sub-categories. These categories are the ship planning process, the storage and stacking logistics and the transport optimization. The ship planning processes aim to optimize all the activities related to the quay-side or sea-side, meaning all the processes related to vessels such as mooring, assigning the right spot and the right crane, loading and unloading. So the problems related to this category are: berth allocation, stowage planning and crane split, quay crane assignment and quay crane scheduling. The storage and stacking logistics problem focus and the land-side and aim to find the best place for placing containers, minimizing reshuffles and transport distance. Indeed the attempt of this optimization problem is to avoid bottlenecks, placing containers

close to destination berth and in the right place and way if they are destined for being moved out of the port, in a short period of time after being stacked, by trains or trucks. The transport optimization problem strive to find the best way to coordinate all the vehicle, automated or not, which work within the terminal and move from ships to yards, quay-side transport, or from yard to rails or trucks, land-side transport. Moreover it is investigated also the crane transport optimization, because cranes have to move along the quay side to serve different vessels berthed all along the wharf. Then it is necessary to schedule, assign and move the right quay crane to serve the vessel just moored in order to get high utilization and performance.

Thanks to the increasing power of informatics tools, such as computer simulation, it is possible to study and model different aspect as well as processes and scenarios in container terminals. Software upgrades help in this simulation phase providing assisting systems and possibility of modeling real existing ports. For this reason the optimization problem focus not only on the previous topics, but it is extended to optimize the handling equipments, human resources and even to experiment new possible solutions, with the ultimate aim of improving efficiency in ports. While talking of handling equipments (Hu et al. 2005, Chu and Huang 2005,Vis 2006) authors refer to common equipment such as the chassis-based transporter, straddle carrier (SC), rubber tired gantry crane (RTGC), rail mounted gantry crane (RMGC), also called automated stacking crane (ASC), or reach stacker. Many study to optimize and propose new solutions and improve those machines to have high performance, in particular in containers storage and transportation to and from terminals in order to avoid port congestion and solve capability problems of terminals, rails as well as highways, which can be affected by ports performance. There are also many studies about human resources (Kim at al. 2004, Legato and Monaco 2004, Lim et al. 2004) focus on the efficient scheduling of operator of handling equipment, with the constrain of minimum workforce assignment to each time slot, maximum operating time per operator per shift, minimum and maximum consecutive operating times per an operator, types of equipment can be assigned for each operator. Scheduling manpower planning problem at marine container terminals is essential to try to overcome the uncertainty of workforce demand as well as to ensure a time continuous efficiency, with the necessity of a long-period planning and a daily planning. Management objective is the minimization of servicemen needed to meet demand as well as the minimization of distances, travel times and waiting times. Next to the mentioned simulation problems there are many studies and publication about new, promising and integrative approaches which aim to improve the terminal performance as an integration of various operations connected one each other. Simulations approaches are slowly replacing analytical approaches, because of the powerful tools they have got

and the simplification they allow in complex scenarios as well as the possibility to find solutions, thanks to heuristic or meta-heuristics methods, to problems of impossible analytical resolution.

Although the port environment generally has become increasingly competitive, it has to consider that each port environment is typical on its own and then these factors can vary between regions and places depending on the proportion with which these forces have impacted the nature of the port environment. Due to the differences between ports it has become quite difficult to find out a general solution for each port that can summarize efficiency and productivity. It is necessary to decide and adopt the right tool to analyze each scenario. It is not easy to measure the port performance, choosing the right key performance indicators (KPIs), because each port has its own features, characteristic and peculiarities, making it quite difficult to create standardization. It is significant to optimize logistic operations at seaport container terminals, because they are really important for the desired success and for high efficiency of ports. It is essential then to reduce unproductive delays at the port and to offer effective processes in order to meet the severe and increasing competition among terminals in this booming line of business with a high prospective growth rate. High investments as well as high operating cost for ships and port equipments enforce improvements of terminal operations. A terminal competitiveness includes issues of waterside operations and internal logistics as well as land-side operations, transport connection and routing with the surrounding area. A new challenge is to handle the mega-vessels. Key to efficiency seems to be automation of in-yard operation, storing and stacking as well as the use of optimization methods, such as intelligent routing and scheduling mechanism for vehicles. Thanks to modern information systems and communications technology optimizations methods can be adopted for different areas of the port. Despite simplifications the topic is really complex and difficult to simulate, analyze and eventually optimize. Usually in fact topics are considered separately, but for getting the best solutions they should be correlated, because great results in a single activity or process can be drastically if connected to others. Increased research on integrated simulation seems to be necessary for increasing terminal performance. Without software incorporating optimization algorithms for control of terminal operations there will not be for sure the expected gain in productivity.

Facing the intense challenge, in order to attract more vessels, container terminal operators have tried to provide more intensive logistic services and meanwhile to reduce costs by utilizing resources efficiently, including human resources, berths, container yards and various container handling equipments. Among all the resources, berths are the most important resource and good berth scheduling improves client's satisfaction and increases port throughput, leading to higher revenues of port (Kim and Moon 2003).

## 1.2    Berth allocation problem

The berth allocation problem (BAP), also known as the berth scheduling or planning problem, is a problem regarding the decision and the allocation of berth space for incoming vessels in container terminals. Vessels arrive over time and the terminal operator needs to assign them to berths, because they need to be served as soon as possible, so they can leave the port for another container terminal. When a vessel has to be served it means that an amount of containers, depending on the length of the vessel, are loaded or unloaded with special quay cranes. During the loading or unloading operation containers have to be moved from the land-side to quay-side or vice versa and so appropriate vehicles are utilized, such as trucks, automated guided vehicles (AGVs), straddle carriers (SCs) or automated lifting vehicle (ALVs), also called automated straddle carrier.



**Figure 5.** Automated guided vehicles (AGVs) are often utilized in ports for increasing productivity and efficiency

Different factors can affect the berth and time assignment for each vessel, such as terminal operator decisions, berthing policies, handling times or other correlated port activities. Those are the reasons why berth allocation problem is the center of attention of many studies.

The berth allocation problem, as mentioned before, is one of the topics deeply study, in order to optimize terminal activities. Most of the times berth allocation problem (BAP) is studied and analyzed with other activities, with the purpose of finding the best correlation between them.
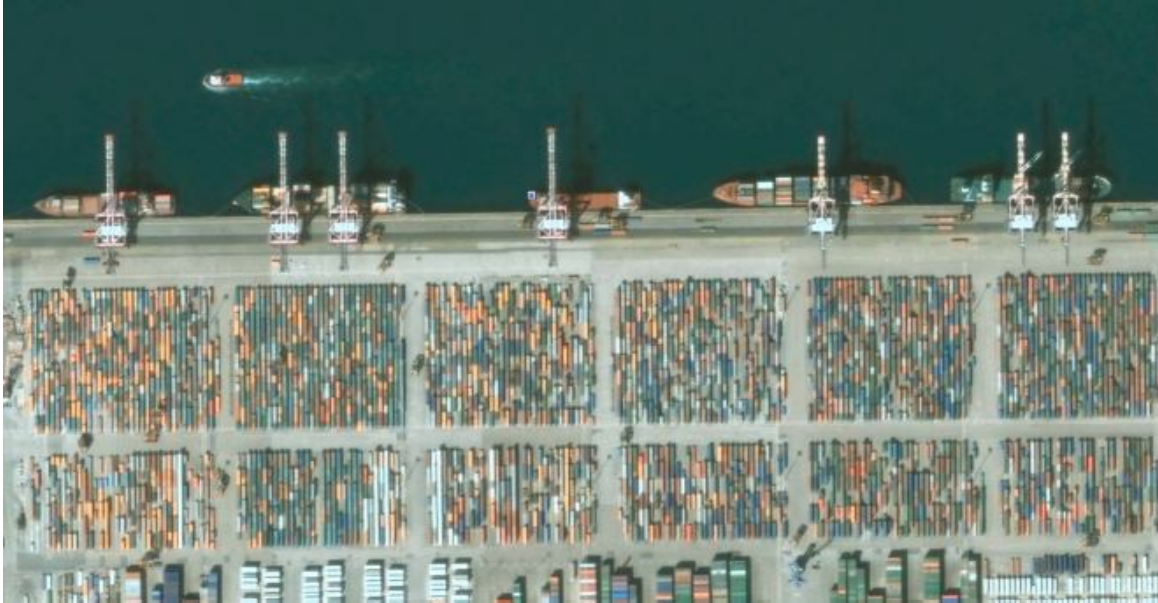
**Figure 6.** Wharf and yard of a port where multiple vessels are served

In fact studying port processes separately may lead to conclusion that cannot be applied in real ports, because an optimal solution of one process can be drastically negative and inefficient if coupled with the following one. Among models studied and published in the literature, there are four most frequently observed cases. The first one focus on the berthing space which a discrete berthing space or a continuous berthing space. The second case regards the vessel arrivals, comparing the static arrivals and the dynamic arrivals. The third case study is about the vessels handling times that can be either static or dynamic. The last most frequent analyzed case study the variable vessel arrivals. In the discrete berthing space problem, the quay is viewed as a finite set of berths one next to the other where vessels can be moored. Between berths there are some sort f bounds which do not allow vessels to be berthed where those bounds are; vessels can be moored in one berth if its length is lesser than the berth one, otherwise vessels can occupy a more appropriate berth, such as a longer one, or utilize two berths at the same time. In the continuous berthing space problem, vessels can berth anywhere along the quay and there are no boundaries, so vessels can be moored one next to the other, indifferently from vessel lengths and as long as vessels do not exceed the wharfs' limits. This situation allows getting more accurate, precise and realistic information about the berth utilization. The majority of research deals with the former case, because it is easier and this situation reflects more often the real-life ports. As far as the vessel arrivals is concerned, in the static problem all vessels, that have to be served, are already at the port, so in this case port is already in a situation of congestion because all the vessels are waiting to be moored, handled and then to left the port. Whereas in the dynamic problem only a portion of the vessels to be scheduled are present; the other vessels are moving towards the port that will serve them. The dynamic vessel

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arrivals scenario is more realistic and indeed the majority of the published research in berth scheduling considers this case. Dealing about the handling time problem, in the statistic problem the vessel handling times are considered as input, so they are already known and constant. This means that there no chances to speed up the handling time or there are no possible slowdowns, for any kind of failures. Whereas in the dynamic case, handling times are decision variables, so they are not known, as in real scenarios, and they are just represented by a probability distribution function which sets the bounds of the handling times. For each vessel they are not a fixed parameter but they can float between a maximum and minimum value and they can vary depending on multiple causes. Finally, the last case regards the variable vessel arrival times which are considered as pure variables, because they are not attributable to a parameter and so the intention of many authors is to simulate arrival times to find the best way of representing the arrival schedule to ports. Technical restrictions such as berthing draft, inter-vessel, end-berth clearance distance are further assumptions that have been adopted in some of the studies dealing with the berth allocation problem, bringing the problem formulation closer to real world conditions. Introducing technical restrictions to existing berth allocation models is rather straightforward and it may increase the complexity of the problem but simplify the used methods. While studying the berth allocation problem and, more frequently, this problem correlated to other terminal activities there are some more important objectives that are common among authors and papers:

- Minimization of vessel total service times: this parameter is assumed as sum of the vessel's waiting time and the handling times, both for loading and unloading.
- Minimization of early and delayed departures: both can cause unwanted costs for carriers, shipping lines or for ports.
- Optimization of vessel arrival times: it is necessary to find the optimal arrival times to avoid excessive waiting time and delayed departures and to get high berth utilization.
- Optimization of emissions and fuel consumption: due to the increasing cost of fuel and to avoid releasing too many emissions, especially in ports while vessels are waiting, there are many studies about the optimization of vessels speed.

Many studies are published every year about the berth allocation (Dai et al. 2004 , Cordeau et al. 2004 and 2007, Laganà et al. 2006, Bae et al. 2007, Imai et al. 2005, Lokuge and Alahakoon 2004, 2005 and 2007, Wang and Lim 2007) trying to determinate the vessel allocation and the planning horizon for minimizing the waiting time for vessels and maximize berths utilization; sometimes this can be obtained by deliberately delay berthing of vessel is an appropriate way to achieve higher throughput. Among papers different policies are analyzed and compared, focusing on the impact of

assignment decisions on resources, such as berth space and cranes for improving the vessels turn-around time, time that goes by to complete all the processes that are necessary to serve a vessel, and increase the cranes utilization. Terminal's efficiency can be increased without cost intensive structural changes.

In the simulation possibilities the ship planning process is one of the choices and in particular it is possible to focus on the berth allocation problem. This problem is quite important because it is strictly connected to other processes which take place within the terminal while moving containers. The berth allocation problem aim to find a precise and steady schedule for berthing ships, choosing the right location and the correct time, considering the dimension of the vessel, the arrival times schedule and the deadlines for the departure of ships. In fact the main objectives are the minimization of the service time, the minimization of the yard travel that vehicles have to do to move containers in the port and ensuring the desired departure times. Berth allocation is deeply connected and interrelated with the crane split, quay crane assignment and quay crane scheduling, but also with the stacking and storage and stowage planning. So choosing the right berth where to moor a vessel it does not affect only the simple berth utilization and efficiency but it is a matter of assign the appropriate quay crane, depending on their schedule, and choosing the more correct operations sequence. There are many papers (Kim and Parker 2004, Li et al 2006, Ng and Mark 2006, Liang and Mi 2007, Linn et al. 2007) about this correlation between berth allocation and quay cranes, even about the new generation cranes which are said to have a twin or tandem lift ability. They can lift four 20-ft containers or two 40-ft containers at the same time. Those cranes allow meeting the demand of mega-vessels loading and unloading processes, boosting the productivity up to 50 % and minimizing turn-around time of vessels as well as maximizing the quay cranes productivity. Despite the quay cranes features the main purpose of authors is the speeding up of vessels service times by solving the problem of the quay cranes scheduling and load sequence problem, minimizing the weighted sum of the makespan of container vessel and the total completion time of all quay cranes, as well as the minimization of the maximum tardiness of vessels departures. Berth allocation problem is greatly correlated to the crane assignment, because the aim is minimizing the weighted sum of service time and avoiding traffic congestion thanks to the reduction of service time: minimization of berthing time while maximizing the cranes productivity. Linked to berth allocation and quay cranes there is the problem of the stowage planning. Indeed while loading or unloading containers there some constrains that avoid making the vessel sink or avoid making some containers to fall in the sea. At any points while handling a vessel, the difference between the number of containers on the left and on the right of the ship can at most be one; in the same way the difference between number of containers on the front and on the back of

the ship can at most be three. Taking into account these constrains many authors (Ambrosino et al. 2004, Sciomechen and Tanfani 2006, Imai et ali. 2006, Alvarez 2006) analyzed the correlated problem of stowage planning pointing to minimize the total stowage time, considering different dimensions and weights of the containers and in order to avoid re-handles, related to loading or unloading of vessels and in yard stacking as well as in ship stability. Stowage planning connected in deep with berth allocation and quay cranes productivity, because improving the cranes productivity, respecting constrains of stowage, enables to decrease vessels handling times and so increase port efficiency and productivity.
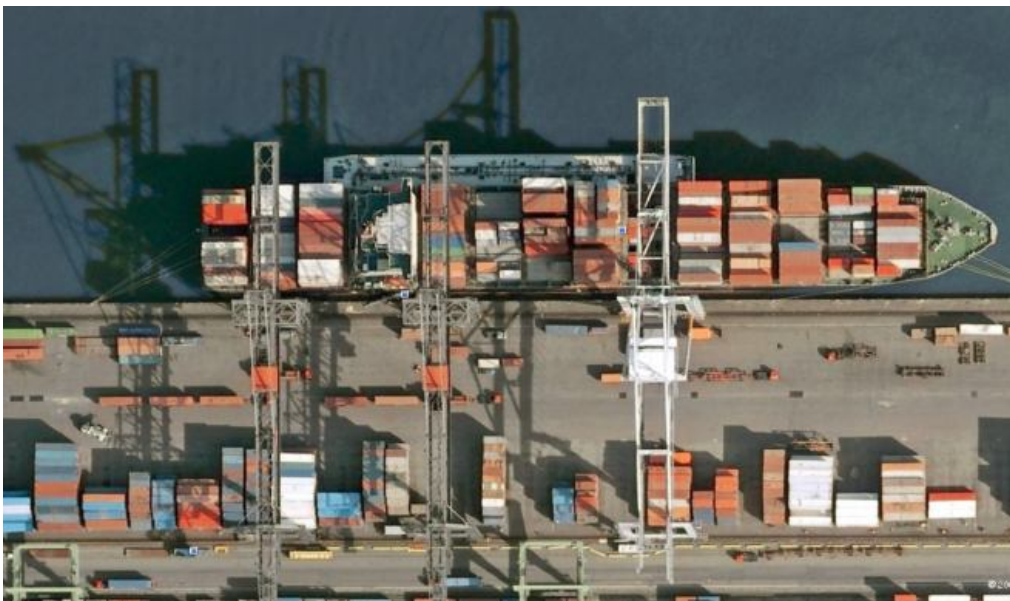


**Figure 7.** Vessels are usually handled with a precise stowage order to avoid collapses or the fall and damage of containers

Berthing vessels in the exact wharf space affect also the time that takes to stack and storage containers, which have to be minimized, and also the efficiency of stacking cranes and the assigned vehicles. Storage and stacking logistics (Saanen and Dekker 2006, Dekker et al. 2006, Harashima et al. 2006, Kang et al. 2006, Kim and Lee 2006, Kozan and Preston 2006, Kim and Kim 2007) focus on minimizing containers transport and distances to reduce the vessels turn-around time, adopting a good stacking strategy which allows to reduce relocation during pickups and maximizing equipment's efficiency and avoiding unwanted losses of time. Moreover usually connected goals are the minimization of the travel cost of vehicles during vessels operations, the minimization of the cost for possible tardiness, earliness as well as the cost for vessels waiting time. Then it is reasonable to consider logistics quite correlated to the berth allocation problem, because finding the best spot to place vessels means minimizing transport times, distances and possible container reshuffles.
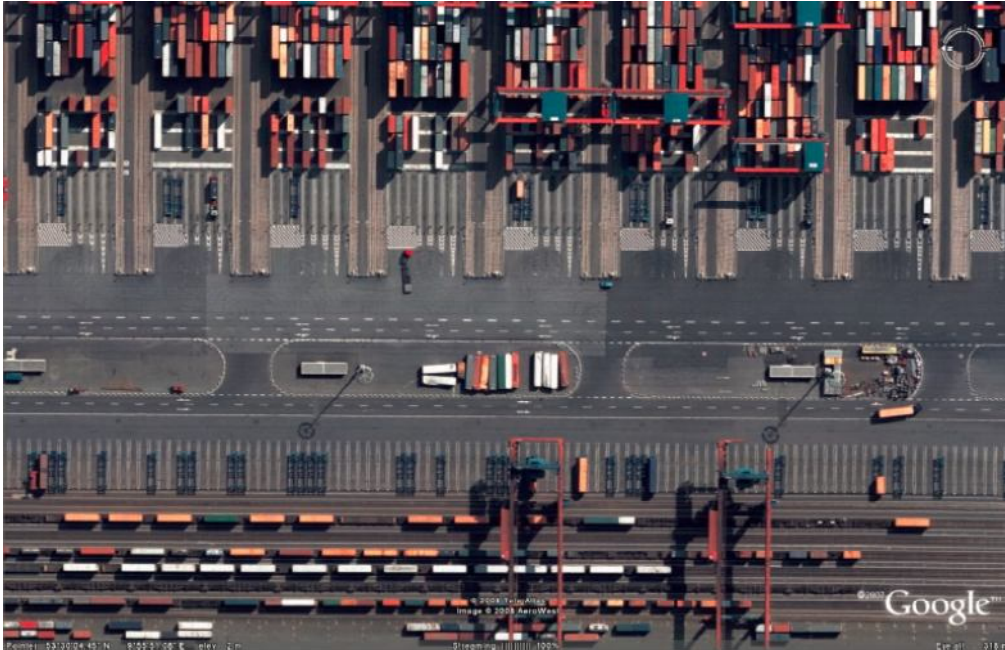
18

**Figure 8.** Integrated ports are connected with the inland thanks to railways and roads

The berthing process performance, as well as container terminals one, can be extremely improved by detailed simultaneous simulation experiments associated with the quay cranes assignment and scheduling, the stowage problem as well as the stacking operations, the vehicles utilization and transportation systems.

## 1.3    Purpose of the research

Ports are become one of the most important rings of the basic transport activities within the international supply chain. Containerized shipping has recently become popular due to the increasing number of advantages it can offer. From this particular point of view, it would not be overestimating to remind that terminal processes are to be run well and smoothly, because any inefficiency in these processes is most likely to affect the whole supply chain system. Improving and perfecting the smooth run of these processes can be achieved if and only if their performances are accurately measured. And with respect to the ship-berthing process, one of the most important terminal processes, one of the most effective means of performance measurement is simulation modeling. Thus this research aims to model, analyze and compare the berthing process of vessel in a general and intended port, utilizing different models, with different berthing policies as well as further constrains, assumptions and limitations. First the pure berth allocation problem is analyzed, modeled to find out the best scenario possible that can maximize the efficiency and productivity of

an integrated terminal container, thus the most profitable one. Then the berthing process is linked the speed assignment to study the existing correlation, between speed and efficiency, and to identify possible improvements for the terminal productivity, as well as new suggestions in simulation. The aim is to simulate and analyze continuous berthing space, which can give a more accurate and realistic expression of performance indicators at port as well as represent systems more flexible, efficient and enables to have a higher utilization of port resource and then higher benefits for the port itself. The continuous berthing space is then compared with the discrete one that, despite the easiness and approximation that it gives in simulation and results, is still the more used to simulate complex models, to assess different processes together, and it is still the more used in real-life ports. As mentioned before, the discrete quay allows splitting the berthing apace in several adjacent berths where vessels can be moored and served if the overlaps with boundaries of berths are avoided. Indeed if vessels require more than one berth adjacent berths are seized, even if they are not completely utilized, so collecting overestimation of performance and misleading results. Thus in this study it is implemented a model that stands in half way between the continuous and the discrete scenarios. This model objective is to approximate the length of vessels by seizing multiple and adjacent berths of reduced length. Thus overestimations are overcome and the outcomes of this precise model do not differ substantially from the continuous case, simulating a more efficient but still limited system. In the illustration below it is shown the methodology to gain more and more accuracy by splitting the existing berths in shorter berth. Increasing the number of this possible sub-berths precision is definitely boosted, as well as efficiency, and limitations minimized.
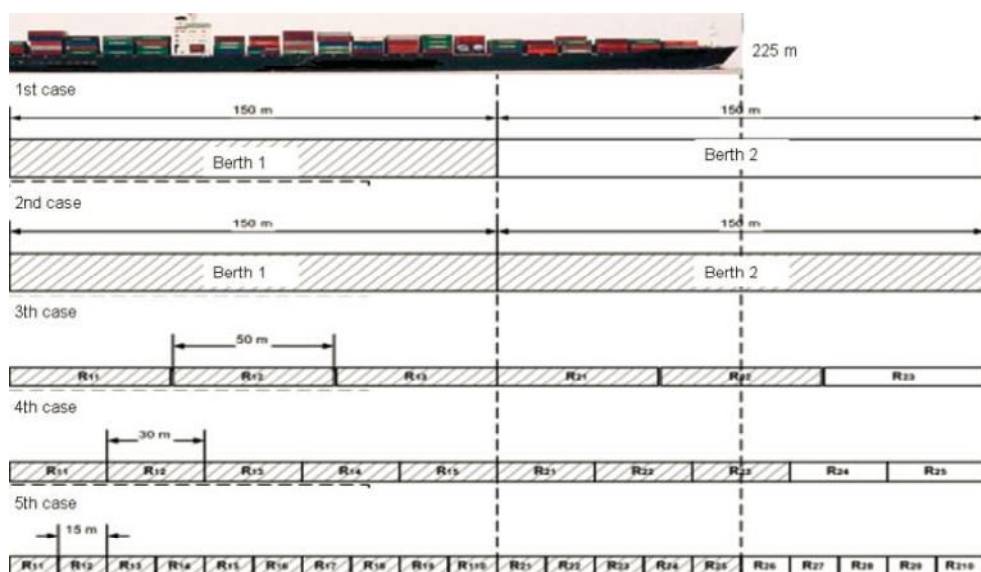


**Figure 9.** Methodology to consider differently the discrete scenario by splitting berths in adjacent and shorter sub-berths

Then berthing processed is further simulated with the speed assignment to analyze and make comparison different models, in order to study and underline the advantages of the continuous berthing space respect to the discrete sea side. Speed is increased or reduced according to the efficiency of the port to increment productivity as well as to reduce emission and most of all fuel consumption, the most influencing cost for shipping lines and carriers. The considered intended port, used in the simulations, is made of two wharfs with four and three intended berths respectively. Each wharf is served by three and two quay cranes respectively, but this study does not focus on the problem of the quay cranes scheduling and assignment. It is hypothesized that every time a vessel is moored, independently from which wharf, a quay crane is always available to handle the vessel, if the length constrain is respected. Indeed if a vessel is not feasible is the first wharf it checks the feasibility in the second one; in case of negative response, in both wharfs it is queued. Once the vessel is queued, it is moored in one of the wharfs only if the constrains of length and of quay cranes availability are satisfied; otherwise it waits until conditions are such to allow berthing. As mentioned before, the simulation is split into two parts. The first one focus only a pure berth allocation problem; instead, the second one points out the correlation between the berth allocation problem and the problem of the speed assignment, which is varied several times in order to reduce fuel consumptions and emission as well as avoiding port congestions or inefficiency. In the first case, while dealing with the pure berth allocation problem, four different scenarios are modeled with different characteristics, problems and policies. These models are even called differently to highlight the features of each one, for differentiating one from the others. The first one is the *Sub-berths* (SB) model, the second one the *Fully Discretized* (FD) model, the third one the *Hybrid Discretization* (HD) model and the fourth one the *Desired Position (DP)* model. Three of these models rely on the consideration of the berthing space as continuous; instead the other scenario is modeled considering a discrete berthing space. Only the third model simulates the discrete berthing space; instead the first, the second and the fourth model simulate the continuous berthing space. Since the purpose is to highlight the advantage of simulating with the continuous berthing side, for then applying it to real life ports, a comparison with the discrete scenarios is required. So advantages and disadvantages are pointed out according to the results and outcomes collected for each simulation. Models are not only analyzed and compared depending on the berthing space, but for each of the models four queue policies are implemented for choosing which vessel has to be served first if more than one vessel waits in the queue to be berthed and handled. The queue represents a precise port area in which vessels are temporary parked because there is no possibility, meaning that there are no resources, to serve them. Most of the simulations implement the use of specific boat, called towing boats, which are resources used appropriately for move

vessels in the port and avoiding the use of the primary engine of vessels. In this research those boats are not implemented and it is hypothesized that vessels are able to move from the special area, where they wait to be berthed, to wharfs, where they are processed.

The four policies mentioned are the following ones:

- *First-come-first-served* (FCFS): the first vessel which reaches the port is the first that is served once berthing conditions are fulfilled.
- *Short processing time* (SPT): among more vessels that are waiting to be berthed it is chosen the one that is the fastest to be served, so the loading or unloading time is the shortest.
- *Earliest due date* (EDD): since each vessel has an expected departure date, once all constrains are satisfied it is moored the vessel which has to leave before the others waiting.
- *Biggest load* (BL): this policy is the opposite of the SPT, so the vessel which is berthed first is the one that has the highest service time, meaning that it is the longest.

Each model is simulated and run with the following queue policies. The objective is to find the best order to berth vessels that are collected next to wharfs. The reason is to minimize the number of vessels and reduce as much as possible the time that vessel, and then containers, have to wait. The aim is to simulate, verify and eventually suggest the way an intended port should work to get the highest throughput, to become competitive, satisfy customers and derive the relative benefits. Through this research, some of the performance measures, key performance indicators (KPIs), of a container terminal such as, average wharf utilization, average vessels waiting time, and average number of vessels waiting in a queue are estimated according to the proposed different modeling approaches. Other performance indicators are collected and the most important one is the measure called *cost function* which differs in the first half of this study from the second one. Performance indicators are necessary to compare models and verify if a continuous quay side is more profitable than a discrete one. The *cost function* measure is used to introduce possible costs in the simulations to justify the recommendation of a model respect to others, because performance measures can all be connected to relative costs, due to use of specific resources, and loss of earnings, cause by the failure to exploitation the available resource in the correct way.

In the second half of this research, the berth allocation problem is modeled with the possibility of assign different speed to vessels, according to the fulfillment or not of a specific condition, to analyze the response of the productivity with a continuous berthing space, and the discrete one, and study the problems jointly. Indeed nowadays this problem is often studied, because shipping lines want to decrease the fuel consumption and emissions, during the shipping, finding the most appropriate speed for vessels and, at the same time, ports want to reduce emissions for improving

the environmental condition for workers and reduce health problems. Shipping lines want vessels to sail at the lowest speed possible, because fuel consumption is directly proportional to speed of vessels; but this condition it is not always possible because ports need to exploit the capacity of their resources as much as they can, and companies have to move goods as fast as possible to follow the market demand and satisfy customers. Then in the simulation of models, speed is varied during the journey of vessels in order to recreate a realistic model that can represent a real life situation to satisfy all parties. The speed of vessels is increased, speed-up condition, if port's operator forecast inefficiency in ports utilization, or the speed vessels is decreased, slow steam condition, if terminals operator forecast possible ports congestion. The slow steam condition is the initial condition of vessels and it is considered unaltered until they get to the first check point, set at 500 nautical miles from the port. From this first check point speed is possibly changed three times. The model and the policies utilized in the second part are the same illustrated before: same four models run with the same queue policies for each one. The difference stands in the speed assignment modeling units. In fact, in the pure berth allocation problem, vessels are modeled just before reaching the port; instead in these simulations vessels are modeled 500 nautical miles away from the port. Once vessels reach this distance the speed is altered depending on the number of vessels that are already waiting to be berthed. This number is the condition checked and that can trigger the speed modification. Speed is modified three times, despite usually in real-life speed of vessels is modified only once at 500 nautical miles from where vessels have to be berthed, while vessels are moving towards the port. After the first check point, speed is update at 300 nautical miles and, definitely, at 100 nautical miles from the port. This continuous updates are necessary to the continuous altering conditions in the port processes. In fact if port congestions occur, incoming vessels can be slow down so shipping line reduces fuel consumption and ports avoid making vessels wait to be berthed and served. In the opposite situation, if port can handle more vessels than the scheduled ones, the incoming vessels can be speeded up, not as much as they can but up to a maximum speed, function of the minimum speed, so ports inefficiency and idleness are avoided. Also the number of vessels waiting to be moored, trigging condition for speeding up vessels or keep the slow-steam condition, is varied to analyze how models react to different situations, always in terms of efficiency and productivity. The number of queued vessels that makes change the speed of incoming vessels is initially set as three, but then is increased to four and finally to five. Increasing the trigging condition more vessels are speeded up and models are stressed and the aim is still to find out the best solutions in each scenarios analyzing and comparing the outcomes. It must be kept in mind that initially vessels are speed up, because there are no queued vessels, until the condition in the queue, which assign the speed, is fulfilled. This is a limit of the simulations under study. In both part of the study vessels are

further classified in three classes according on length ranges. Vessels are respectively called Feeder, Medium and Jumbo. In the pure berth allocation this division enables to calculate the cost of possible delayed departures of vessels, depending on the length. In the speed assignment scenario linked to the berthing process this classification is used to find the cost of delayed departures of vessels as well as to determine the minimum and maximum speed and to add the time approximation to the vessels time required to cover the journey distance. The minimum speed can vary in an equal range for all vessels and the maximum speed is four nautical knots higher than the minimum speed, once it is calculated

Some performance indicators are recorded in both sections to enable the process of analysis and comparison of models. The final step of the comparison is to point out the best scenario, between all the models and applying all the queue policies and speed changing condition, while dealing with the measure called *cost function*. This indicator, sum of different factors, allows highlighting the costs derived from the use of a specific model in appropriate condition, because the competitiveness of a port stands in the ability of performing high efficiency with the lowest possible cost.

# Chapter 2

# *Computer Simulation Analysis*

## 2.1   Simulation analysis advantages and usefulness

The term simulation can be used in many fields and contexts and that is the reason why it has many definitions. Simulation can be explained with the Rossetti's definition:

- "The imitation of the operation of a real world process or system over time."

Or with the engineering science definition:

- "A numerical technique for conducting experiments on a digital computer which involves logical and mathematical relationships that interact to describe the behavior of a system over time."

Indeed the two definitions are related, because they point out the same thing from different points of view: the simulation one, more practical an external, and the scientific one, more theoretical and internal in the simulation.

A computer simulation, or simulation, is a reconstruction and run on a single computer, or a network of computers, to reproduce, understand and analyze a system's behavior. Computer simulations, using an abstract model for the simulation, have become an important, useful and necessary tool in engineering too: they allow having an overall view of the system as well as exploring and gaining new insight for estimating the performances of the system. Nowadays it would be too complex to get system performance from analytical solutions.

Traditionally, the formal modeling of systems has been done through a mathematical model, which attempts to find analytical solutions enabling the prediction of the behavior of the system from a set of parameters and initial conditions. Computer simulation is then used to gain something more from, or as a substitution for, modeling systems for which simple, basic and ineffective analytical solutions are not possible. There are many different types of computer simulation, the common feature they all share is the attempt to generate a sample of representative scenarios, which then can be altered, modify, enlarge, disrupt or twisted to analyze responses, for a model in which a complete enumeration of all possible states would be prohibitive or impossible.

Computer simulations have increased exponentially in the last fifteen years making possible to simulate different scale of events: simulations have exceed everything possible and they even consent to create, model and run imaginary system that are not built yet but of which deep analysis can be made, estimating the convenience of some investments. So simulations is an extremely useful tool for predicting effect while changing an existing system or for predicting performance of new system under modifying conditions.

Simulations systems can be split in stochastic and deterministic, which can be static or dynamic; the latter one can be also divided in continuous or discrete scenarios.

Simulations can describe a discrete system or a continuous system differing from the way the state variables change over time, either in a discrete set of points or continuously, respectively.

Discrete event, dynamic and stochastic system are the most used in simulations because they can perfectly reproduce a duplicate of a system changing, not continuously, at some point during its life, simulating that all the systems can change only by steps, depending on mathematical correlation used in the simulation.

Stochastic systems stand at the base of simulations: the system is non-deterministic so the changing state of the system is determined probabilistically. Any system or process that must be analyzed using probability theory is stochastic, and since interrelation, processes, added time, transfer time or waiting time are ruled by probabilities, simulation widely spread in order to analyze those scenarios which are unknown and impossible to model analytically. Stochasticity relies on probability and statistics and it is controlled by probability distributions which define the bounds of the possible outcomes of a random variable. Indeed simulating means build a non-deterministic model with two kinds of input: controlled input and uncertain one. The former one is controlled by modelers, but the latter one is not known with precise certainty and it can be represented by a probability distribution. Unknown input is a random variable so modelers should consider what distribution to apply, what are the effects of one distribution respect to another and how to use the distribution in a simulation.

The more common distribution used in simulation are the Normal distribution (NORM), Lognormal distribution (LOGN), Triangular distribution (TRIA), Uniform distribution (UNIF), Exponential distribution (EXP), Poisson distribution (POIS),Empirical distribution (CONT), Erlang distribution (ERLANG), Beta distribution (BETA) and Gamma distribution (GAMMA). Each one characterized as continuous or discrete, bounded or unbounded and characterized by a support domain, center and variation. The variation of a distribution can be summarized using the mean value and the standard deviation, respectively the central tendency of a random variable and the dispersion from this expected value.

In computer simulations random variables are only a theoretical concept, because they are pseudo-random, meaning that giving a specific seed the corresponding draw are always the same and they should end up with a distribution close to the desired distribution.

Both scenarios of this research are non-deterministic systems, so many probability distribution and other statistical parameters are used. With regard on simulations, controlled inputs are ending condition or the ending time for the simulation and the number of replication; instead the uncertain inputs are the time between entities arrival, processing time, estimated time of arrival before the port and the estimated time of departure, and all of them are implemented with probability distribution. Either system are finite horizon, with a well defined ending time or ending condition clearly distinguishing the end of the simulation, and for this reason often called *terminating simulations*. Finite horizon simulations are juxtaposed to infinite horizon ones: there is not a well defined ending time or condition and the planning time is over the time of the system, and often called *steady state simulations*, denoting the long-term or steady state behavior of the simulated system. Systems modeling find wide utilization not only in distribution and logistics but also in manufacturing, simulating the scheduling or the inventory, health care, such as emergency or operating rooms, public policy, staffing personal-service operations, like banks, fast food, postal office, theme parks, and even in military. Simulations can be considered as a tool to validate analytical solutions and reinforce them. System's alteration can be monitored and studied allowing collecting information and to trace the important variables of the system for assessing their interaction and eventually make some strategic improvements. Under the right circumstances, simulation is a powerful tool for analyzing, designing, and operating complex systems. It enables companies to test hypotheses without having to carry them out, with the significant result of making managements choosing the right solution and saving them from doing wrong investments or reject possibility of enlarging and improving companies. In fact systems' implementation is a cost-effective means of exploring new processes, providing a method for checking the understanding of the market and helping produce better, faster, stronger and more concrete results. Simulation is also an efficient communication tool; in fact it lets to have an overview of all the company or of a specific area, enabling to focus on how a company should work, or how an operation should be done, while all the processes, employers and machines are working, even with different scenarios in order to find the best, accurate and precise solution. One of the principal benefits of a model is that it is possible to begin with a simple approximation of a process and then the model can be refine step by step, focusing on the goals of the company or improving possible bottlenecks and slowdowns. This "step-wise refinement" enables firms to achieve good system approximations, more and more accurate, of very complex problems.

Another key advantage of simulation modeling is its capability of modeling entire systems and complex interrelationships, creating flexible models that are required for understanding these systems and companies condition, imitating a quite close behavior of the real system.

Since real world systems are too complicated for analytical models and too expensive for direct experimentation, simulations allow the visible, simple and real time responding modeling of this complexity in a low-cost possible behave of the actual system. Thus the importance of simulation stands on the possibility to experiment with real system for analyze, disrupt or improve its behavior, overcoming the simplifying assumptions that are not possible with analytical techniques.

Through simulation systems can be studied with preliminary data and identify critical situation or areas, collecting more data, in easier way and avoiding assumptions. Systems can be split in modules, run separately and then put together with the significant advantage of the visualization of the working system. Even if systems are messy or complicated, simulation has a high flexibility and it can be used when no other methods are possible or when other modeling methods have no simple and practical analytical solutions, with an expected high accuracy even in not stationary models.

Then simulations can be considered as prototypes which enable to built and experiment big system cutting down cost, avoiding critical changes that can cause big disruption or compromise the company's success. Despite all the advantages that simulations can bring, there are anyway some disadvantages that are specific situations in which simulation is useless and not recommended.

First of all it is necessary to understand the real purpose of simulating in order to create the right and effective system which can highlight possible solutions, changes and goals. Then simulation is not recommended when problems can be solved analytically or when performing direct experiments is easier than modeling. Another significant factor is the cost of simulating. If savings are lesser than costs, then simulation is not convenient at all. Moreover if there is not enough time or personnel available to collect, interpret and verify data simulation, which must be used in models, implementation should be avoided, as in the case that there is few data because the system is too complex or it cannot be defined in an appropriate and effective way. It must also be kept in mind that simulations do not get exact answer and results but only approximations and estimates, because all variables rely on the stochastic and non-deterministic model. Then if modelers want to create a system too complex they can end up building a long, tedious and arduous model for which validation results really difficult. Moreover results can be wrong and there is the possibility that they contain some errors, which are extremely difficult to find out. At the end modelers should not forget get that, despite the great advantages that simulation can bring, they have not to become addicted to it, misunderstanding the real usefulness of modeling. Recreated systems represent reality only under specific experimental conditions, so analytical techniques should still be taken

under consideration and must be used whenever and wherever possible because they get as an output the system's behavior under all experimental conditions, not only under a set of experimental conditions as simulations rely on.

## 2.2   Computer simulation methodology

A simulation modeling methodology is clearly a series of following steps which are necessary to find out the best representation of a real system. Since simulation involves systems modeling, a simulation methodology based on the general precepts of solving a problem through systems analysis is required. A general methodology for solving problems can be stated as follows:

1. Define the problem
2. Establish measures of performance for evaluation
3. Generate alternative solutions
4. Rank alternative solutions
5. Evaluate and iterate as necessary
6. Execute and evaluate the solution

The first step in the *DEGREE* methodology helps to ensure that modelers are solving the right problem in the right way. The second step helps to ensure that the problem is solved for the right reason, avoiding wasting time and money, referring to the metrics adopted that have to be coherent with the simulation problem. The next two steps ensure that multiple solutions to the problem are assessed and considered, with the purpose of find the best solution and not only a feasible solution with validate, accurate and concrete reasons to declare a solution as the best one. In other words, these steps help to ensure that the right solution to the problem is developed. In a good methodology the analyst has to check, verify and modify, if necessary, the method itself to get a good evaluation. In the fifth step, the analyst evaluates how the process is proceeding and allows for iteration, highlighting that the problem-solving process can be repeated until the desired degree of modeling fidelity has been achieved. It is important to start with small models that work and build them up until the desired goals are reached, getting something established at each step, and then continually enlarge the model until it is representing reality in the closest way intended. The final step is often overlooked. Simulation is often used to recommend a solution to a problem, meaning that if there is the chance, modelers should execute the solution by implementing the decisions, to

get a direct response from the results of the simulation and ensuring that there planned benefits are satisfied.

However, a general simulation methodology involves certain unique actions that must be performed during the general overall problem-solving process. The first phase is the *problem formulation*, followed by the *model building*, which is the second phase and consists in developing certain design alternatives. The third phase can be named *experimental design and analysis*, specifying and analyzing the quality of the design alternatives respect to problem objectives. The fourth phase is called *evaluate and iterate*. Finally, the fifth and sixth phases, *documentation* and *implementation* complete the simulation process. *Documentation* represent the future use of the simulation model, and *implementation* recognizes that simulation projects often fail in finding good solutions. The *problem formulation* phase of the study consists of five primary activities:

1. Defining the problem
2. Building the system
3. Establishing performance metrics
4. Building conceptual models
5. Documenting modeling assumptions

A problem starts with a perceived need. The basic output of the problem definition activity is a problem definition statement, essentially a narrative discussion of the problem, which necessary, accurately and concisely represent the problem for modelers. The problem definition statement should include all the required assumptions made during the modeling process, examining their effects on the model during the verification, validation, and experimental analysis steps of the methodology. The general goals of a simulation study often include:

- Comparison of system alternatives and their performance measures across various factors with respect to some objectives
- Optimization, a particular comparison which tries to find the best system configuration that optimizes performance subject to constraints
- Prediction of system behavior at some future point in time
- Investigation to learn about and gain insight into the behavior o f the system changing some inputs

The problem definition should include a detailed description of the objectives of the study, the desired outputs from the model, and the types of scenarios to be examined or decisions to be made.

The second activity of this phase produces a *system definition statement* which accurately and concisely define the system, particularly its boundaries and the major elements. This ensures that the simulation study is focused on the appropriate areas of interest and that the scope of the project is well understood. The third activity of problem is supposed to define the required performance measures and metrics, both quantitative and qualitative, for the model under study. The focus should be placed on the performance measures that are considered to be the most important to system decision makers, evaluating the scenario perform best. The problem definition statement, the system definition statement, and explicit performance metrics set the stage for more detailed modeling. With a good understanding of the problem and of the system under study, it should begin the detailed model formulations, which does not mean an Arena program. Conceptual modeling tools, including conceptual diagrams and flow charts should be adopted before using software to implement a model. The purpose of conceptual modeling tools is to convey a more detailed system description so that the model may be translated into a computer representation. General descriptions help to highlight the areas and processes of the system that the model will simulate. Detailed descriptions assist in simulation model development and allow reducing possible coding efforts. Some relevant diagramming constructs include:

- *Context diagrams* assist in conveying the general system description.
  This diagram, developed without precise rules, includes typically encountered flow patterns are often part of the system description document.
- *Activity diagrams* are a representation of the process for an entity and its interaction with resources while in the system. If the entity is temporary, the activity diagram is called an activity flow diagram; if the entity is permanent, the activity diagram is called an activity cycle diagram.

Activity diagrams will be utilized and shown in the further description of the models built, analyzed and compared in this research. In each model and in the speed assignment scenario an activity diagram is exposed to better understand how simulations are built and how they work.

- *Software engineering diagrams* are a diagramming technique which utilizes engineering software to provide more information for the model builder and documenting complex modeling situations.

These techniques assist development and coding efforts by focusing attention on describing, and thus understanding, the elements in the system. The first step of simulating is to an easy conceptual model which captures the basic aspects and behaviors of the system. Then details and additional functionality should be added. Finally, it should always be remembered that the complexity of the

model has to remain proportional to the quality of the available data and the degree of validity necessary to meet the aims of the study.

After developing a solid conceptual model of the situation, the simulation model building phase can begin, with creating different alternatives based on the previously developed conceptual models. The simulation models used to evaluate the alternative solutions are then developed, verified, validated, and prepared for analysis.

Within the context of a simulation project this process includes:

- *Input data preparation*: input data is analyzed to determine the nature of the data and to determine further data collection needs.

- *Model translation*: The act of implementing the model in computer code, including timing and general procedures and the translation of the conceptual models into computer simulation program representations.

- *Verification*: Verification of the computer simulation model is performed to determine whether the program performs as intended. Verification consists of model debugging to locate any errors in the simulation code. Model debugging also includes scenario repetition using identical random number seeds, stressing the model through a sensitivity analysis to ensure compliance.

- *Validation*: Validation of the simulation model is performed to determine whether the simulation model adequately represents the real system.

In addition, further observations of the system are performed to ensure model validity with respect to actual system performance. After models can be considered confident, they have to be verified and validated to suit the required purposes, so model can be used to perform experiments that investigate the goals and objectives of the project. Preliminary simulation experiments should be performed to set the statistical parameters associated with the main experimental study. The experimental method should use the simulation model to generate benchmark statistics of current system operations. The simulation model is then altered to conform to a potential scenario and is re-run to generate comparative statistics. However, often there are a significant number of design factors that can affect the performance of the model, leading modelers to utilize experimental design techniques. This step should include a detailed specification of the experimental design and any advanced output analysis techniques that may be required during the execution of the experiments. During this step of the process, any quantitative models developed during the previous steps are exercised. Within the context of a simulation project, the computer simulation model is exercised at each of the design points in the stipulated experimental design. Using the criteria

specified by system decision makers, and using the simulation model's statistical results, alternative scenarios should then be analyzed and ranked. A methodology should be used to allow the comparison of the scenarios that have multiple performance measures that trade off against each other. Good documentation should consist of at least two parts: a technical manual, for modifying the system or for software re-usability and portability, and a user manual, a simple and clear manual useful for non-modelers who want to use and exercise the same architecture to simulate a similar system. Given the goals of the study, the modeler should develop plans to implement the recommended solutions and follow through with the installation and integration of the solutions. After implementation, the project should be evaluated as to whether the proposed solution met the intended objectives.

## 2.3   Arena simulation software

The software adopted to implement this research is the Arena simulation software, precisely the version 14.50. Arena is a discrete event simulation software developed by Systems Modeling and acquired by Rockwell Automation in 2000. It uses the SIMAN processor and simulation language, then it is not necessary to create a code program because Arena allows to choose the closest representation possible and fill in modules with stochastic data, in order to consider, analyze and interpret how a dynamic system, changing at discrete points, evolves over time.

In Arena, the modeler builds an experiment model, with the logic drag and drop, by placing, the so called, modules, essentially boxes of different shapes and usefulness, that represent processes or logic. Connector lines are used to join these modules together and specify the flow of entities, which can be customers, vehicles, pallets, workers or machines. While modules have specific actions relative to entities, flow, and timing, the precise representation of each module and entity relative to real-life objects is up to the modeler.

Modules work in predefined conditions among which the modeler has to choose to recreate the model as close as possible to the real system.

Statistical data, such as cycle time, WIP (work in process) levels, transfer time, resources' utilization or makespan can be recorded and outputted as reports.

This power simulating tool enables to model processes to define, document and communicate, simulate system performance for understanding complex interrelationships and focus on possible improvements, reproducing different scenarios for obtaining the best solution.

Arena simulation allows also modeling the reality with a graphic recreation of the designed system, aiming to associate a basic simulation with a graphic interface to make more tangible current systems, particular changes or future projects and investments.

Arena can be integrated with Microsoft technologies. It includes Visual Basic for Application so models can be further automated if specific algorithms are needed. It also supports importing Microsoft Visio flowcharts, as well as reading from or outputting to Microsoft Excel spreadsheets and Access databases. Hosting ActiveX controls is also supported.

While working with Arena all the modules are collected in the Project Bar in which are split in panels. The main ones are the Basic Process, Advanced process and Advanced Transfer, and next to them there are the Report Panel, where results of simulation can be checked, and the Navigate Panel, which enables different visualization of the model.

The modules in the Basic Process are the *Create*, *Assign*, *Decide*, *Process*, *Batch*, *Separate*, *Record* and *Dispose*; they are basic because they allow creating small models that can be enlarged, but without them no simulations can be done.

The modules in the Advanced Process, partially inserted in this project, are the *Delay*, *DropOff*, *Hold*, *Match*, *PickUp*, *ReadWrite*, *Seize*, *Release*, *Remove*, *Search* and *Signal*. They are used to simulate the interrelation between vehicles, personnel and machines in respect to others machines, process event or specific situations; in this bar it is possible to collect or read data into and from external files. The modules in the Advanced Transfer, which are not adopted in this project but are as important as the previous ones, are the *Enter*, *Leave*, *PickupStation*, *Route*, *Station*; these module, and some more, can simulate the transport of goods in a factory, the movement of workers or specific personnel or the trajectory of simple pallet or even automatic vehicles thanks to the implementation of stations and the setting of specific routes.

In this simulation program it is also possible to create some sort of Sub-Models which can simplify the graphic visualization, in complex model, or can simulate inner processes of a specific area or they can even model complicated conditions in the real behavior of a company. This is possible thanks to more templates which are available and can be added in the Project Bar of Arena.

The language of Arena is based on the correlation that can be established between the use of the previous modules and the following elements: entities, queues, resources, attributes, variable, expression, processes, files, decisions, records and more. More elements can be used to better simulate a real system, but they are not mentioned and the Rossetti's book, included in the references, is extremely useful for further information and deepens. Before running the model the run parameters have to be set up correctly. In the tool bar there is a drop-down menu title *Run* and choosing *Setup* it is possible to modify and set all the appropriate parameters before simulating,

such as number of replications, length of replications, the base time unit and likely warm-up periods. Arena can be associated with typical programs which permit to simulate at best the stochasticity of the system and to valuate which are the most accurate choices or investments to make. There are also some external tools that can help Arena to improve the simulation. These accessories are the *Input Analyzer*, *Output Analyzer* and *Process Analyzer*. The Input analyzer grant to find the distribution that fit most from some random value, choosing from the most common distribution like Normal, Beta, Triangular, Erlang, Uniform, Exponential, Weibull, Gamma, Empirical, Lognormal or Poisson. Once the analysis is ultimate the program automatically makes a histogram of the data and performs a basic statistical summary of the data, which can be later used in the simulation with Arena. The fitting process depends on the chosen intervals for the data histogram, because changing the number of intervals the most fitting distribution can change so it is recommended to verify the sensitivity of the fitting process to the number of intervals in the histogram. The fitting process can be performed with two methods: individually, trying to find out the more appropriate and accurate distribution or by fitting all of the possible distributions. Once the intervals are specified the Input Analyzer computes a statistic fit in order to find the distribution with the minimum squared error. The Output Analyzer is usually used to compare alternative system configurations, layouts, scenarios, and perform sensitivity analysis. It also let to gain knowledge of how results are affect by a parameter that is changed, so comparing two alternative systems on a precise output. It is a reasonable tool but it does not give a quite right solution, because confidence intervals are made on expected outputs from each alternative, assessing if they overlap. So it cannot be considered for a precise, efficient and statistical conclusion. Instead of comparing separately two solutions, they are put together in a single parameter, which is the difference between the two possible solutions. The output Analyzer performs the analysis and as results gives mean value and confidence of interval of the precious parameter, pointing out the difference between the considered possibilities. The Process Analyzer allows to set up and to run multiple scenarios of the same model. Controlling different input parameters, called *Controls*, such as variables, resources capacities or number of replications, it is possible to check, compare and analyze specific output parameters, called *Response*. Once the main model is set and it is run, with the decided controls and response, it is possible to modify one by one the fixed controls. It is recommended to alter controls one by one and not two or more at the same time otherwise it is not possible to understand and correct the cause of the response changes.

# Chapter 3

# *Literature Review*

The berth allocating problem is a topic deeply studied in the past year and it is also nowadays a popular topic since it is continuously evolving and there is a lot of room for improving the current situation, in terms of economical and environmental benefits. Many studies have been done from different point of view and many articles were published about the berth allocation problem and all the other correlated activities, which tale place in a container terminal. In this scenario, simulation programs have been widely applied to modeling and measuring port performances, and in order to find out how to make this complex system work in the best way possible, in terms of efficiency, productivity and throughput. The pure berth allocation problem, despite its complexity and approximations required to study it, is a restrained, but deeply studied, problem to which all the other activities in ports are connected; indeed most of the times complex algorithms are applied to analyze and improve the berth allocation problem with, for example, the crane assignment or scheduling. The cranes problem is the adjacent process to the berthing one, but all the activities that take place afterwards are affected by all the previous processes. One of the most important activities in ports is the handling of vessels that arrive at the port to be processed, and load or unload containers for moving goods all over the world. In order to handle and serve those vessels specific constrains have to be fulfilled, such as the required space to berth vessels or the availability of resource to serve them and transport containers from or to ships. First of all, it is extremely significant to choose the correct time of arrival of vessels at the port for the port efficiency and this schedule has to reflect the port productivity. Indeed the right schedule for ports rules the utilization and exploitation of the resources and enables the maximization of the benefits and minimization of the costs. The best way to control the arrival of vessels is changing the speed of vessels while they are reaching the port, optionally more than one times so it is possible to avoid choosing speed that can lead to complications or that can stress ports. Moreover speed modification can allow shipping line to save in fuel consumption, since fuel consumption is directly proportional to the speed assigned to vessels; also emission can be decreased, during the sailing as much as while vessels wait in appropriate areas in ports to be handled. Once vessels reach the port it is challenging to

determine the right way, order and methodology to berth incoming ships, minimizing the waiting time as well as the total time required by vessels to go through the port.

The static variant of discrete berth allocation problem has been studied by Imai *et al.* (1997) which minimizes the total service times of vessels and the deviation between arrival order and service order of vessels, Imai *et al.* (2001) and Imai *et al.* (2008). The dynamic discrete Berth allocation problem is considered by Imai *et al.* (2001), Monaco and Sammarra (2007) and Imai *et al.* (2003). More recent approaches, such as Zhou and Kang (2008) and Han *et al.* (2010), solve the problem considering stochasticity in both arrival times and handling times of vessels. Cordeau *et al.* (2005) uses a Tabu Search method to solve the discrete dynamic berth allocation with due dates, which is further improved upon by Mauri *et al.* (2008) using a column generation approach that delivers better solutions in shorter runtime.

The static continuous berthing quay has been considered by Li *et al.* (1998), Guan *et al.* (2002) and Park and Kim (2003). Guan and Cheung (2004) consider continuous dynamic berthing space with fixed handling times using a tree search procedure to minimize the total weighted port stay time of vessels. Gao *et al.* (2010) use a robust planning approach to solve a dynamic continuous quay with stochastic vessel arrivals via feedback procedure in the planning stage. Minimization of tardiness as an objective in continuous dynamic berth allocation is considered by Park and Kim (2002) using the berth allocation problem in bulk ports. The minimization of quay length, with given berthing times as an objective, is studied by Lim (1998) and Tong *et al.* (1999). The continuous quay with handling times depending on berthing positions is studied by Imai *et al.* (2005) and Chang *et al.* (2008) who further considers draft restrictions in the berth allocation model.

Esmer, Yildiz and Tuna (2013) study a new simulation modeling approach to continuous berth allocation. They consider a port with two perpendicular wharfs which are made out of four and three berths respectively. Instead of modeling and studying the port performance with a discrete berth allocation they apply the continuous berth allocation. They divide berths in adjacent smaller sub-berths and they eliminate physical bounds between berth, allowing ships to be moored one next to the other. The authors analyze the effect of mooring ships in a more accurate and realistic way, overcoming the problem of mooring a vessels in two adjacent berths, or not mooring the ship at all, if the length of the ship is bigger than berth's length. This article points out the utilization of the berth both for ships longer than the berth's length and the smaller. They analyze five cases which differ in the length of the sub-berths, and they compare the results of average utilization of each berths, average overall utilization and ship waiting time in a queue and average number waiting in a queue. In the first two cases there are no sub-berths, but the real length of each berth is considered, and if a ship has a bigger length respect to the berth one it is moored anyway. The difference stands

in the consideration of the second berth's utilization: first scenario considers the utilization 0 %, making an underestimation; the second scenario instead considers 100 % the utilization of the second berth making an overestimation. The third, fourth and fifth case each berth is dived into three, five and ten equal sub-berths each and ships are moored in the idle sub-berths, adjacent to the busy one, depending on their length. The number of required sub-berths is calculated rounding the value to the greater nearest integer, making a quite small approximation, cutting down the huge overestimations assumed in the model which consider discrete the berthing space. Results point out that the fifth case is the more realistic and accurate one, but authors underline than increasing the number of sub-berths the accuracy of the results can increase from the estimations. In fact the idea is to asymptotically assume the real length of vessels by continuously decreasing the approximations while the number of sub-berths is enlarged.

Imai, Sun, Nishimura, Papadimitriou (2004) define a heuristic algorithm for a multi-user container terminal comparing the discrete berth problem with the continuous one. The aim of the research is to minimize the total service time where the ship's handling time depends on the ship's berthing location in the quay. Authors point out that the continuous locations is especially necessary in busy hub port, as in Europe and China, where vessels of different size are moored and in order to guarantee high flexibility and efficiency. The discrete allocation, previously examined by the authors in Imai et al. (1997, 2001, and 2003) and Nishimura (2001), allows an easy schedule but the terminal usage is not efficient, pointing out a weakness of this methods. The continuous one instead shows exactly opposite characteristics. The solution procedure is made of two steps: the problem is firstly solved with the discrete locations heuristic and then processed by the continuous one based on the discrete solution. In the article nine basic scenarios are showed with different quay lengths and number of ships served. For each problem authors consider two different values for the handling time and five ships arrival data sets, in order to generate ten different problem samples. The number of berth is varied too in this simulation to assess the relationship between the solution accuracy and the number of berths, for each quay length.

Meisel and Bierwirth (2008) investigate the combined problem of berth allocation and crane assignment (BACAP), constructing a heuristic and two meta-heuristic. This article highlight the main role of cranes in berth planning and in the terminal port productivity: marginal productivity of quay cranes assigned to a vessel can decrease and the increase of handling time if vessels are not moored at the desired position at the quay. Authors don't consider the handling time a fixed parameter but they evaluate the role of the crane resource as strictly related to the handling time.

The aim of the research is to minimize the total service time, to point out the total cost structure and, at the end, optimize the model thank to the proposed formulation of the meta-heuristic named

Squeaky Wheel Optimization (SWO). This approach is compared with results reported by Park and Kim (2003), in order to point out the strength of this model and to analyze the productivity effects of resources which are ignored in the model provided by Park and Kim (2003).

Buhrkal, Zuglian, Ropke, Larsen and Lusby (2010) consider the problem of discrete berth allocation for allocating arriving ships at container terminals. Five different models for the discrete and dynamic berth allocation problem are analyzed and compare, with the aim of minimizing the total service time. The model proposed are discrete berth allocation problem (DBAP), heterogeneous vehicle routing problem with time windows (HVRPTW), the respective of previous models with a reduced computational time, which means an improved formulation, and generalized set-partitioning problem (GSPP). The former four models are referred as compact models while the latter is referred to as an extensive model, differentiating the growth in the number of decision variables and constrains as a functions of the instance size, in OPL Studio or Java language. The comparison of the models is made considering two scenarios: the first one is implemented assuming twenty-five ships berthed in five, seven and finally ten berths; instead, the second one consider thirty-five ships handled in seven and ten berths. Authors demonstrate that GSPP model is superior to the two best compact models, which have the best formulation and the fastest resolution, and the best heuristic from the provided literature.

Arango, Cortés, Muñuzuri and Onieva (2011) study the berth allocation problem in the Port of Seville, the only inland port in Spain, in order to simulate and optimize the current berth management strategy. Authors propose a mathematical model and develop a heuristic procedure based on genetic algorithm to solve non-linear problems. The model aims to minimize the total service time for each ship applying the policy first-come-first-served. The total service time is considered as a sum of handling operation time, berth waiting time and logistic operation time.

The port of Seville in a multi-purpose terminal made of two berths and two yards. Authors propose two different resolutions for the port improvement: a simulation model and an optimal mathematical one, integrated with the previous. The solution proposed uses a heuristic model based on a genetic algorithm. The chromosome used for the berth's programming is composed of 20 genes. Authors point out that the results obtained a relevant improvement of the current situation in the average handling time and in the maximum handling time, concerning berths and the total system.

Sheikholeslami, Ilati, Hassannayebi (2013) simulate the berth allocation (BAP) and dynamic quay crane assignment problem (QCAP) at Rajaee port. The discrete event simulation (DES) is implemented with a heuristic which consider berth allocation and crane assignment at the same time, adding the availability of the tugboat, considered a resource, as a constrain. At Rajaee port

there are two terminals with four and three berths respectively. The aim of the research is to minimize the average service time of ships and the average waiting time of vessels, in order to identify bottlenecks in the process and perform a scenario analysis to eliminate added times and create a more efficient system. Authors want to model a scenario to highlight the possibility to decrease port operation cost by a more efficient utilization of the resources, such as berths, quay and yard cranes, various yard equipment and speeding up the port services.

The speed assignment and modification is a topic strictly related to the berth allocation problem and correlate to the possibility of decreasing costs and increase savings and benefits, as well as port efficiency. As remarked before, ports management is unwilling to have many vessels waiting to be berthed and processed, because those vessels cause port congestion and they can also create a high rate of pollution in the working place, due to their emission produced by auxiliary engines, compromising the efficiency and productivity of workers and resources, as much as their health condition. Thus it is required to find the best solution between fuel consumption and berth utilization, in order to reduce waiting times and number of vessels in queue, as well as reducing pollution and emissions, during the journey of vessels and in ports. The sailing speed of vessels is usually assigned as the lowest possible, allowing shipping lines to minimize fuel consumptions and emissions, but this speed can be increased on specific conditions which are forecasted by ports operators. Since ports are system continuously evolving it is recommended to check, and possibly update, speed of vessels systematically, in order to meet the productivity of the port and avoid port congestions or, on the opposite side, ports inefficiency and idleness of resources for long periods.

Controlling the speed of vessels can allow setting a, so called, *win-win* economy for both ports and shipping lines, getting also environmental benefits. In fact thanks to the speed assignment both ports and shipping lines can satisfy their interest of reducing costs as much as possible and maximizing benefits. Many studies are published every year due to the continuously improvements in port managements and increase of the fuel cost, dominant part of operation cost of shipping lines. Alvarez, Longva and Engebrethsen (2010) evaluate the potential benefits can be obtained with a new berthing policies, proposing a hybrid simulation-optimization model as an extension of the traditional berth assignment problem. The contribution of this article is consist to suggest a more ingenious berth and speed schedule to get considerable cost saving and reduction of gas emissions, since fuel consumption of a vessel is approximately proportional to the cube of the ship's speed (Alderton, 2005). Authors propose that ships depart from remote port at full speed and at 500 nautical miles before the focal port the speed is dictated to be maintained till the arrival. The ship remains idle till it receives the signal to reach the berth for being processed. At this point Land-side equipment (LSE) starts to work. The port's planner decide berths that have to be assigned to each

ship in order to specify the best speed of incoming ships, which is optimized only once. The objective of the study is to compare three berthing priority policies: first-come-first-served (FCFS), standardize estimated arrival time (SEAT) and global optimization of speed berth and equipments allocation (GOSBEA). The main results authors want to compare are total fuel consumption and fuel cost, average land-side service time for all ships, average dwell time in the harbor for ships and total cost. The conclusion of the research is that GOSBEA is better that FCFS and SEAT, for the mentioned parameters, obtaining reduction of overall fuel consumption, and carbon emission, while decreasing port congestion, although GOSBEA is distinctly beneficial when all parties are considered jointly.

Du, Chen, Quan, Long and Fung (2011) analyze the effect of the fuel consumption on the berth allocation, calculating the vessel emission with the widely-used emission factor. Vessel emissions refer to berthing periods and waiting time, in the optimal solution. Authors decide to refuse the constant arrival time (CAT) strategy and adopt the variable arrival time (VAT) strategy that means the arrival of ships is not a known value but it varies. The VAT strategy has a double effect in the port efficiency: reduction of fuel consumption and emission and the reduction of departure delay, respect to the CAT strategy. Authors focus on the waiting time emission for mooring periods, because the waiting time has a considerable economic influence on the cost of operating ships and possibility to serve other ships and moves others cargoes, but also has an important influence on the volume of ship emissions during berthing periods. The proposed model points out that VAT strategy cut down emissions for sailing and for mooring periods, focusing on the latter one because it is more sensitive since it is more noticeable and visible in the port and influence the environmental atmosphere of terminals and the health of people working in ports or living in port cities. The results indicate the reduction of fuel consumption and ship emission but maintaining the terminal efficiency, or even increasing it: speeding up ships allows fulfilling the real berth capacity and slowing them down avoids overloading terminals. Despite the revolutionary topic authors analyze the quay crane assignment is not considered and it is quite important because it has an impact on the handling time of ships.

Kontovas and Psaraftis (2001) present the speed reduction as a way of reducing fuel consumption and emissions, with the purpose of decreasing time in the port. One way to gain this result is to reduce port service time; another is to minimize disruption and maximize efficiency in the berthing of ships. Decreasing service time means that terminals can serve more ships then move more containers and earn more money. As important as the port service time is the time each ship waits before being berthed. In order to reduce both service time and waiting time port's management has

to optimize all port's operations: terminal has to work in the best way to interface sea-side, containers and ships, with the land-side, trucks and trains, for transporting of goods.

Authors investigate three correlate problems with the reduction of port service time: berth allocation problem (BAP), quay crane assignment problem (QCAP) and the quay crane scheduling problem (QCSP). This paper correlates the fuel consumption with the change of engine load and assesses it using a regression analysis to identify the more fitting relation between ships' speed and fuel consumption. Speed reduction, under some conditions, is convenient in terms of emission reduction and port time reduction. Moreover authors present a system that can reduce the waiting time in port before mooring and its implication on the emission was examined. Despite there is no port congestion, speed reduction can be the answer to an increasing price of bunker and a decreasing market demand.

# Chapter 4

# *Simulated Models and Queue Policies Utilized*

## 4.1   Models implemented in the simulations

The simulation implements the berthing process firstly, and the speed assignment related to the berth allocation problem afterwards. Four models are run, analyzed and compared, in order to find out the best solution, according to the performance measures recorded. All the models used for the simulations have common structure and rely on almost the same data. The berthing process is made out of two parts, where the first one, the vessels creation and attributes assignment, is the same for each model; the berthing process instead, the second part, is typical and singular of each model and where models differ, both in the way they consider the berthing space and how the control the berthing process itself. Three out of four models implement the continuous quay scenario differently to compare the outputs with the discrete quay case of the last model simulated. The discrete quay methodology is often applied, due to its easiness and approximation, but it leads to misleading results and gets limitations than can be overcome with the continuous berthing space. This analysis and comparison is studied to point out advantages of utilizing the continuous quay instead of the discrete one, while simulating four different models that model the berthing process of vessel in the same intended port, changing the berthing policy. Then a more dynamic scenario is simulated in order to point out, and at the same time try to reduce, the fuel consumption and emission of vessels. The speed is thus a variable that can be modified and assigned properly to vessels to get the highest efficiency possible and the minimization of cost, such as fuel misuse. The objective is still to improve the berth allocation and maximize its efficiency and productivity, but also to avoid useless waste of fuel or port non-utilization and inefficiency by playing appropriately with the speed of incoming vessels. The speed assignment studied with berth allocation problem differs only initially. Vessels are no more simulated when they arrive at the port but before they reach the port. While they sail to the port their speed is changeable, according to a precise and specific condition. For that reason new data is added and implemented. Partially also from the

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simulating point of view data are different between pure berth allocation and speed assignment associated with berthing process. The basic structure of the two scenarios is the same, but when dealing with the speed assignment models are extended, parameters increased and some data changed or set as new. Since this implementation is studied on an intended berths all the simulations work in the same way and differ only in the policy of the model as well as in the policy set in the queue of vessels which are not berthed yet and wait to be served, to be able to leave the port as soon as possible.

## 4.1.1 Pure berth allocation process

In all the four models, vessels are split into five classes, depending on their length, and to each length interval is associated a percentage of arrival at the port, as well as a processing time. The percentages are necessary to simulate the models, because they allow recreating the most similar scenario to a real life port. Vessels are not all equally long and different lengths means different service times. Indeed the time required to serve vessels is directly proportional to their length; the longer the vessel the longer the processing time is.

The table below shows the arrival percentages depending on the classified length of vessels.

| Length of Vessels (m) | Arrival Percentage (%) |
|:---:|:---:|
| 50 - 100 | 13.88 |
| 100 – 150 | 39.61 |
| 150 – 200 | 34.51 |
| 200 – 250 | 8.33 |
| 250 – 300 | 3.67 |

**Table 1.** Percentage of arrival of vessels at the port according on the length classification

The arrival of vessels is determined thanks to the Arena Input Analyzer which allows finding out the best distribution that fits data which are randomly collected. All the recorded values are inserted in the Arena tool and analyzed by it, giving back, as result, the distribution that best can represent the arrival of vessels at the port. This assumption allows simulating in the most realistic way how the port correctly works, in order to find out interesting result to be then possibly applied in real life scenarios. In the picture below the values of the interarrival times collected are illustrated and used to determine the time between arrivals of vessels at the port to be utilized in the simulations.
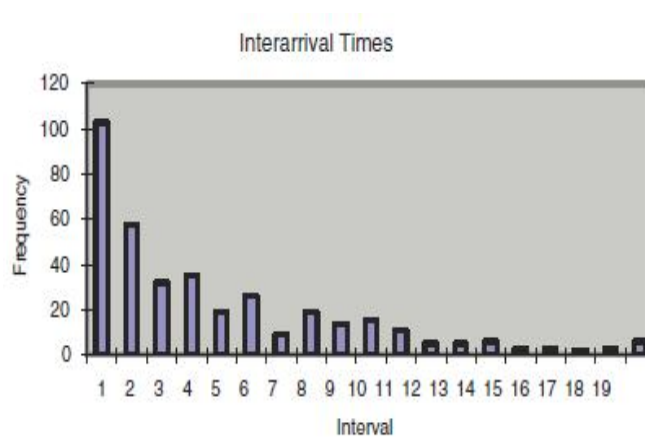
**Figure 10.** Interarrival frequency of vessels at the port

Vessels are then created with a time between creations ruled by a Gamma probability distribution function. The shape parameter and the scale parameter of the distribution are respectively 440 and 0.744; the first one defines the shape of the distribution instead, the second one affects the width of the probability function. The time between arrivals (TBA) of vessels used in the Arena simulations is exposed below.

$$TBA = GAMMA(440, 0.744) \qquad (1)$$

This probability distribution is the result of the fitting of multiple functions to find the best response to the data represented in the figure above. The distribution that best follow the data is the Gamma distribution with the illustrated parameters, which are determined by Arena once the fitting process is completed. It is important to highlight that the unit for this distribution is set on minutes and not on hours as the simulation time base unit. Thus simulations time is ruled by hours but the vessels show up at the port according on the distribution considered in minutes.

The processing times are results of a study which is also implemented with the Arena Input Analyzer, after a collection data of three months already done and utilized in the following models. Once again results are analyzed with this tool which allows getting the best probability functions that represent at best the obtained data. For each of the five categories remarked above many values for the processing time, of the vessels with specific lengths, are collected and used to feed the Arena tool and get the most reliable outcomes. The five different scenarios of the service time for ships (STS) are illustrated to represent the five classes of vessels. All the data are illustrated below,

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depending on the length classification, in the Arena Input Analyzer, before the best distribution is determined to create a general case to be applied in the models for simulations.
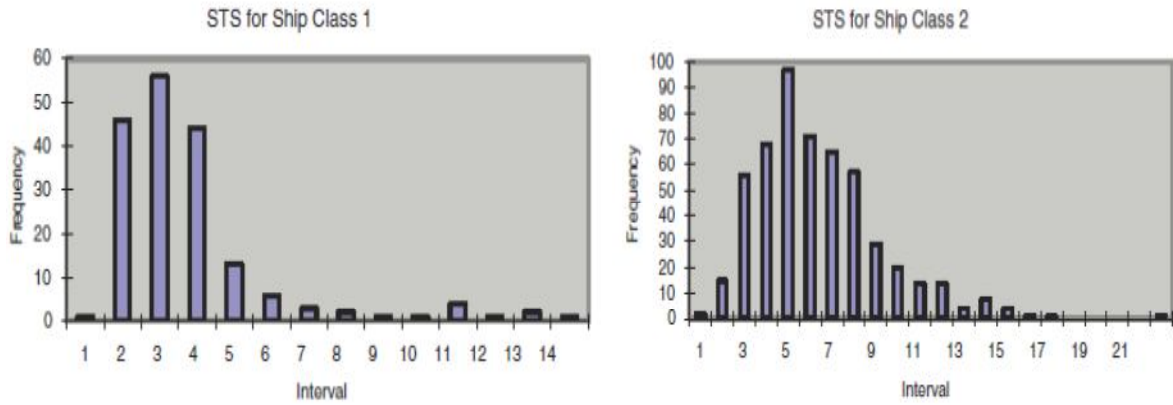


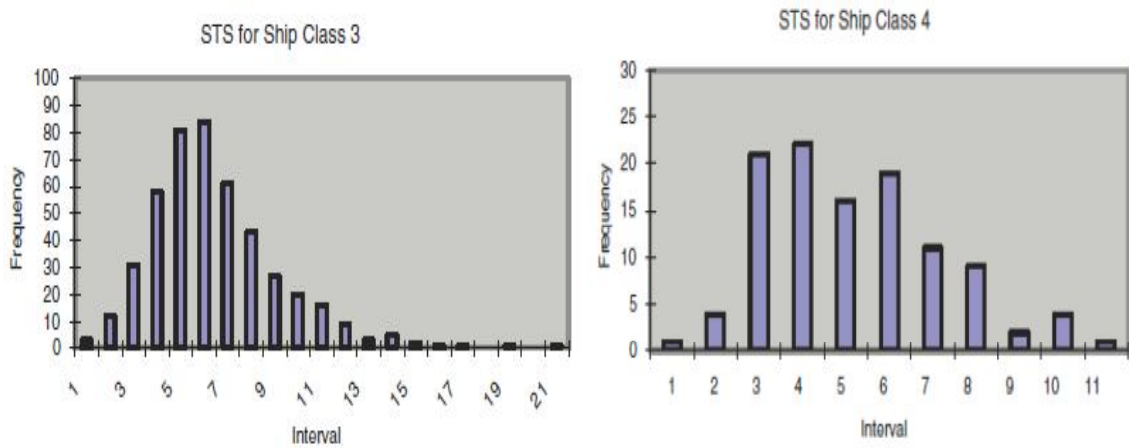**Figure 11.** Service time for ships of the first and second class



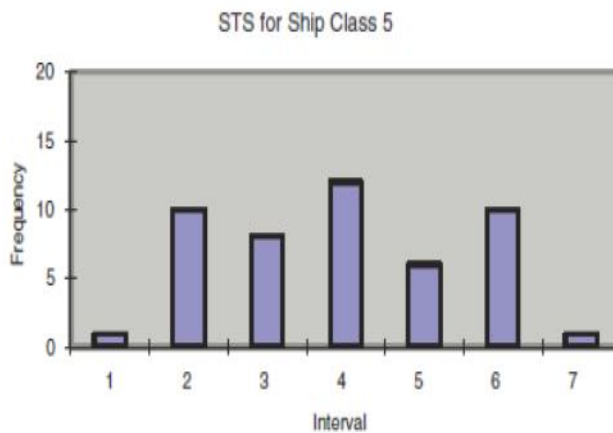**Figure 12.** Service time for ships of the third and fourth class



**Figure 13.** Service time for ships of the fifth class

The following table summarizes the outputs of the Area Input Analyzer for each of the categories of vessels.

| Length of Vessels (m) | Processing Time (h) |
| --- | --- |
| 50 - 100 | 1.5 + ERLANG(5.73,2) |
| 100 – 150 | -0.5 + ERLANG(3.27,5) |
| 150 – 200 | -0.5 + ERLANG(4.06,5) |
| 200 – 250 | 6.5 + ERLANG(7.26,3) |
| 250 – 300 | 29.5 + 52*BETA(1.17,1.68) |

**Table 2.** Service time for ships for each category of vessels

To properly run simulations some parameters are required to be fixed. Those values are necessary because they enable implementing the systems under study for a precise period and repeating the simulations an accurate amount of times. The multiple replications let finding the most precise expected values from the probability distributions. The simulation parameters that have to be set to run the simulations are the number of replications, the length of replications, or the stopping criteria, the time base units of simulations and possible warm-up period. In the berth allocation problem the length of replications is set as *Infinite*, because the stopping criterion is the maximum number of vessels implemented. The set-up parameters are exposed in the following table for the berth allocation problem.

| Set-up Parameter | Value |
| --- | --- |
| *Replication Length* | Infinite |
| *Warm-up Period* | 2500 hours |
| *Time Base Unit* | Hours |
| *Number of Replications* | 20 |
| *Stopping Criteria* | 50000 Vessels |

**Table 3.** Parameters required to correctly running the simulations

Once vessels are created, to each of them is assigned the following attribute, necessary to estimate the time in the simulation, which is *Tnow*, when vessels are created and it is significant to find out if vessels leave the port in time or late.

$$myTime \ = \ Tnow \qquad (2)$$

Independently from which models, together with the previous one, some attributes are assigned to vessels, once they are created, such as to which class they belong, their length and processing time and their expected departure time. The class to which vessels belong is decided by a discrete function, depending on the percentages of vessels that arrive at the port, as mentioned above. The probability that a vessels belong to a precise class depends on the percentage, which is expressed cumulatively in the following expression by a discrete probability distribution.

$$myVesselTpe = DISC(1, 13.88, 2, 53.49, 3, 88, 4, 96.33, 5, 1) \qquad (3)$$

The Discrete distribution defines the probability that one of the five solutions occurs. In fact the five solutions are respectively followed by the cumulative percentage of their probability, up to 100 %. The possible lengths in the simulation are set as a vector with five rows, depending on the length of vessels. Once the class of belongings of vessels is decide, thanks to the discrete function, the same value of the class is associated with the row of the vector. Each row contains a uniform function between two possible lengths, so after the class assignment the length assignment follows. In the simulations the length are assigned thanks to an expression, which define the intervals of length, and then assigned with an attribute.

$$eVesselLength = (U(50,100), U(100,150), U(150,200), U(200,250), U(250,300)) \qquad (4)$$

$$myVesselLength = eVesselLength(myVesselType) \qquad (5)$$

The processing times are set as a vector of five rows as well. In the same way as before, the processing time is find out once the class of belongings is define, exactly in the same way as the length is determine. The expression sets the processing times which are later assigned to vessels.

$$eProcessingTime = (STS\,1, STS\,2, STS\,3, STS\,4, STS\,5) \qquad (6)$$

$$myProcessingTime = eProcessingTime(myVesselType) \qquad (7)$$

The expected time of departure is calculated similarly to the length and the processing time, but it must be figured out after the time of creation and the processing time are assigned. Indeed the expected time of departure is a function of the previous attributes as shown below. This value is still

defined by the class of vessels, associating it with the row of the vector. The expression defines the five possible solutions assigned with as an attribute to vessels when the class of belongings is fixed.

$$eETD = (myTime + UNIF(1,1.1) \times myProcessingTime) \qquad (8)$$

$$myETD = eETD(myVesselType) \qquad (9)$$

After the assignment of attributes, vessels check the feasibility to be berthed, because it is necessary that a quay crane is available and that there is enough space to berth them in the wharf; if there is not enough space in the first wharf, always primary inspected, the second wharf is checked before sending the vessels back to the waiting queue, expecting the berthing condition to occur.

When vessels are handled for the process of loading or unloading containers, which is not specified, the resources seized and utilized are the wharfs and not the quay cranes, because the aim is to evaluate the wharf utilization, hypothesizing that quay cranes are always available and vessel do not have to wait for being processed, once the previous constrains are fulfilled. In fact a peculiarity of the Arena simulation software is the ability of implementing systems while giving as outputs the utilization of a specific resource, missing factor of the other simulations software, which stand out for other features. After vessels are released from the wharfs, once they finish the process, some key performance indicators (KPIs) are collected, because they are necessary to allow the analysis and the comparison among models. If vessels are in time, according with their expected time of departure (ETD), assigned as an attribute, they wait until the time of simulation is greater or equal to the scheduled time, as shown below.

$$Tnow \geq ETD \qquad (10)$$

Until this condition is not fulfilled, vessels are hold in another specific area of ports.

The models, implemented and compared, differ one from the other in how they consider the berthing space, either continuous or discrete, as well as how they implement these two different scenarios. The models implemented are four and named differentially as follows:

- *Sub-berths*
- *Fully Discretized*
- *Hybrid Discretization*
- *Desired Position*

Among the recorded KPIs, there is one that is the most effective and in which port management is usually interested. This performance indicator is named the *cost function*, and it is calculated as the sum of the non-utilization of wharfs and the cost for delayed departures. This cost is the result of the utilization of a precise model, and then this measure points out the resource exploitation capability of a system and the relative efficiency once it is applied. The *cost function*, as a sum of the factors just mentioned, is shown below.

$$Cost\ Function = \sum \left( \left( 1/(Wharfs\ Utilization) \right) \times Wharf\ Utilization\ Cost + Delayed\ Departure\ Cost \right) \quad (11)$$

The non-utilization cost, the first addend, comes from the impossibility, and then the inefficiency, of the port to exploit the maximum capacity of the available resources. It is the multiplication of the inverse of the wharfs utilization times the fixed cost of the wharfs per day, set as 20 k$ per day, as exposed below.

$$Wharf\ Utilization\ Cost\ =\ 20\ k\$\ per\ day \quad (12)$$

The delayed departure cost is the cost that ports have to pay if vessels leave the port later than the scheduled date, most probably because vessels are kept longer due to too long periods of waiting time or resource unavailability. Thus to calculate this cost vessels are split in three categories, different and wider than the previous ones, which allow determining the cost, once again functions of the length of vessels. This measure is the overtime respect to the expected departure time (ETD) by the cost for the delayed departure, according to the length of vessels. The cost for a delay departures varies from 1 k$ per day to 3 k$ per day, as shown in the following table.

| Length of Vessels (m) | Delayed Departure Cost (k$) |
|:---:|:---:|
| 50 – 100 | 1 |
| 100 - 180 | 2 |
| 180 - 300 | 3 |

**Table 4.** Cost for delayed departures of vessels according on a looser classification

## 4.1.1.1 Sub-berths model

The lengths of the two wharfs of the intended port are respectively 600 meters and 450 meters long, divided in four and three virtual berths of 150 meter each. Those berths are taken under consideration only because this is the starting point to move from a discrete policy to a continuous one. Indeed the just mentioned berths are equally split in sub-berths of the same length. Each berth counts ten sub-berths of fifteen meters. Thus the model relies on the assumption of a continuous berthing space, so vessels are moored one next to the other starting from the first available sub-berth. Thus the berthing space is not split with hypothetical physical boundaries. This sub-division in sub-berths leads anyway to an overestimation of the wharfs utilization. Indeed the length of vessels is rounded to the nearest multiple of fifteen, since fifteen meters is the length of sub-berths. Then more space that is really necessary is seized to handle vessels. This system is a more accurate approximation than using actual berths, but still not as precise as using the real length of vessels. Then this model stands in half way between the discrete and continuous cases. The wharf are served respectively by three and two quay crane each, so if the length constrain is fulfilled the first wharf can handle three vessels at the same time and the second one two vessels simultaneously. The subdivision of wharfs into smaller sub-berths, of fifteen meters each, gets forty sub-berths in the first wharf and thirty sub-berths in the second one.

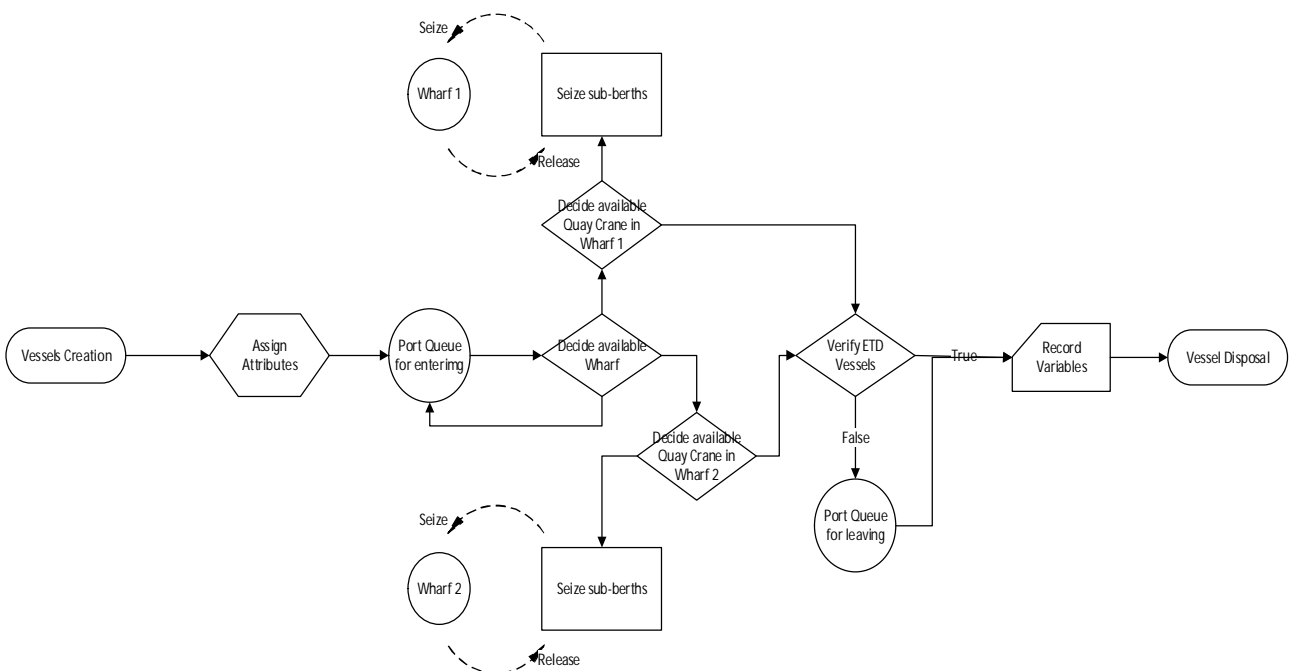The activity diagram of this model is shown below.



**Figure 14.** Activity flow diagram of the *Sub-berths* model

The feature of this model is to focus on the number of sub-berths vessels need to be berthed. In fact once vessels are created, in the simulation, the number of required sub-berths is calculated, dividing the length of vessels by fifteen, and then it is rounded to the greater nearest integer. Following the general description, mentioned above, vessels are queued if there are no available quay cranes or if their length is greater than the available space. Then feasible vessels start checking the condition from the first wharf and then moving to the second one. Since more than one vessel can be handle simultaneously, in order to not exceed the wharf length, a simulation constrain, and the initial sub-berth and the final one of each quay crane which is serving a vessel is temporary recorded as variables called $vStart_{(i)}$ and $vFinish_{(i)}$ and they are checked to avoid overlaps while berthing vessels. The letter placed as subscript of the variables refers to the number of the seized quay crane which goes from one to five. When the simulated processing times of vessels end, ships check if they are in time or not before leaving the port and some performance measure are recorded.

As for this model as for the following one the pseudo-code of each simulation is exposed. Indeed pseudo-code is an informal high-level description of the operating principle of a computer simulating program. It uses the structural conventions of a programming language, but is intended for human reading rather than machine reading, because it is easier and more effective.

The pseudo-code of the model described above is explained in detail below by steps.

STEP 0. Set as resources $Wharf_1$ and $Wharf_2$ with a capacity respectively of 40 and 30 (which are the number of sub-berths in each wharf)

STEP 1. CALCULATE the required number of adjacent sub-berths, based on the length of vessels; ASSIGN the number 1, 40 and 1,30 to the variables $vBW_1$, $vEW_1$, $vBW_2$, $vEW_2$ referring to the first and the last index of each wharf

STEP 2. ROUND UP the value to the nearest integer

STEP 3. ASSIGN this number to the attribute *myRealNumSB*

STEP 4. Check IF $Wharf_{(i)}$ is available, satisfying the availability of quay cranes and the number of sub-berths required

STEP 5. Check IF there are already vessels berthed and calculate the number of idle sub-berths

STEP 6. IF *myRealNumSB* ≤ number of idle sub-berths go to STEP 7, ELSE go to STEP 12

STEP 7. ASSIGN the index of the first idle sub-berth with the variable $vMIN_{(i)}$ (where *i* stands for the number of the quay cranes seized by the vessel)

STEP 8. CALCULATE the index of the last sub-berth required by the vessel with length *myRealNumSB* (i.e. $vMIN_{(i)}$ + *myRealNumSB* – 1 )

STEP 9. ASSIGN this number to the variable $vMAX_{(i)}$

STEP 10. IF between $vMIN_{(i)}$ and $vMAX_{(i)}$ there are busy sub-berths or $vMAX_{(i)} > EW_{(i)}$ go to STEP 12, ELSE go to STEP 11

STEP 11. SEIZE all the adjacent sub-berths (as a capacity of the resource Wharf1) from $vMIN_{(i)}$ and $vMAX_{(i)}$ during the service time

STEP 12. Increment the variable $i$ in STEP 4 by one and go to STEP 5, ELSE go to STEP 13

STEP 13. WAIT in a queue

## 4.1.1.2   Fully Discretized model

This model differs from the so called *Sub-berths* model, because lengths of vessels are no more assumed as a sum of sub-berths. The *Fully Discretized* model analyzes the berthing space also as continuous, but considering the real length of vessels and no approximations on their lengths are utilized. No physical boundaries divide the wharfs, which is a big berth where vessels can be moored one next the other. This scenario allows a more realistic and accurate evaluation of the wharfs utilization. The quay cranes available for both wharfs are the same: three in the first one and two in the second one. In the same way as in the previous model, the remarked constrains that have to be fulfilled are the quay crane availability and the feasible berthing place. It has to be kept in mind that now the feasibility of berthing vessels is higher because there are no berths and overestimations. Vessels seize the exact space that is really required.

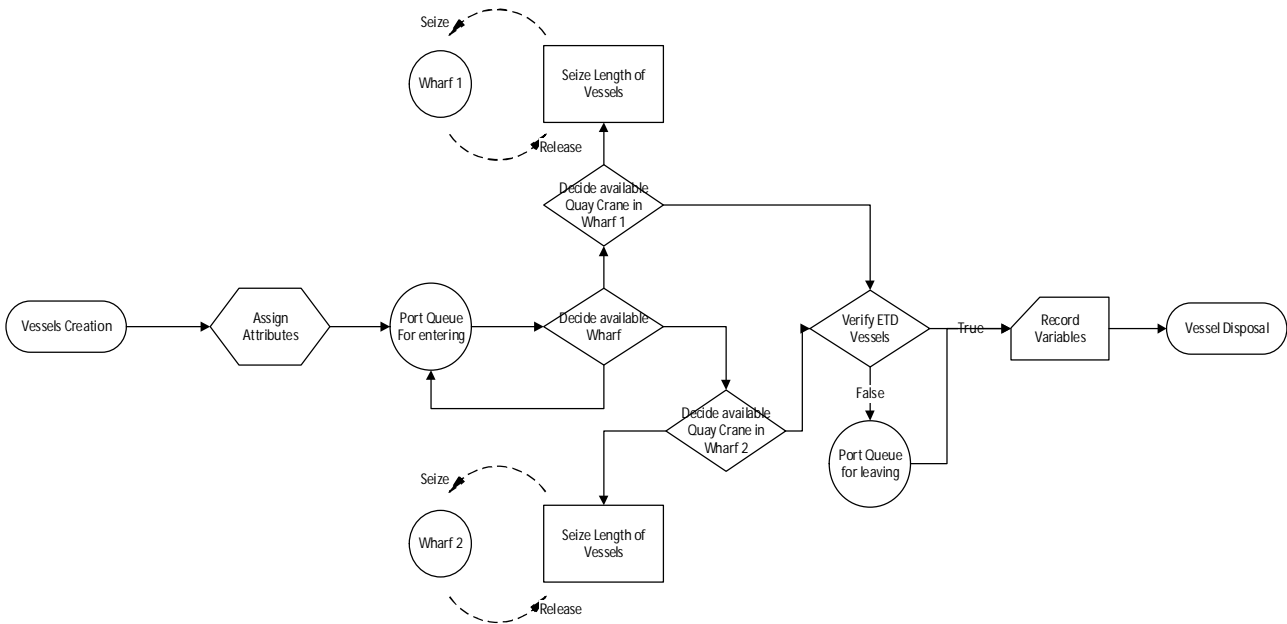The activity diagram of the model is shown below.

**Figure 15.** Activity flow diagram of the *Fully Discretized* model

Except from the difference in how length of vessels is analyzed, the *Sub-berths* model and the *Fully Discretized* one work in the same precise way. This model temporary records the initial point from which the vessels are berthed and the last one in the variables called *vStart(i)* and *vFinish(i)*, exactly as before referring to the number of quay crane. Then when the processes are completed, vessels are kept in the port or they leave it according on the expected time of departure (ETD), and the measures of performance are collected.

The pseudo-code of the model is described below.

STEP 0. Set as resources Wharf$_1$ and Wharf$_2$ with a capacity respectively of 600 and 450 (which are the lengths of each wharf)

STEP 1. CALCULATE the required space in the wharf, equal to the length of vessels; ASSIGN the number 1, 40 and 1,30 to the variables vBW$_1$, vEW$_1$, vBW$_2$, vEW$_2$ referring to the first and the last index of each wharf

STEP 2. ASSIGN this number to the attribute *myVesselLength*

STEP 3. Check IF Wharf$_{(i)}$ is available, satisfying the availability of quay cranes and the length of wharf required

STEP 4. Check IF there are already vessels berthed and calculate the idle length in the wharf

STEP 5. IF *myVesselLength* $\leq$ idle length go to STEP 6, ELSE go to STEP 11

STEP 6. ASSIGN the index of the first idle length with the variable *vMIN$_{(i)}$* (where *i* stands for the number of the quay cranes seized by the vessel)

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STEP 7. CALCULATE the index of the last length required by the vessel with length *myVesselLength* (i.e. *vMIN(i)* + *myVesselLength*)

STEP 8. ASSIGN this number to the variable *vMAX(i)*

STEP 9. IF between *vMIN(i)* and *vMAX(i)* there are busy lengths or *vMAX(i)* > EW(i) go to STEP 11, ELSE go to STEP 10

STEP 10. SEIZE all the adjacent length (as a capacity of the resource Wharf1) from *vMIN(i)* and *vMAX(i)* during the service time

STEP 11. Increment the variable *i* in STEP 3 by one and go to STEP 5, ELSE go to STEP 12

STEP 12. WAIT in a queue


## 4.1.1.3   Hybrid Discretization model

The *Hybrid Discretization* model is the model that assumes the berthing space as discrete and it is modeled, simulated and analyzed to allow the comparison with the other models, which assume the quay as continuous. This model studies the length of vessels as the first model. The length of vessels is divided by ten meters, instead of fifteen meters, because the length and the number of berths are different. The first wharf, 600 meters long, is made out of six berths of 100 meters each; the second wharf, 450 meters long, is assumed as the sum of three berths of 100 meters and one berth of 150 meters. The berthing space is analyzed as a discrete one, so in each berth can be berthed maximum one vessel, as long as the length of the vessel is lesser or equal to the length of the berth. Indeed the minimum length of vessels that are handled in the port in longer than fifty meters. Otherwise vessels can seize more than one berth, if their length is longer than the berth's one, and all the seized berths are considered utilized, even though they are not completely exploited. An additional constrain is implemented when vessels are berthed in the second wharf. If the length of vessels is greater than 100 meters but lesser than 150 meters, the specific vessel is berthed in the appropriate fourth and longer berth, instead of seizing two shorter berths. If the mentioned berth is not enough it is seized or when needed with others. The other conditions are always the same, such as three and two quay cranes as well as the berthing constrains, as well as the scheduled departures and the indicators collection.
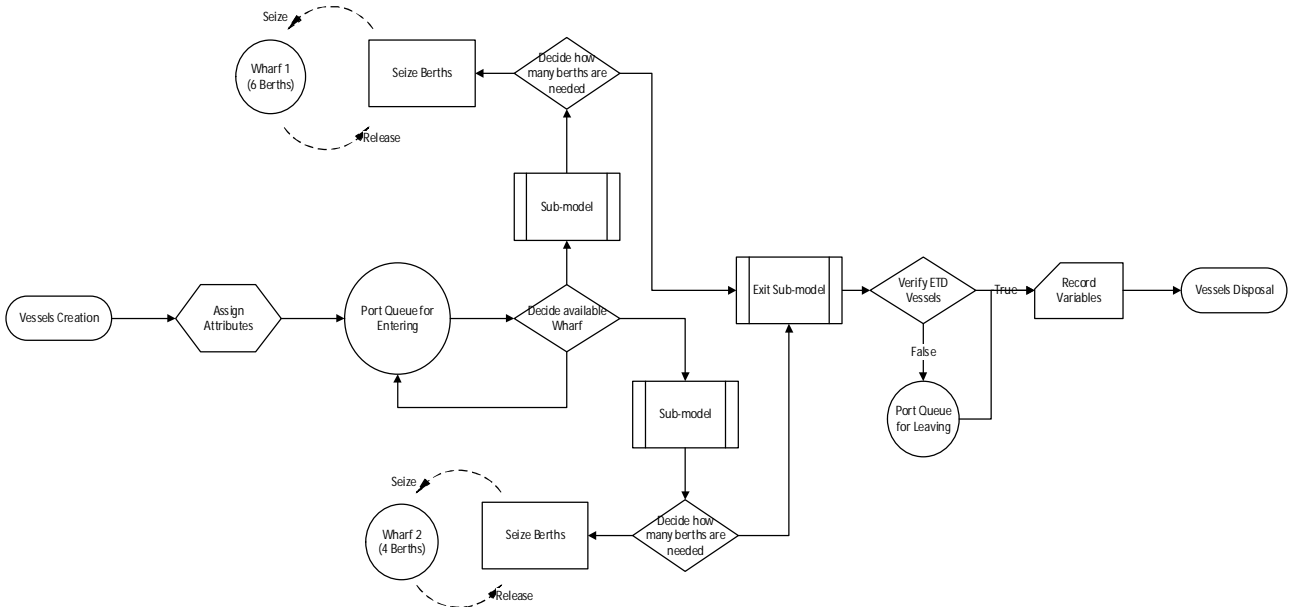
Te activity diagram of the model is exposed below.

**Figure 16.** Activity flow diagram of the *Hybrid Discretization* model

This model is implemented with a sub-model in the Arena simulation program. The sub-model allows to model complex situation separately from the all model itself, to make it easier, more readable and graphically better arranged. In the simulation it is possible to study the utilization of each berth which composes the wharf, instead of considering the overall utilization as in the *Sub-berths* model. Moreover since the utilized sub-berths are smaller the number of simultaneously utilized berth is higher and then this model would it be quite messy and complex if simulated in the normal environmental of Arena. This model, as the previous ones, follows the same general structure and vessels go through the same activities and processes. The sub-model implementation simulates the seizing of multiple berths by vessels. In fact since in the fifth class vessels have a length up to 300 meters and it is possible that three berths are seized at the same time. In the second wharf instead, as quoted before, the 150 meters berth long plays a significant role in the simulations, avoiding useless overutilization and correlated overestimations, thanks to the decisions made depending on the length of vessels. In this model the variables previously used to avoid overlaps are not recorded. In fact it is impossible to berth two vessels in the same berth and thus there are no possible overlaps. Thanks to utilization of multiple berths and the discrete berthing space, those variables are no more useful because every time all the complete berths are seized.

The pseudo-code of this model is presented below.

STEP 0. Set as resources Berths 1, 2, 3, 4, 5, 6 in Wharf$_1$ and Berths 7, 8, 9, 10 in Wharf$_2$ with a capacity respectively of 10 (which are the number of sub-berths in each berth)

STEP 1. CALCULATE the required number of adjacent sub-berths, based on the length of vessels;

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STEP 2. ROUND UP the value to the nearest integer

STEP 3. ASSIGN this number to the attribute *myRealNumSB*

STEP 4. Check IF Wharf$_{(i)}$ is available, satisfying the availability of quay cranes and the number of berths required

STEP 5. Check IF there are already vessels berthed and calculate the number of idle berths

STEP 6. IF *myRealNumSB* ≤ length of idle berths go to STEP 7, ELSE go to STEP 11

STEP 7. ASSIGN *myRealNumSB* = length of berth

STEP 8. IF *myRealNumSB* > length of idle berths go to STEP 9, ELSE go to STEP 11

STEP 9. CALCULATE the number of berths required to handle the vessel, and if not available go to STEP 11

STEP 10. SEIZE completely (even if it is not totally utilized) the berth or all the adjacent berths needed

STEP 11. Increment the variable *i* in STEP 4 by one and go to STEP 5, ELSE go to STEP 13

STEP 12. WAIT in a queue


## 4.1.14  Desired Position model


The *Desired Position* model goes back again in using the real length of wharf and vessels, as the *Fully Discretized* model, while assuming the berthing space as continuous. The berthing space is continuous and vessels can be berthed where there is enough space to moor them, without any constrain or restriction of physical boundaries. The wharfs are 600 meters long the first one and 450 meters long the second one, because the intended port is the same. Moreover the quay cranes number and availability remain always the same. Vessels are no more berthed one next to the other, but a different berthing policy is applied, singularly in this implementation. As highlight in the name of this model the starting point from which the vessels are moored is calculate by a uniform distribution function, depending on the length of vessels and in which wharfs they are berthed.

The so called desired position is calculated with the following expression.

$$b0 \; = \; UNIF \, ( \, 0 \, , (Lwharf - Lvessel) \, ) \qquad (13)$$

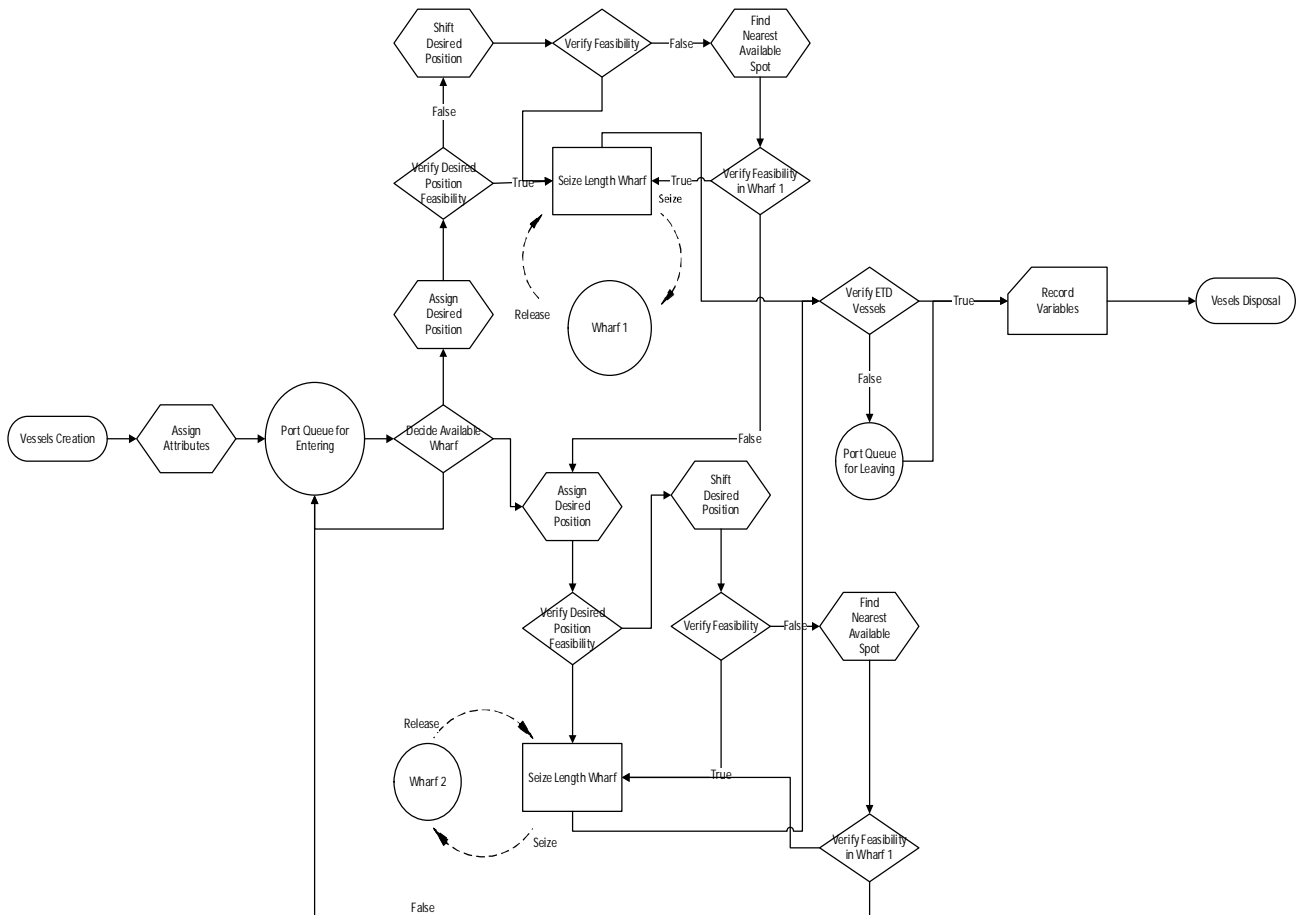The activity diagram of this model is illustrated below.

**Figure 17.** Activity flow diagram of the *Desired Position* model

If the desired position in already busy or the length of vessels leads to overlaps, vessels cannot be berthed. Then the vessel needs to find another available spot which respects the same mentioned constrains. Thus vessels are shifted of thirty meters forward and backward and the feasibility is checked again. If vessels are feasible they are berthed; otherwise they find and check the nearest available spot to the desired position to be berthed and then be processed. If none of the former conditions allow berthing the vessels in the first wharf, the same process is implemented in the second wharf. The desired position is determined again and the feasibility is checked and eventually vessels are berthed, otherwise they are moored in the appropriate area of the port expecting the fulfillment of the berthing conditions.

The pseudo-code of this model is shown below.

STEP 0. Set as resources Wharf$_1$ and Wharf$_2$ with a capacity respectively of 600 and 450 (which are the lengths of each wharf)

STEP 1. CALCULATE the required space in the wharf, equal to the length of vessels; ASSIGN the number 1, 40 and 1,30 to the variables $vBW_1$, $vEW_1$, $vBW_2$, $vEW_2$ referring to the first and the last index of each wharf

STEP 2. ASSIGN this number to the attribute *myVesselLength*

STEP 3. Check IF $Wharf_{(i)}$ is available, satisfying the availability of quay cranes and the idleness of the desired position

STEP 4. ASSIGN the desired position $b_0$, depending on the length of the vessel and of the wharf (as specify above)

STEP 5. Check IF there are already vessels berthed and calculate the idle length in the wharf

STEP 6. IF $b_0$ + *myVesselLength* $\leq$ idle length go to STEP 6, ELSE go to STEP 11

STEP 7. ASSIGN the desired initial position with the variable $vMIN_{(i)}$ (where $i$ stands for the number of the quay cranes seized by the vessel)

STEP 7. CALCULATE the index of the last length required by the vessel with length *myVesselLength* (i.e. $vMIN_{(i)}$ + *myVesselLength*)

STEP 8. ASSIGN this number to the variable $vMAX_{(i)}$

STEP 9. IF between $vMIN_{(i)}$ and $vMAX_{(i)}$ there are busy lengths or $vMAX_{(i)} > EW_{(i)}$ go to STEP 11, ELSE go to STEP 10

STEP 10. SEIZE all the adjacent length ( as a capacity of the resource $Wharf_{(i)}$ ) from $vMIN_{(i)}$ and $vMAX_{(i)}$ during the service time

STEP 11. Shift the desired position $b_0$ forward and backward of 30 meters

STEP 12. IF vessel is feasible go to STEP 10, ELSE go to STEP 13

STEP 13. SEARCH for the nearest available spot to the desired position

STEP 14. IF the vessel berthing is feasible in the nearest spots go to STEP 10, ELSE go to STEP 15

STEP 15. Increment the variable $i$ in STEP 3 by one and go to STEP 5, ELSE go to STEP 16

STEP 16. WAIT in a queue

## 4.1.2 Integrated speed assignment and berth allocation

When studying the speed assignment connected to the berth allocation problem, models are not modified, and they are still the, so called, *Sub-berths*, *Fully Discretized*, *Hybrid Discretization* and the *Desired Position*. All these models are extended at the beginning, because in the simulation vessels are no more created before entering the port. Instead, during those further simulations, vessels are created 500 nautical miles away from the port, because in literature this is the distance

where usually the speed is possibly altered. In the same way as in the first part of this research, vessels are divided in five classes, which assign the percentage of time a vessel of the specific class that shows up at the port, and then they are also further divided in other three categories which define the distance of the journey as well as the cost for possible delayed departures. The vessels are then called *Feeder*, *Medium* and *Jumbo*, according to the last three categories.

| Sailing Distance (m) | Type of Vessel |
|---|---|
| 50 – 100 | Feeder |
| 100 – 180 | Medium |
| 180 - 300 | Jumbo |

**Table 5.** Vessels names classification depending on their length

Once again simulations need to be appropriately set in terms of parameters. Those implementations have to represent as much as possible real life situations, in order to verify conditions or prove changes. Thus the simulation parameters for appropriately run simulations are partially changed; indeed, despite the topic is still the berth allocation problem, some changes are required to simulate at best this further scenario in which the speed modification is applied to incoming vessels, directed to the port. The replications length of simulations is set as one month, so this is also the stopping criteria, and there is no warm-up period. Moreover there is not a precise number of processed vessels, but this parameter is directly dependent on the models implemented. The time base units are still set as hours and models are again iterated twenty times. All the parameters are collected in the table below.

| Set-up Parameters | Value |
|---|---|
| *Replication Length* | 1 Month |
| *Warm-up Period* | 0 hours |
| *Time Base Units* | Hours |
| *Number of Replications* | 20 |

**Table 6.** Parameter required to correctly runnning the simulations

Some attributes are the same, such as the length of vessel and the processing times, and they are assigned in the same way as explained before. Instead some other parameters are changed, such as the expected time of departure (ETD) and the related cost for delayed departures, or they are added, such as the minimum and maximum speed and the fuel consumption. Vessels can sail with a

specific range of speed, independently on their length. The three categories, mentioned above, do not define typical speed for different length of vessels. The minimum speed is calculated with a uniform function between two precise values, for each vessel, independently from the length of vessels. The maximum speed is instead define as the minimum speed plus four nautical knots, meaning that it is not a precise value but it can be only four knots greater than the minimum speed, once the latter one is determined and assigned to vessels.

| Length of Vessels (m) | Minimum Speed | Maximum Speed |
|---|---|---|
| 50 – 100 | UNIF (10, 14) | Min Speed + 4 knots |
| 100 – 180 | UNIF (10, 14) | Min Speed + 4 knots |
| 180 - 300 | UNIF (10, 14) | Min Speed + 4 knots |

**Table 7.** Minimum and maximum speed assignable to the three further categories of vessels

The extension of the model focuses only on the speed assignment, which is the initial part on each model, maintaining the rest of models as in the pure berth allocation simulations.

In these simulations vessels are created 500 nautical miles before reaching the port and the time between intervals of vessels is set in hours and differently from the pure berthing process. The probability distribution that represents the interval between vessels arrival is the exponential distribution, with a mean value of four. This means that averagely every four hours a vessel shows up at the port during all the 720 hours, equal to a month length, of the simulation. The time between arrivals (TBA) of vessels is illustrated below.

$$TBA = EXPO\ (4) \qquad (14)$$

As mentioned in the literature, once vessels leave port they keep the same speed until they reach the 500 nautical miles distance from the port they have to be processed. In order to reduce fuel consumption vessels keep the minimum speed, which they do not change until the 500 nautical miles distance from the port. Usually speed is altered only once, but in this research it will be changed, if necessary, up to three times, in order to meet the productivity of the port and to avoid port congestion or inefficiency. The speed is initially updated at 500 nautical miles and then at 300 and finally at 100 nautical miles. In the simulation this scenario is modeled by checking the condition for changing the speed and then calculating and assigning, for all the checking points, an expected time of arrival (ETA), according to the speed, either maximum or minimum. Initially since

vessels sail with the minimum speed, it is calculated an expected time of arrival assuming that they keep the same speed till they reach the port.

$$myETA = \frac{500\ (miles)}{myMinSpeed} \qquad (15)$$

This is the required time to sail 500 nautical miles at the minimum speed. This parameter is utilized afterwards to determine and calculate the expected time of departure (ETD). After that, at each specified distance, the expected time of the arrival (ETA) to the following check point is determined, in order to model the real time needed by vessels to sail the specific distances.

$$myETA300 = \frac{200\ (miles)}{Assigned\ Speed} \qquad (16)$$

$$myETA100 = \frac{200\ (miles)}{Assigned\ Speed} \qquad (17)$$

$$myRealETA = \frac{100\ (miles)}{Assigned\ Speed} \qquad (18)$$

The condition that governs the speed changes is the number of vessels that are already in queue waiting to be berthed. If the number is lesser than a fixed parameter than vessels are speeded up; if the number of vessels is greater or equal than a fixed parameter than vessels are slowed down, moving to the port in the so called slow steam. In this research the number of queued vessels that makes the speed change is initially set as three queued vessels, but then it is increased to analyze how the models react at this change. The number of queued vessels waiting that affects the speed assignment is then set as four and finally at five. It must be highlighted that initially, in the simulations, all vessels are speeded up because there are no other vessels waiting to be berthed, so the speed is altered only once there are enough queued vessels waiting to make the speed assignment system works. Moreover it is hypothesized that all the vessels are sailing at the minimum speed and this is a condition is kept till the first check point. The speed assignment starts only once the condition that make it change is fulfilled, that is once some vessels wait to be berthed because all the quay cranes are busy or the length constrain are not satisfied.

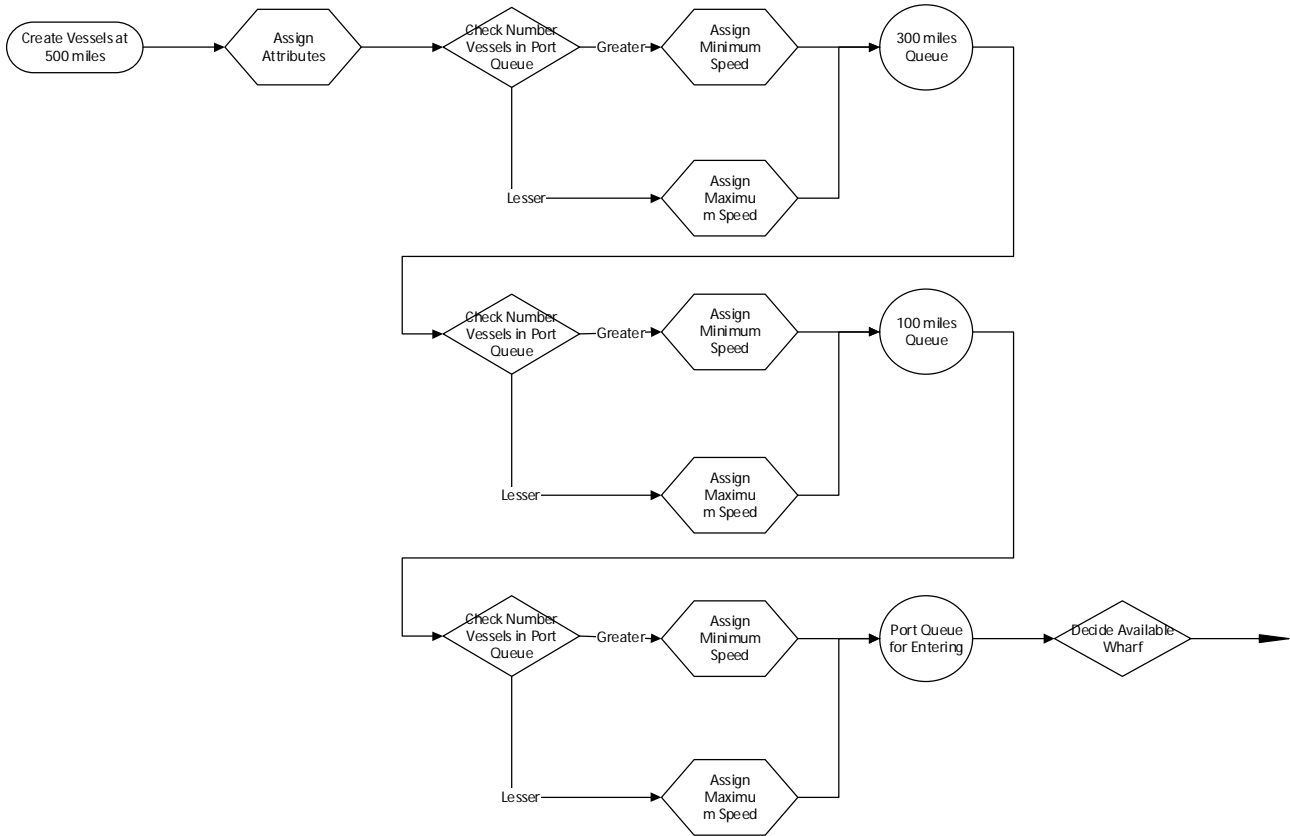The activity diagram of this added implementation is illustrated below.

**Figure 18**. Activity flow diagram of the speed assignment to vessels

The new attributes that are used in this simulation are those used to calculate the fuel consumption. The bunker fuel price is considered at 500 \$ per ton; a bunker of fuel is equal to 0.14 ton and then the price of the fuel for 1 ton is 3571, 43 \$. First of all the Deadweight Tonnage (DWT) is calculated, which is a measure of how much weight a ship can safely carry, as a sum of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers, and crew. This attribute is required for the determination of the fuel consumption and it depends on the length, according on the three categories classification, of vessels as exposed in the table below.

| Type of Vessels | Dwt |
|:---:|:---|
| Feeder | UNIF (10,40) |
| Medium | UNIF (40,60) |
| Jumbo | UNIF (60,100) |

**Table 8**. Dead weight tonnage for each class of vessels

Thus the fuel consumption is found out thanks to the following expressions, which are required to find the ton per day necessary for vessels to sail with a specific speed.

$$k\,(v,14) = 19.5 + Dwt \times 0.00034 \qquad (19)$$

$$k\,(v,s) = k_{(v,14)} \times \frac{s^3}{14^3} \qquad (20)$$

The first one allows calculating the fuel consumption, as ton per day, if the speed of vessels is fourteen knots, once the deadweight tonnage is determined; the second one enables finding the ton per day of fuel consumption, as a function of the previous expression, according on the speed of vessels, which is different from the fourteen nautical knots. This parameter is calculated every time the speed changes and then it is recorded to find the cost of the total fuel consumption, during the simulation. The fuel consumption is a new parameter introduced in this simulation, because strictly connected with the changing of the speed and because it affects deeply the costs. A parameter which is changed from the former simulations instead is the expected time of departure (ETD) of vessels. As in the pure berth allocation, to each vessels is assigned an attribute that defines the time of simulation, tagged as *Tnow*, when each vessels is created.

$$myTime \; = \; Tnow \qquad (21)$$

This attribute allows recording the total time required by vessels to complete the simulation and to record possible delayed departures. In fact the expected time of departure (ETD) differs from the previous way of determining it; it is the sum of the time of creation, the required time to sail 500 nautical miles with the minimum speed, a time uniformly proportional to the processing, specific of each vessel and dependent on its length, and a time approximation. Then once this value is defined for each class of vessel, It is assigned, as an attribute, in the same as before. The complete expression and the assignment are exposed below.

$$eETD \; = \; myTime \; + myETA \; + \; myRealDelay \; + \; UNIF\,(2,3) * ProcessingTime \qquad (22)$$

$$myETD \; = \; eETD\,(myVesselType) \qquad (23)$$

The time approximation is added delay value which depends on the distances of the journey that vessels have to sail. The actual time to complete the voyage is modified by adding this random delay that is uniformly distributed between two parameters dependent on the distance *d*, which is the distance of the trip, in nautical miles, to be sailed. According to the length of vessels and once the minimum speed is determined, this approximation is calculated with the following expression,

thanks to the table below from which the sailed distance is extracted, for each vessel. Once the distance is set, according to the length of vessels, this value is multiply by two constant parameters and divided by the distance in which the speed of vessels is possibly changed, due to the check points where the speed changing condition is verified. The final expression and the table where the sailed distances values are extracted are shown below.

$$myRealDelay \ = \ UNIF \left( \frac{-8*d}{500}, \frac{16*d}{500} \right) \qquad (24)$$

| Length of Vessel (m) | Distance for Time Approximation (m) |
|:---:|:---:|
| 50- 100 | UNIF ( 400,800 ) |
| 100 – 180 | UNIF ( 800,1500 ) |
| 180 - 300 | UNIF ( 1500,2400 ) |

**Table 9.** Range of distance possibly sailed by the vessels split into the three main categories

This additional delay has not to be mistaken with the possible delayed departures which are assigned to each vessel if they leave port later than their scheduled departure. The expected time of departure is a function of the length of vessels, according to the five classes in which vessels are initially divided to determine length and processing time. So the class of vessels defines the values of the expected time of departures, associating the class number with the row of the vector.

$$myDelay \ = \ eETD \left( myVesselType \right) \qquad (25)$$

The simulation is then the same to the previous one, once vessels reach the port. They check the berthing conditions and if they are fulfilled they are berthed, checking he first wharf initially and the second one afterwards; otherwise they wait in the queue, a specific area of the port where vessels are temporary anchored, until the berthing conditions are satisfied. The performance measures are still the same, with exception for the measure called *cost function*. This performance indicator is updated and it is calculated as the sum of the non-utilization of wharfs, costs for possible delayed departures and of the fuel consumption. The cost for the utilization of wharfs is increased up to 50 k$ and also the cost for delayed departures is extended. Those two costs are calculated as described before in the pure berth allocation models. The cost of the wharfs utilization per day is exposed below.

$$Wharf\ Utilization\ Cost\ =\ 50\ k\$\ per\ day \qquad\qquad (26)$$

The cost for delayed departures is calculated according on the three categories classification of vessels, but costs are increased, for each class. The delay of vessels is multiplied by the correlate cost, depending on the length of vessels, defining the cost that occurs when vessels leave the port later than the schedule. Data are illustrated in the table below.

| Length of Vessels (m) | Delayed Departure Cost (k$) |
|:---:|:---:|
| 50 – 100 | 7 |
| 100 - 180 | 12 |
| 180 - 300 | 15 |

**Table 10.** Cost for delayed departures of vessels depending on their length

The third factor that affects the total cost is the fuel consumption and it is calculated as the ton required by vessels to sail the 500 nautical miles, from which simulation start, according to the speed assigned to them, thank to the former expressions. Thus the *cost function* is the sum of the three factor just mentioned: wharfs non-utilization cost, delayed departures cost and fuel consumption, as shown below.

$$Cost\ Function\ =$$
$$\sum\left(\left(\frac{1}{Wharfs\ Utilization}\right) \times Wharf\ Utilization\ Cost\ +\ Delayed\ Departure\ Cost\ +\ Fuel\ Consumption\right) \qquad\qquad (27)$$

The extension of the model regarding the speed assignment can be illustrated, step by step, to better understand how the simulation works. The pseudo-code of this model is shown below.

STEP 0. CREATE vessels (at 500 nautical miles from the port)
STEP 1. ASSIGN attributes, considering initially vessels in slow steam
STEP 2. CHECK at 500 nautical miles the queue condition
STEP 3. IF the previous condition is satisfy ASSIGN maximum speed to vessels, ELSE ASSIGN
        minimum speed

STEP 4. HOLD vessels until the simulation time is equal to the real time needed to sail 200 nautical miles

STEP 5. CHECK at 300 nautical miles the queue condition

STEP 6. IF the previous condition is satisfy ASSIGN maximum speed to vessels, ELSE ASSIGN minimum speed

STEP 7. HOLD vessels until the simulation time is equal to the real time needed to sail 200 nautical miles

STEP 8. CHECK at 100 nautical miles the queue condition

STEP 9. IF the previous condition is satisfy ASSIGN maximum speed to vessels, ELSE ASSIGN minimum speed

STEP 10. HOLD vessels until the simulation time is equal to the real time needed to sail 100 nautical miles

STEP 11. WAIT in the queue to enter the port for being processed

## 4.2   Queue policies applied to waiting vessels

In this research are collected different key performance indicators, in order to study and compare all the models, both for the pure berth allocation problem and for the speed assignment problem. Two of these performance measures are the average number of vessels waiting to be berthed and the average waiting time of vessels in the queue. These two measures point out the efficiency of the port to process incoming vessels and reduce as much as possible the number and the time vessels have to wait in the port before being served. For this reason not only are considered different policies for models, referring to the four different models analyzed, but also in the queue where vessels wait before being processed. In fact it is not known in which order vessels, which are waiting in the queue, need to be served in order to get the maximum efficiency and productivity of the port, and so the maximum throughput.

The policies of models are not only dependent on how they consider the berthing space, either continuous or discrete, but also on their approaches to try solving the berth allocation problem. The Sub-berths model studies the problem by dividing berths in sub-berths and considering length of vessels as a sum of the required sub-berths, while considering the berthing space as continuous. The Fully Discretized models the continuous berthing space but studying the case with the real length of vessels, with the aim of finding a more accurate and realistic evaluation of the wharfs utilization. The Hybrid Discretization is juxtaposed to other models because it analyze the berthing space as

made out of separate berths, which can be seize singularly or more than one together, so considering he berthing space as discrete. This model is studied to compare the continuous berthing space with the discrete one and describe the advantages and disadvantages of the continuous scenario. The last model, the Desired Position goes back to the continuous berthing space but the policy make vessels to be berthed no more next to the last moored, but according to a fixed berthing position calculated with a uniform function, according to the length of vessels and the length of the wharf where they are berthed. If this position is not available or the berthing process from the desired position leads to overlaps, vessels are initially shifted forward or backward to check the feasibility. If the berthing process is still unfeasible they are moored to the nearest free space next to the assigned position.

All this four models are studied, modeled and analyzed thanks to the collection of some key performance indicators which enable the comparison between models.

Regarding the pure berth allocation, thanks to the simulation program utilized, it is possible to decide how to release the vessels form the virtual queue which models the vessels that wait in the port before being berthed. The choices are to release the first entity which comes in or the last one which comes in as well as the entity which has got the highest value or the lowest of a specific attribute. As default the simulation release from the queue the first entity which comes in and for this reason the first policy adopted for the queue is the so called first-come-first-served. But this is the first out of four queue policies which are modeled and analyzed; the reason is to find out, thanks to the performance measures, which is the right way to make vessels leave the queue, with the same purpose of increasing the efficiency and productivity, while reducing idleness. Thus all the policy studied and compared are:

- First-Come-First-Served (FCFS)
- Short Processing Time (SPT)
- Earliest Due Date (EDD)
- Biggest Load (BL)

The first policy, the *first-come first-served* (FCFS), as mentioned before, when more than one entity, in this simulation vessels, is waiting to be processed, as soon as one resource is available, and all constrains are fulfilled, the first vessel arrived at the port can leave the queue and be berthed. Analyzing this policy vessels are berthed independently from length, class of belongings or other any attribute. The sequence of berthed vessels depends only on the discrete function which, during the simulation, decides which vessels are created and to which class belong, to assign them length and processing time. The second policy compared is the *shortest processing time* (SPT), meaning that among the waiting vessels the first that is berthed, once a resource if available, is the one that has got the shortest processing time. This vessel seizes the resource, wharf, for the shortest time and

leaves the system sooner that the other vessels. As mentioned before the processing time is assigned to each vessel as an attribute when vessels are created and this attribute is only function of the length of vessels and then to the class of belongings. Simulating with this policy means that when more vessels arrive at the port the shortest one are processed, because the processing time is directly proportioned to the length of vessels; longer vessels wait more in queue, despite they arrive earlier.

The following policy applied is the *earliest due date* (EDD), referring to the date that vessels have to leave the port according to the schedule. When vessels are created some attributes are given to them, such as the length, the processing time and the expected day of departure (ETD), which is the simulation time on which vessels have to leave to port by schedule. Thus with this policy vessels which have to leave the port before the other are berthed first. In fact delay departures can cause important penalties that port management wants to avoid. Despite vessels which have a tighter schedule than others are processed first it does not means that every vessel is in time. Delayed departures happen anyway, but at least the number is reduced as well as the relative cost.

The last policy applied is named *biggest load* (BL), because it refers to vessel which can carry the highest number of containers, independently from loading or unloading process. This policy is the opposite one of the *short processing time*. Indeed vessels that can carry the highest amount of containers are the longest ones and so the ones that need more time to be processed. So with this policy it is given priority to the longest vessels which seize the resources, wharfs, for a longer period. With respect to the extended problem of speed assignment all the previous model are considered and all the previous policy are compare as well. While simulating the speed assignment with different model policies and queue policies one more condition is added to the models. This new condition rule the speed changing and it deals with the same queue where the *first-come-first-served*, *short processing time*, *earliest due date* and *biggest load* policies work. In fact the speed is altered if there are too many or too few vessels in the queue, in order to avoid port congestion and too many vessels waiting or idle resources and then decreasing benefits. The number of waiting vessels that make the speed changes trigger is a fixed parameter and this parameter is changed three times, to see possible improvements or inefficiencies .The number of waiting vessels is initially set as three, then as four and finally as five. So if initially the number of vessels waiting at port is higher than three, the incoming vessels sail till the following check point with the minimum speed, which is the one that is assigned for all the journey; if there are lesser than three vessels that are already at the port, incoming vessels are speeded up till the following check points. This process of checking the number of queued vessels and then change or keep speed is done three times; at 500 nautical miles, when vessels are created in the simulation, and then at 300 miles and finally at 100 miles from the port. This implementation is repeated, and then models are simulated and

performance indicators collected for analysis and comparison, increasing the trigger condition for the changing of speed. So from the first situation to the third one, many more vessels are speeded up in the simulation, and port is stressed to evaluate the response and possible increase in efficiency and productivity.

Recapping in the first scenario of the pure berth allocation, four models with four different queue policies are applied, meaning that for each performance indicator there are sixteen different values to be analyzed and compared. Instead, in the second scenario of the speed assignment and berth allocation, due to the fact that also the speed is changed in three different ways and that models and queue policies are always the same, the results for each performance measure is between forty eight values.

# Chapter 5

# *Measures of Performance*

## 5.1    Key performance indicators

Key performance indicator (KPI) or performance indicator is a measurement of the performance that an organization can use to evaluate its success or the success of a particular activity, organization's branch, dealer or employee.

Key performance indicators, according to the *Wikipedia* definition are:

- *"Key Performance Indicators (KPI) are financial and non-financial metrics used to help an organization define and measure progress toward organizational goals."*

- *"KPI's are frequently used to "value" difficult to measure activities such as the benefits of leadership development, engagement, service, and satisfaction."*

Understand what is a KPI is extremely important to perform at the same level, at least, or to thrive in a more and more competitive market.

KPIs are not the same for all the organization but each area has its own performance indicators, because each member has to make its part work in the best way and be coordinated with all the other divisions in order to get the best combination to make to organization gain the highest benefits possible.

Performance indicators are frequently associated with "performance improvements" initiatives: the main focus of managements is to find out the more relevant and coherent KPIs and try to make them improve with the final purpose of a potential organization's improvements, both general and partial.

Assessing the KPIs managements should be able to understand to situation of the organization and decide which decisions are necessary and required for the prospering of the company; indeed those indicators summarize all the needed information to evaluate the condition of a society.

There are many ways to represent KPIs, or key success indicators (KSIs), but they can be summarized into the following categories:

- Quantitative indicators
- Qualitative indicators
- Leading indicators
- Input indicators
- Output indicators
- Process indicators
- Directional indicators
- Financial indicators

KPIs must be defined in an easy way to understand and measure them and they must be meaningful. Uncontrollable factor or situation don't have to influence or take part in the evaluation of performance indicators because they are no more objective and they do not add value to the business but they just led to a misunderstanding of the real situation and wrong decisions can be taken.

So those success indicators have to reflect the exact goals the business unit wants to achieve, constantly measuring the progress through them.

One way to define a KPI is the SMART criteria, Peter Drucker's concept, which allows setting specific, measurable, attainable, relevant and time-bound objectives. This means the measure has a specific purpose for the business, it is measurable to really get a value of the KPI, the defined norms have to be achievable, the improvement of a KPI has to be relevant for the success of the organization, and finally it must be time phased, which means the value or outcomes are shown for a predefined and relevant period. Key performance indicators usually are long-term considerations, so it is important to keep the same definition from year to year. If a key performance indicator is going to be of any value, there must be a way to accurately define and measure them, as well as to set targets for each of them. Organizations should follow a number of steps before choosing the best key performance indicators:

    1. Defining clearly the business processes

    2. Setting appropriate requirements for the business processes

    3. Having the possibility to get qualitative and quantitative measurements of results

    4. Determining variety and adjusting processes to meet short-term goals.

When choosing the right KPIs, a company should start by considering the factors management uses in managing the business. Then it must be considered and identified whether these factors are helpful in assessing the company's progress.

What is more important is how relevant the indicators are to the business or its units. There is no specific number of KPIs a company needs, but generally, the number may be anywhere from four to ten for many types of businesses, and they must be crucial to the success of the business. Most of the times it is not recommended to select more than seven performance measures, because they can get opposite results of the same measures, considering the same aspect from two different points of view. That is the reason why usually less than seven indicators are enough to avoid misjudgments.

Companies should also review their objectives and strategies regularly and make necessary adjustments on their key performance indicators, following the changing of the market and the possible changing in the companies themselves.

If companies find out relevant and proper KPIs they are really useful to help pursuing the direction to success. Key performance indicators are important to a business because they help it focus on common goals and ensure those goals stay aligned within the organization. This focus will help a business to stay on task and work on meaningful projects that will assist in reaching faster goals.

Once managements have define the goals the organization wants to achieve, performance indicators provide reliable measurements which lead to achieve, sustain and elevate the specify success.

Fixing precise performance measurements it does not end in itself but it is important to interpret the consequences from using it and the impact it may create on other areas of performances.

In fact finding a confirmation that data and measures are valid and conform to what companies purpose are represent fairness, transparency and accuracy.

These measures need to be checked and arranged during a period of time and their variability must be considered to decide if and when companies have to do something or not, finding the most suitable moment.

So KPIs have to provide the most beneficial information in the most useful way so organization can make decision and take action to continuously improve processes and then the overall business.

Another useful way to find out the most effective performance indicators is the QCD approach.

Quality, cost, delivery (QCD) approach is a typical topic used in lean manufacturing that let to measure a business activity and develop key performance indicators (KPIs). Despite the deep use in manufacturing area, QCD can be used also in supply chain management and engineering.

This approach makes products or services made of three dimensions: quality, cost and delivery. Quality is the attribute desired by users that conceive the value of the product and usefulness to him. Cost, the second dimensions, involve the cost of the delivery of the service to customers,

influencing the cost of users altering the "price" he has to pay for it. Delivery involves bringing the completed service to customers at the right time, quantity and place.

So referring to this research it is possible to correlate the three dimension of this approach with some of the more important performance measures collected during the simulations from the models.

Dealing with the pure berth allocation problem, *quality* can be associated with the total time required by vessels to go through the port; *cost* is due to the non-utilization cost and the delayed departure cost; *delivery* can be related to the average number of vessels in queue and the average time they have to wait in queue. Focusing on the second half of the study, regarding the speed assignment connected to the berth allocation problem, *quality* can be considered as the number of vessels which are handled in the port, during the simulation time; *cost* can be associated with the cost coming from the non-utilization of wharfs, the cost of delayed departures and the cost of the fuel consumption; finally *delivery* can be correlated with the average number of vessels waiting in the queue, before being berthed, the average time of vessels waiting in the queue, as well as the average makespan, or the average flow time required by vessels to complete the process.

The QCD approach is summarized in the tables below.

| Focus | Key Performance Indicator |
|---|---|
| *Quality* | Makespan |
| *Cost* | Wharfs non-utilization cost |
| | Delayed departure cost |
| *Delivery* | Number of vessels waiting in queue |
| | Time of vessels waiting in queue |

**Table 11.** QCD approach for the berth allocation problem

| Focus | Key Performance Indicator |
|---|---|
| *Quality* | Number of served vessels |
| *Cost* | Wharfs non-utilization cost |
| | Delayed departure cost |
| | Fuel Consumption |
| *Delivery* | Number of vessels waiting in queue |
| | Time of vessels waiting in queue |

**Table 12.** QCD approach for the speed assignment analyzed with the berthing process

On the other hand, focusing particularly on ports, Trujillo and Nombela (1999) stated that there are many ways of measuring port efficiency or productivity, although reducible to three broad categories: physical indicators, factor productivity indicators, and economic and financial indicators. Physical indicators generally refer to time measures and are mainly concerned with the ship, such as the ship turnaround time, ship waiting time, berth occupancy rate and working time at berth. Sometimes, coordination with land modes of transport is measured, such as, cargo dwell time or the time elapsed between cargoes being unloaded from a ship until it leaves the port. Factor productivity indicators also tend to focus on the maritime side of the port, for example, to measure both labor and capital required to load or unload goods from a ship. Similarly, economic and financial indicators are usually related to the sea access; for example, operating surplus or total income and expenditure related to gross registered tons or net registered tons, or charge per TEU (Bichou and Gray 2004).

## 5.2   Measures collected in the models

While dealing with the pure berth allocation (BAP) the key performance indicators (KPIs) which are collected regard wharfs utilization, vessels timing and the cost due to the berthing process, by using respectively all models and queue policies together. As illustrated in the previous chapter, the cost is a direct response of two factors, set appropriately for the pure berthing process simulations.

The collected performance indicators are precisely the wharfs overall utilization, as a result of two single berths or the sum of more berths according to the model, the number of vessels waiting in a queue before being berthed as well as the time they have to wait in the queue. The overall time that vessels spend to go through the port is collected too and this measure is called the *makespan*, or average flow time. This time is the necessary interval from the arrival of vessels at the port to when they leave it; this time interval is another performance indicator, because it reveals the time needed to handle vessels and the velocity with which vessels go through the port and thus the efficiency of the port to process incoming vessels. Then the most important performance indicator is the, so called, *cost function* which is the sum of the cost of delayed departure of vessels and the cost of wharfs non-utilization. Then collecting the possible delayed departure of vessels is necessary, so the delay collected in hours is another measures, and they are considered as the intervals of time required by vessels to leave port with respect to the scheduled departure; the delayed departures cause a cost which is another measure of performance, depending on the length of vessels and then on the classification in which vessels are split. As mentioned before the total cost, caused by the

implementation of a precise model, is the sum of the cost of delayed departures of vessels and the cost derived from the incapability of not utilize completely the intended wharfs, so the non-utilization of wharfs is the last indicator. This measure points out how much the berthing process exploit the resource of the port, which are the wharfs for those simulations; so the efficiency of models is highly dependent on this indicator. It must be highlighted that the total cost recorded for every single model, precisely reflect the capability of a simulated system to be competitive or inefficient. Indeed the higher the wharfs utilization the lower is the cost for the incomplete wharfs exploitation; then the higher is the number and time of queued vessels the higher the delays and then the relative delayed departures and finally the derived costs. Lastly the delayed departures cause to increase the total time required by vessels to leave the port. The same scenario is modeled and implemented for the further simulations, where the total cost is once again a reflection of the efficiency and productivity of the models themselves.

When the speed assignment is studied next to the berth allocation problem, the main performance indicators that are collected, when all the models are implemented applying all the queue policies and added constrains, are exactly the same mentioned and described above. They are still the utilization of wharfs, the number of vessels waiting in a queue and the number waiting, possible delayed departures, in terms of time, and the makespan, or average flow time of vessels. The latter indicator is now calculated as the interval of time required by vessels from when they reach the distance of 500 nautical miles from the port, to when they leave it. The cost due to the non-utilization of wharfs is still collected, analyzed and compared, as well as the cost for delayed departure of vessels, dependent on the possible delay in respect to the expected departure.

There are two new measures which are collected and these are the fuel consumption and the average number of vessels that are handled, according on models and policy applied. Fuel consumption is in the second half of this research a new factor for the *cost function*. So it is the sum of the cost of delayed departure and non-utilization of wharfs, as in the pure berth allocation, plus the fuel consumption. The number of vessel averagely processed is extremely significant in the assessment of the port efficiency. The fuel consumption is in fact the factor that affects more the cost function so the more vessels are served the higher this factor is. It must be reminded that a lower value for cost function does not always mean that the model is better or more efficient, because the number of vessels handled can be lower too. So these further measures are strictly correlated and they must be analyzed together because they are significantly dependent.

# Chapter 6

# Outcomes Evaluation and Results Validation

All the models are run with the simulation parameters explained in the previous part and all the main performance indicators are collected in order to evaluate the models and compare them to find the best model to be applied in real life ports. The objective is to point out the more accurate and efficient model than allows port management to get the higher productivity and throughput, with the lower cost and the higher benefits.

This research mainly focuses on modeling and analyzing an intended port with continuous berthing space thanks to the comparison of three different models, but, at the same time, the discrete berthing space, the fourth model, is modeled and studied. The purpose is to stress the advantage of utilizing a continuous quay instead of a discrete one. All the models are simulated, analyzed and compared assessing four different queue policies for deciding in which order vessels are berthed. In fact vessels arriving at the port may not find an available quay crane which can handle them, so they have to wait in an appropriate area of the port. These four different queue policy and modeled and analyzed with the ultimate aim to increase productivity and efficiency by choosing the most appropriate order to moor waiting vessels. Those policies differ in the way the order is created and updated every time a vessel either leave the queue or enter the port. The policy can stand on the simple timing factor, berthing the first vessel that get the port first, or on the processing time needed to serve vessels, both the shortest and the longest, or finally on the expected departure time of vessels, assessing the schedule of vessels and giving priority to vessels that have a tight schedule.

The pure berth allocation problem and the speed assignment problem linked to the berth allocation are analyzed separately, in order to highlight the effects of changing the speed of incoming vessels to the port. Speed of vessels is altered to study the costs of fuel consumption and balance them with the costs of the port to find the most convenient solution.

While analyzing the pure berth allocation it is possible to compare different models through the policies, because the models are simulated for the same amount of time and the same number of vessels, fifty thousand. So resources, waiting time and cost are comparable independently from the

policies, allowing finding out the best policies between the ones adopted. Since each models is has the same length of replications and the stopping criteria is the same, assessing the outcome recorded it is clear which is the most efficient and profitable model to apply. Instead while dealing with the speed assignment associated with the berth allocation it is quite difficult to compare some performance indicators, such as the *cost function*, among different policies. Indeed the number of vessels processed it is not the same because it is a variable that comes from the combination of the model and the policies, as well as of the fixed queue condition that trigger the speed changing. The only constant parameter is the replications length that is set to 720 hours, equal to one month of port simulation. The *cost function* in fact may seems more suitable in some cases, but it must be kept in mind that the number of handled vessels is different so management port must consider this factor before choosing the most appropriate and efficient policy. The more vessels are served the higher the profits can be; then higher costs are not always a sign of an inefficient solution. The fuel consumption is the bigger factor which makes the *cost function* floats, but even if it seems too high compared among policies it comes from the possibility of speeding up vessels because the berthing allocation is efficient and there is the possibility to serve more vessels. Otherwise wharfs and all the other port resources will be idle and inefficient, causing an important reduction of the productivity and consequent benefits. That is the reason why the number of vessels handled in the second half of the research is an indicator of performance.

## 6.1   Berth allocation outputs

The average values of all the key performance indicators (KPIs) are shown and described in the tables and histograms below.

The wharf utilization represents the measure of how much those resources are utilized over the simulation time, by the vessels that arrive at the port to be handled for loading or unloading processes.

**Wharfs Utilization (%)**

|  | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | 56 | 56 | 56 | 56 |
| **Fully Discretized** | 54 | 54 | 54 | 54 |
| **Hybrid Discretization** | 69 | 69 | 69 | 69 |
| **Desired Position** | 54 | 54 | 54 | 54 |

**Table 13** Percentages of wharfs utilization for each model and queue policy

As it is possible to assess from the table above, the model with the highest utilization is the *Hybrid Discretization*, which records a utilization of almost 70 %. This is due to the fact that it seizes an entire berth or more berths simultaneously whole berths simultaneously, independently from the length of vessels and if it is completely utilized or not. The other models record a lower utilization. *Fully Discretized* and *Desired Position* models have the lowest utilization, because they consider the real length of vessels; instead the *Sub-berths* model, which stands in half way between continuous and discrete quay, has utilization a little bit higher than the previous ones. The different queue policies do not affect significantly the wharfs utilization, which varies on the second decimal place. Considering the average values and not the percentages the most efficient queue policy is the *shortest processing time* (SPT). From the charts below, referring to the most effective queue policy, it is highlighted the percentage of wharf utilization and non-utilization. As just mentioned the best solution is the third model, followed by the *Sub-berths* model because it approximates the length of vessels with the highest possible number of 15 meters long sub-berths. This models is smaller version of the discrete quay, where the number of berths is exponentially increase to maximize accuracy. The last two remaining models have utilization percentages that is lower compared to the former model because they use the real length of vessels, meaning they are free from approximation or overestimations.
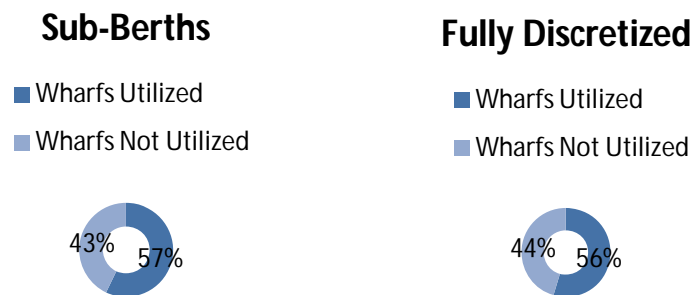


**Figure 19**. Wharfs utilization and non-utilization in the *Sub-berths* and *Fully Discretized* models

81

## Hybrid Discretization

■ Berths Utilized
■ Berths Not Utilized

31%
69%

## Desired Position

■ Wharfs Utilized
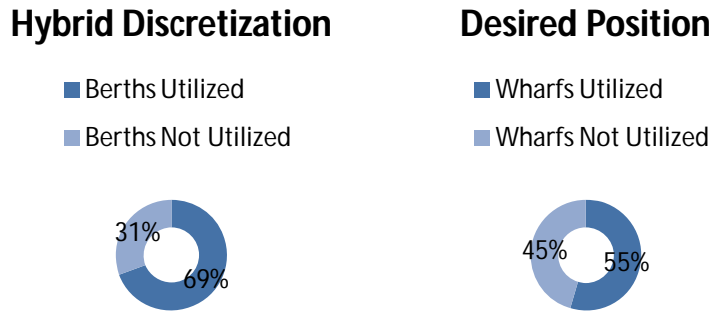■ Wharfs Not Utilized

45% 55%

**Figure 20.** Wharfs utilization and non-utilization in the *Hybrid Discretization* and *Desired Position* models

The average time that vessels have to wait in the appropriate area of the port before being processed is measure of the capability of the port of handling incoming vessels as fast as possible, cutting down slowdowns and waiting time.

### Waiting Time in Queue

|  | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | 5,3371 | 5,27 | 5,3202 | 5,3633 |
| **Fully Discretized** | 5,3198 | 5,2494 | 5,3031 | 5,3466 |
| **Hybrid Discretization** | 5,2117 | 5,1554 | 5,1919 | 5,2631 |
| **Desired Position** | 6,3927 | 6,4071 | 6,4196 | 6,4053 |

**Table 14.** Average time that vessels wait for each case

As it is shown numerically in the table above and in the chart below, the time that vessels have to averagely wait in queue before being berthed has quite the same value for the *Sub-berths*, *Fully Discretized* and Hybrid *Discretization* models. Indeed in the chart curves are almost overlapped. While for the *Desired Position* model higher values are recorded. This performance measure is recorded in hours, so that this last model differs averagely of one hour from the three previous ones. Queue policies make values to float a few but they do not point out substantial differences. The *shortest processing time* (SPT) queue policy is slightly better than all the others for each model and in the graph below it is possible to see a small valley.
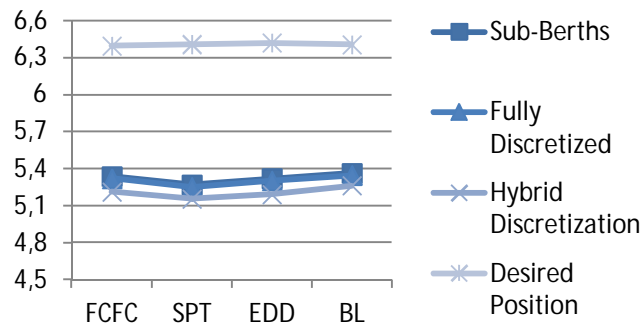
## Time Waiting in Queue



**Figure 21.** Average time that vessels wait before being berthed in each model

The average number of vessels waiting in the queue is calculated on the complete simulation and it represents the number of vessels, and then the amount if container, which are not moved or processed. This is a situation of stacked profits and of increasing costs.

## Number Waiting in Queue

|  | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | 0,4611 | 0,4505 | 0,4573 | 0,4783 |
| **Fully Discretized** | 0,4533 | 0,4428 | 0,4501 | 0,4704 |
| **Hybrid Discretization** | 0,7787 | 0,7657 | 0,7737 | 0,786 |
| **Desired Position** | 0,5539 | 0,5473 | 0,5539 | 0,5836 |

**Table 15.** Average number of vessels in queue at the port before being processed

From the chart below it is illustrated how the *Hybrid Discretization* model is the worst scenario because it has the highest average number of waiting vessels. The *Desired Position* model is quite better than the previous one but it still represent a bad situation compared with the other ones, which have slightly different values. Queue policy does still not affect considerably average values of models, but the *shortest processing time* (SPT) results to be the best solution, especially when applied with the first two models. In the histogram below is easily possible to get the difference among models of the average number of vessels that have to wait in the queue.

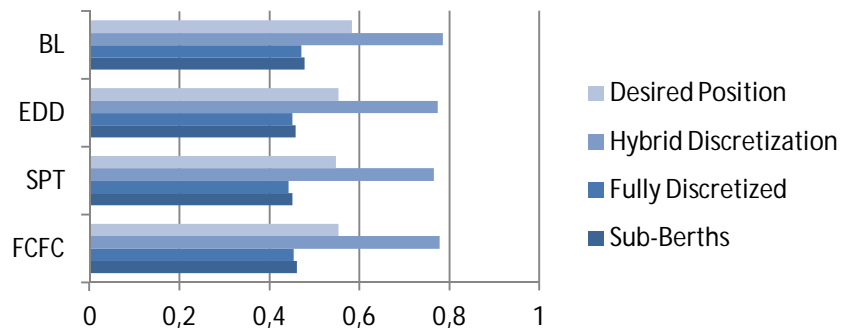83

# Number Waiting in Queue



**Figure 21.** Average number of vessels that wait before being processed for each model

The makespan is a measure of the time, expressed in hours, which describes the amount of time required by vessels to go through the port. All the activities that are required to handle all the incoming vessels in the port, from when they arrive to when they leave it, are counted in the makespan, or average flow time.

## Makespan

| | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | 32 | 28 | 30 | 45 |
| **Fully Discretized** | 31 | 27 | 30 | 44 |
| **Hybrid Discretization** | 72 | 48 | 70 | 127 |
| **Desired Position** | 40 | 32 | 42 | 66 |

**Table 16.** Total time necessary for vessels to go through the system

*Sub-berths* and *Fully Discretized* model have the best solution with the lowest value; indeed in the chart below curves are practically overlapped. The *Hybrid Discretization* model registers the highest values and the *Desired Position* models stands in half way. Queue policies affect extensively this measure of performance. The *biggest load* (BL) policy has for sure to be avoided, because, when applied, the maximum values are recorded, independently from the model. The *first-come-first-served* (FCFS) and *earliest due date* (EDD) policies do not diverge among models. The *shortest processing time* (SPT) policy results to be the best queue policy to apply, because models work with the highest performance, as shown in the chart below.
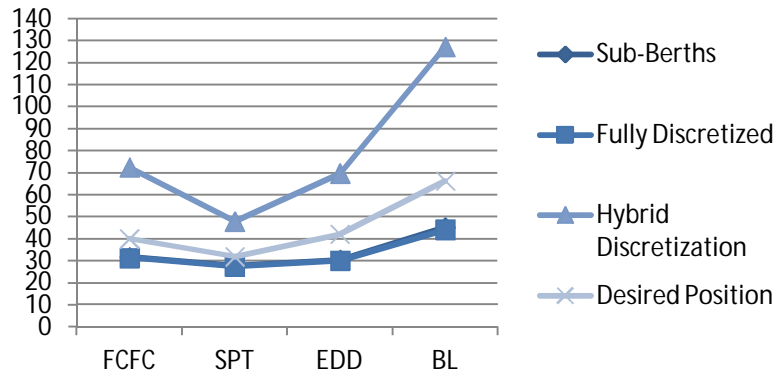
## Makespan



**Figure 22.** Time that averagely vessels require to go through the port in each scenario

The delay time is collected as the time, expressed in hours, which goes by from the scheduled departure time of vessels and when they really leave the port. This measure is negative to point out the fact that has to be as highest as possible. No delayed departures mean that the port can handle incoming vessels without stressing or overloading the resources. Since most of the times delays are caused by failures, breakdowns and slowdowns, which are inevitable, the objective is to minimize delayed departures of vessels.

## Delay Time

|  | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | -12 | -8 | -10 | -25 |
| **Fully Discretized** | -11 | -7 | -10 | -24 |
| **Hybrid Discretization** | -56 | -30 | -54 | -126 |
| **Desired Position** | -20 | -12 | -18 | -46 |

**Table 17.** Delay time that averagely occurs in respect to the scheduled departures

Once again values of the *Fully Discretized* and *Sub-berths* models are quite the same as well as the best solutions; instead the *Hybrid Discretization* model has the worst scenario with the highest delayed departures. As before, the *Desired Position* model stands s in half way. Queue policies influence results enough to make them diverge. The *biggest load* (BL) policy is once again the worst queue policy. The *shortest processing time* (SPT) instead is the again the best solution that allows maximizing efficiency and reducing delayed departures. The spared two queue policy record results closer to the most effective queue policy than the poorest one. It is important to keep in mind

that delayed departures cause penalties and cost that are to be avoided. Those costs are set to be dependent on the length of vessels; so the longer the vessel is the bigger is the cost of delayed departure. Reminding that the expected departure time is function of the processing time of vessels, directly proportional to their length, queue policies are extremely significant fro minimizing delays and relative costs. The chart below summarizes the outcomes, pointing out the overlap of more efficient models and the convenience of adopting the correct and specific queue policy.

## Delayed Deaprtures Time
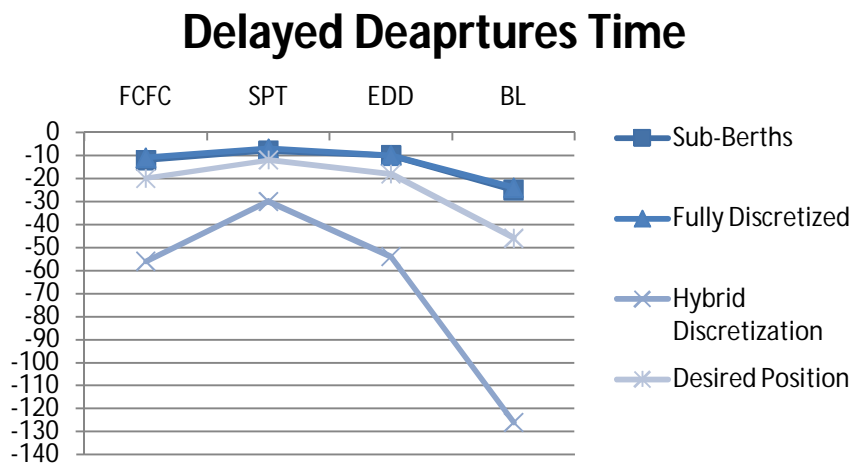


**Figure 23.** Delay time for each scenario according to the expected time of departure (ETD)

The *cost function* is a measure of the possible costs coming from the utilization of a precise models and queue policy. Those costs gather the costs of non-utilization of the resources and the costs of delayed departures of vessels. The values of this performance indicator are expressed in thousands of dollars (k$). The non-utilization cost comes from the cost, per day, that port management has to utilize all the available resource; it is calculated as the inverse of the wharf utilization times the cost of the wharf. Then the more the wharfs are utilized, the lower the cost of non-utilization. That is the reason why utilization of wharfs is an extremely relevant measure. The cost per day of the wharfs is set as twenty thousands of dollars per day, as illustrated below.

$$Wharf\ Utilization\ Cost\ =\ 20\ k\$\ per\ day \qquad (28)$$

The delayed departure cost is the result of delay times the cost for the delayed departures, which depends on the length of vessels. The longest the vessel is the highest the cost. The delays are former measure which is collected previously. As mentioned before, the cost that derives from

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possible delayed departures is function of the length of vessels. The classification of vessels in Feeder, Medium and Jumbo defines the correlate cost, which are expressed in thousands of dollars. In the table below costs and length of vessels are illustrated, according to the categorization just discussed.

| Length of Vessels (m) | Delayed Departure Cost (k$) |
|:---:|:---:|
| 50 – 100 | 1 |
| 100 - 180 | 2 |
| 180 - 300 | 3 |

**Table 18.** Cost for delayed departures according to the classification of vessels

The first two tables below expose the result of the wharfs non-utilization cost and delayed departure cost, according to the expression and correlations quoted. The last table is the sum of the two costs which define the *cost function*. The wharfs non-utilization tables shows that, as mentioned, the *Hybrid Discretization* model has the lowest values, due to the highest, but not realistic, results. The other models have the same outcomes. Queue policies do not affect this cost as well as the utilization percentage itself. The cost of delayed departures reflects the scenario described of the delay time. The *Hybrid Discretization* model has the highest costs, due to the maximum delays of vessels, in respect to the schedule. Queue policies affect again results and the best scenario is obtained when the *Fully Discretized* model is applied with the *shortest processing time* (SPT) policy; the other policies do not diverge so much from the most effective one, except from the *biggest load* (BL) that ,when utilized, make even the most efficient model to triplicate the costs.

**Non-utilization Cost**

|  | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | 35 | 35 | 35 | 35 |
| **Fully Discretized** | 36 | 36 | 36 | 36 |
| **Hybrid Discretization** | 28 | 28 | 28 | 28 |
| **Desired Position** | 36 | 36 | 36 | 36 |

**Table 19.** Wharfs non-utilization cost

**Cost of Delays**

|  | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | 24 | 16 | 20 | 51 |
| **Fully Discretized** | 23 | 14 | 21 | 50 |
| **Hybrid Discretization** | 148 | 79 | 142 | 260 |
| **Desired Position** | 42 | 25 | 38 | 97 |

**Table 20.** Cost for delayed departures

The following table is the result of the sum of the value soft e two previous tables. The histograms below shows the results of the *cost function* dividing them in two cases. The first one illustrates the costs

of the same model applying different queue policies; the second one instead, shows the different cost of the four models while using the same queue policy. Thanks to the histogram outcome are more visible and it is easier to discuss them, as well as find out the best or worst scenario.

## Cost Function

|  | FCFC | SPT | EDD | BL |
|---|---|---|---|---|
| **Sub-Berths** | 60 | 51 | 55 | 87 |
| **Fully Discretized** | 59 | 51 | 57 | 87 |
| **Hybrid Discretization** | 177 | 108 | 171 | 296 |
| **Desired Position** | 79 | 62 | 74 | 134 |

**Table 21.** Total cost that derive from a specific model and queue policy application

The *Fully Discretized* and *Sub-berths* are the best possible solutions, because they minimize costs, especially when the *shortest processing time* (SPT) queue policy is applied. These two models do not diverge in results, despite changing queue policy, and so can be easily replaced or interchanged. The continuous quay is without any doubts more efficient and profitable than the discrete one. The *Hybrid Discretization*, as illustrated in the chart below, is the worst model, independently from the queue policy applied, but particularly when the *biggest load* (BL) policy is implemented. The *Desired Position* stands once again in half way between the discrete berthing space and the continuous one, represented by the most productive models. If the continuous quay is utilized this models has to be avoided or improved, but it is still more effective than the one using the discrete quay.
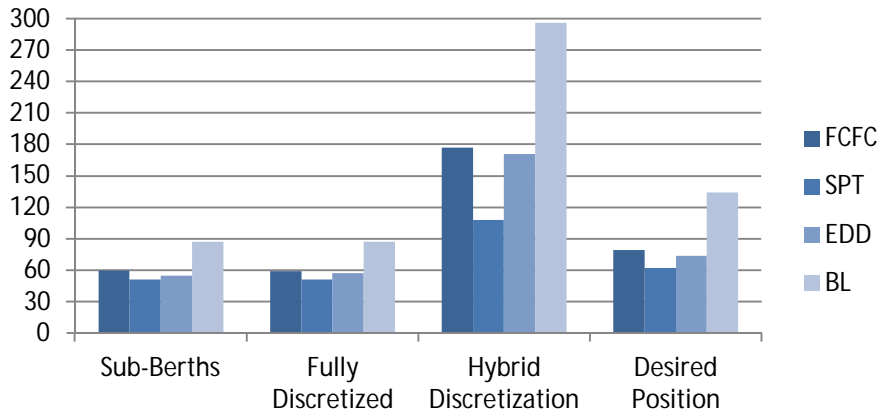
**Figure 24.** Total cost compared for each model when all the four queue policy are applied

Assessing a comparing for the same queue policy all the models, the *Hybrid Discretized* model is always the less effective model and the one to be avoided. The *shortest processing time* (SPT) is the best scenario for each model and especially when the *Sub-berths* and *Fully Discretized* models are applied.
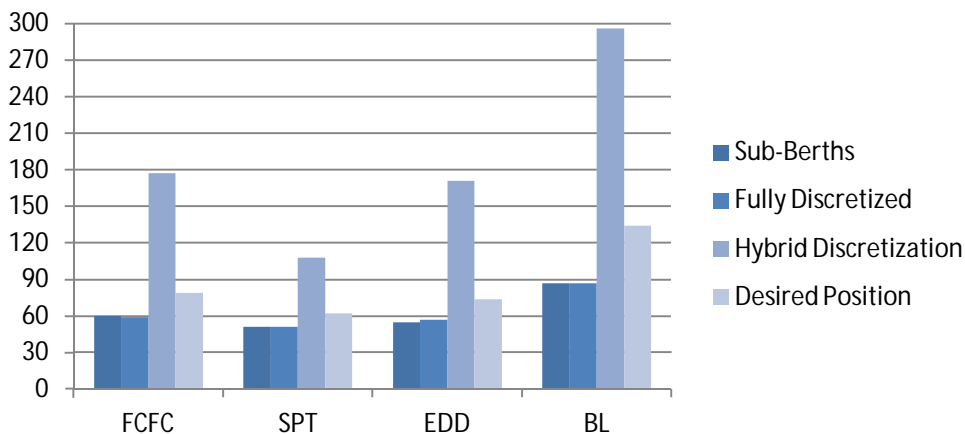


**Figure 25.** Total cost for each queue policy when all the four model are implemented

In the pie charts below, selected from the best scenario for each model, it is shown how much the two cost impact on the total cost, according on the four different models. The first three models, which rely on the continuous berthing space, show that the wharfs non-utilization cost affects more,

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from 60 % to 70 %, the total *function cost* than the delayed departures cost, which is around 40 %. When dealing with the discrete berthing space, the *Hybrid Discretization* model shows how the wharfs non-utilization cost goes down to the 30 % of the total cost; in fact, as mentioned before, this model, thanks to its approximations, has the highest wharf utilization but, at the same time, the highest value for delayed departures. The discrete quay allows seizing more resources that actually utilized, but this condition makes the vessels to wait more before being berthed and then the delayed departures are substantially increased. The wharfs non-utilization cost is more than halved, which goes down to less than 30 %, and the delayed departures cost is boosted to almost 80 % of the total costs. It must be reminded that the non-utilization cost is an unrealistic result, due to the overestimation of the approximation of the discrete quay. This assumption makes impossible to berth vessels among adjacent berths even if there is enough space, constrain that is overcome by the continuous quay. Thus the discrete scenario makes the berthing vessels order extremely significant for maximizing the port efficient and competitive. Those considerations are illustrated in the charts above and in the pie charts below.
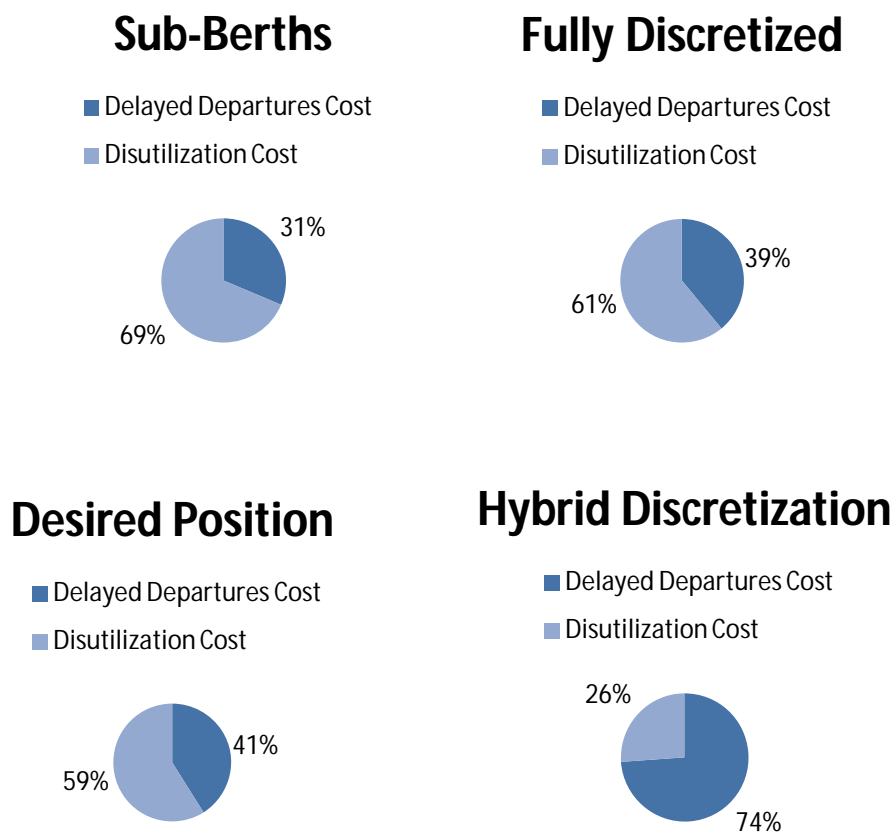
## Sub-Berths

■ Delayed Departures Cost
■ Disutilization Cost

31%
69%

## Fully Discretized

■ Delayed Departures Cost
■ Disutilization Cost

39%
61%

## Desired Position

■ Delayed Departures Cost
■ Disutilization Cost

41%
59%

## Hybrid Discretization

■ Delayed Departures Cost
■ Disutilization Cost

26%
74%

**Figure 26.** Cost incidence for each model

## 6.2   Integrated speed assignment and berth allocation outputs

The speed assignment is controlled by the number of queued vessels that wait in the port before being berthed and processed. So in this half of the research, output are shown for each model and queue policy as well as for the changing parameter which affects the speed assignment. The number of vessels in the queue that can influence the speed modification is initially set as three and then moved, by integer numbers, up to five. The letters *NQ* stand exactly for number in queue, and in the results exposition is placed next to the queue policies. The order of the performance indicators is the same exposed for the pure berth allocation, but the fuel consumption and the number of vessels served are further performance indicators. Moreover the fuel consumption is the third added factor that affects the measure of the *cost function*. The number of vessels instead is quite important because depending on the policy adopted it changes, meaning that the port, during the same time of simulation, according to the model and queue policy, can handle a specific number of vessels. The number of vessels must be the highest possible to get the highest benefits, efficiency and throughput. The percentage of utilization for each model, queue policy and speed assignment conditions are shown in the table below. The scenario is similar to the pure berthing process. The *Hybrid Discretization* model records the maximum wharfs utilization, around 70 %, due to the assumptions of the model. Berths are seized and totally occupied even if they are not completely utilized. If the length of vessels is longer than the berths one, multiple berths are used simultaneously. The remaining models have more or less the same wharfs utilization, around 60 %. The *Sub-berths* model records a bit higher values among the three models, which consider continuous the berthing space, especially in respect to the *Desired Position* model which has the lowest results. The *Fully Discretized* model stands in half way between the two previous models in terms of wharfs utilization percentages, due to the most realistic and accurate considerations on which it relies as well as the efficiency of the model. Considering the real length of vessels, in the continuous quay case vessels seized exactly the portion of quay equal to their length, cutting down overestimation and utilizations reflects perfectly the real situation. Queue policies do not affect the utilization significantly, in fact values do not float according to the four different queue policies, and also the possibility of speeding up vessels does not alter the wharfs utilization visibly, in each of the three cases.

**Wharf Utilization (%)**

|  |  | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|---|
| **Sub-Berths** | 3 | 60 | 59 | 60 | 61 |
|  | 4 | 60 | 59 | 59 | 61 |
|  | 5 | 60 | 59 | 60 | 60 |
| **Fully Discretized** | 3 | 58 | 57 | 57 | 59 |
|  | 4 | 56 | 57 | 57 | 59 |
|  | 5 | 57 | 56 | 58 | 57 |
| **Hybrid Discretization** | 3 | 70 | 67 | 66 | 68 |
|  | 4 | 68 | 68 | 67 | 68 |
|  | 5 | 68 | 68 | 67 | 69 |
| **Desired Position** | 3 | 56 | 55 | 56 | 56 |
|  | 4 | 55 | 56 | 56 | 56 |
|  | 5 | 56 | 56 | 56 | 56 |

**Table 19.** Percentage of wharfs utilization for each model queue policy and speed assignment condition

The four charts below represent averagely the percentages of wharfs utilization and non-utilization. The considerations just mentioned are summarized in the charts below, where it is more visible and direct the outcomes recorded for each model, since queue policies and speed up conditions do not influence the resources exploitation.
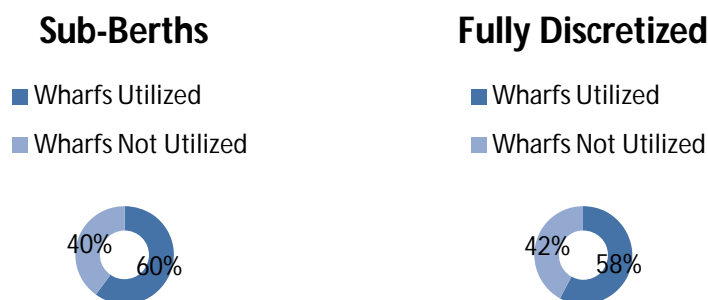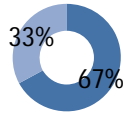


**Figure 27.** Wharfs utilization and non-utilization percentage for the *Sub-berths* and *Fully Discretized* models

## Hybrid Discretization

■ Berths Utilized
■ Berths Not Utilized

33%
67%

## Desire Position

■ Wharfs Utilized
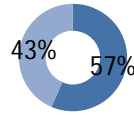■ Wharfs Not Utilized

43%  57%

**Figure 28.** Wharfs utilization and non-utilization percentage for the *Hybrid Discretization* and *Desired Position* models

The outcomes of the average time that queued vessels have to wait in the appropriate area of the port, before being berthed and served, are exposed in the table below.

## Waiting Time in Queue

|                        | NQ | FCFC | SPT | EDD | BL |
|------------------------|----|------|-----|-----|----|
| **Sub-Berths**         | 3  | 39   | 19  | 26  | 38 |
|                        | 4  | 38   | 19  | 25  | 38 |
|                        | 5  | 37   | 18  | 29  | 33 |
| **Fully Discretized**  | 3  | 33   | 18  | 26  | 34 |
|                        | 4  | 28   | 17  | 26  | 34 |
|                        | 5  | 34   | 18  | 32  | 31 |
| **Hybrid Discretization** | 3 | 44  | 20  | 33  | 35 |
|                        | 4  | 47   | 20  | 38  | 34 |
|                        | 5  | 48   | 21  | 32  | 35 |
| **Desired Position**   | 3  | 49   | 19  | 31  | 38 |
|                        | 4  | 45   | 20  | 40  | 39 |
|                        | 5  | 43   | 20  | 37  | 38 |

**Table 20.** Average time that vessels wait before being served

The waiting time of vessels does not show enormous differences between models which result to record approximately the same values. Queue policies influence the performance of each model, where the *first-come-first-served* (FCFS) queue policy makes models get the same results or even worse than the *biggest load* (BL), especially when dealing with the *Hybrid Discretization* or the *Desired Position* models. Once again the *Sub-berths* and *Fully Discretized* models are the best

models in terms of productivity and, in this case, in terms of minimum waiting time, respect the discrete quay model. The latter one is also the most efficient model among models that assume continuous the berthing space. Lower outcomes are collected in each model when the *earliest due date* (EDD) queue policy; but the best scenario is implemented, for every single model, when the *shortest processing time* (SPT) queue policy is applied. Since this measure is recorded in hours, according to queue policy, vessels averagely are stuck at the port, without being processed, almost two days, in the worst case, or a bit more than half a day, in the most effective case. The speeding up condition has various effects on the models and it does not affect them in the same way. From the charts below it is more clear the influence on models of queue policies and speed assignment. The valleys in each curves point out, as just remarked, that the *shortest processing time* (SPT) queue policy allows the port to obtain the best productivity, thank to the lowest that vessels have to wait in the queue. The previous considerations are summed up in the curves below. The speed assignment makes value to diverge for every single queue policy, except for the most efficient one; in fact from the charts results are overlapped, so speeding up vessels does not affect substantially the time that vessels have to wait, both in positive or negative way.
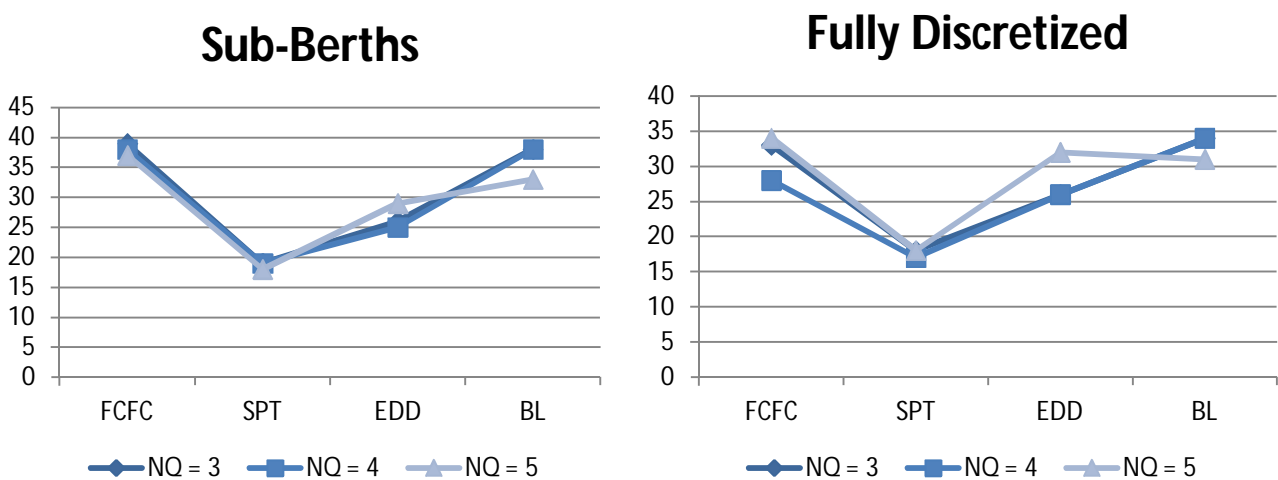


**Figure 30.** Average time that vessels wait in the appropriate area of the port for the *Sub-berths* and *Fully Discretized* models
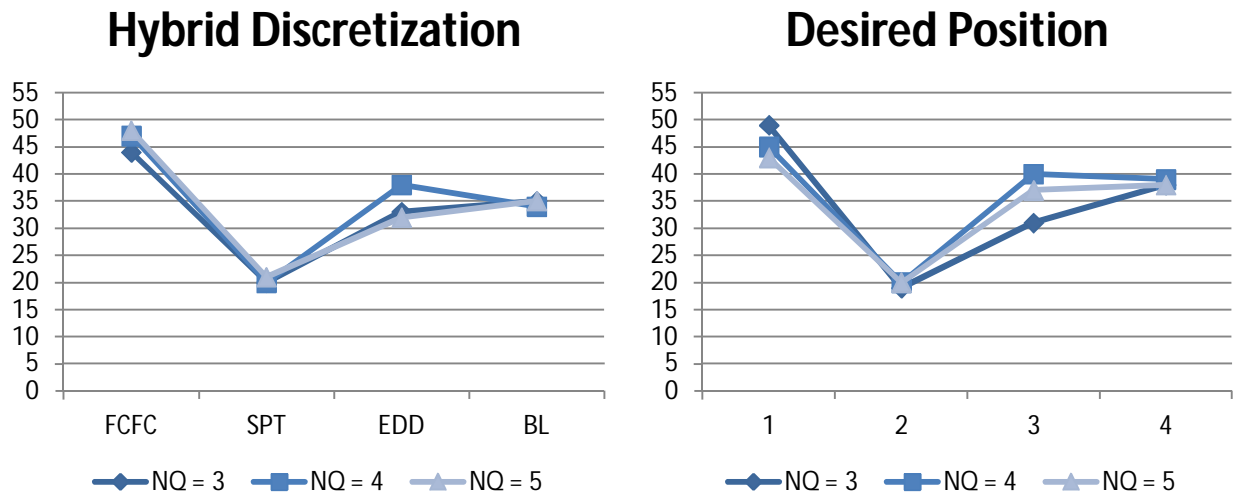
**Figure 29.** Average time that vessels wait in the special area of the port for the *Hybrid Discretization* and Desired Position models

The average number of vessels that have wait in the specific area of the port, due to the fact that there are no available resources, is correlated to the time vessels wait in the queue. This measure is also dependent on the efficiency and productivity of the wharfs. Those resources have to be able to handle as fast as possible the incoming vessels, in order to avoid the number and the time vessels have to wait is not to long. All the results are shown in the table below.

### Number Waiting in Queue

| | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-Berths** | 3 | 9 | 5 | 6 | 15 |
| | 4 | 8 | 5 | 5 | 15 |
| | 5 | 8 | 5 | 6 | 13 |
| **Fully Discretized** | 3 | 7 | 4 | 6 | 13 |
| | 4 | 6 | 4 | 6 | 14 |
| | 5 | 8 | 4 | 7 | 11 |
| **Hybrid Discretization** | 3 | 10 | 5 | 7 | 16 |
| | 4 | 10 | 5 | 9 | 16 |
| | 5 | 10 | 5 | 7 | 17 |
| **Desired Position** | 3 | 11 | 5 | 7 | 18 |
| | 4 | 10 | 6 | 10 | 18 |
| | 5 | 9 | 6 | 8 | 19 |

**Table 21.** Average number of queued vessels before they are berthed and served

The histograms below are a graphical representation of the value collected in the previous table. The results point out that among models the *Fully Discretized* one is the best scenario, because it records the minimum values averagely. The discrete quay, represent by the *Hybrid Discretization* model, and even the *Desired Position* one, have to maximum vessels queued that wait to be served; the latter model is also worse than the discrete quay solution. Queue policy influences extensively the outcomes of models. The *biggest load* (BL) queue policy is, in each scenario, the one to be avoided, because it make models collected the highest values, around fifteen vessels, of average vessels that wait in the queue. While applying the *first-come-first-served* (FCFS) queue policy, results are halved, but they are still not the lowest values. Outcomes are decreased when the *earliest due date* (EDD) queue policy takes place; queued vessels drop down around an average value of five, during the simulation time. The most efficient models are achieved when the *shortest processing time* (SPT) queue policy is introduced, particularly when it is implemented with the *Fully Discretized* model. The histograms that summarize the results and the descriptions are illustrated below.
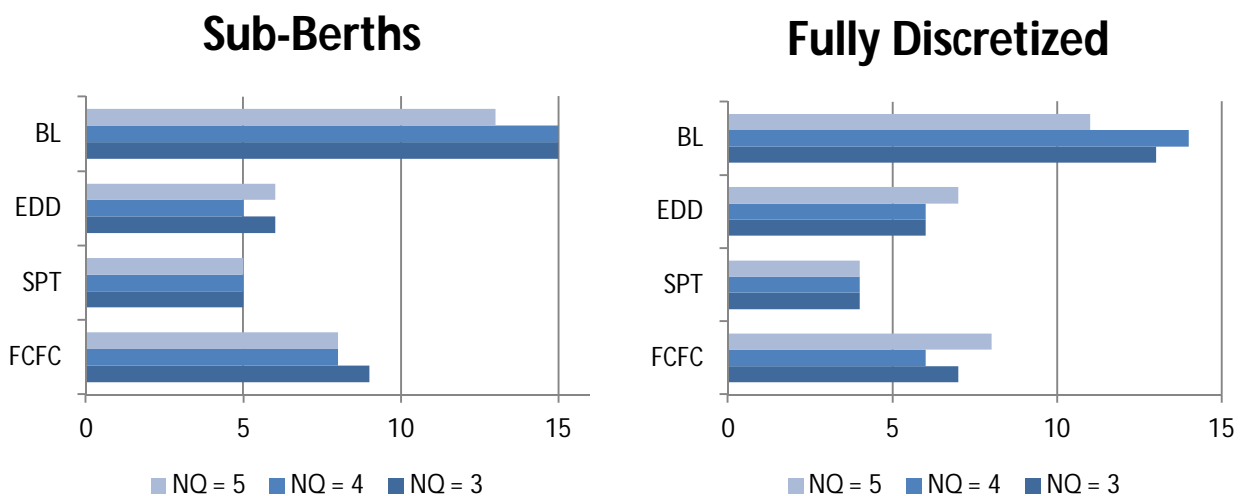


**Figure 30.** Average number of vessels that have to wait in the queue for the *Sub-berths* and *Fully Discretized* models
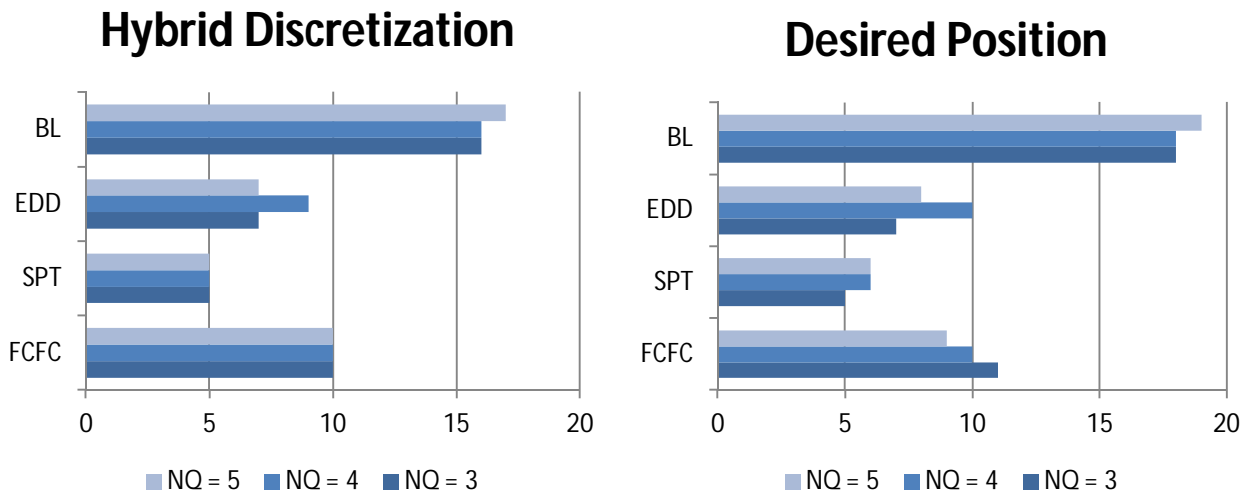
**Figure 31.** Average number of vessels that have to wait in the queue for the *Hybrid Discretization* and *Desired Position* models

The makespan is the time required by vessels to complete all the processes, simulated in the models. Vessels have to sail 500 nautical miles, alter the speed three times, according to the specified condition, enter the port, and possibly wait before being served, and eventually be berthed. This is the time necessary to reach the port and go through it. The average values, expressed in hours, are exposed in the table below.

### Makespan

|  | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-Berths** | 3 | 164 | 161 | 152 | 176 |
|  | 4 | 164 | 162 | 152 | 177 |
|  | 5 | 164 | 163 | 155 | 173 |
| **Fully Discretized** | 3 | 164 | 166 | 154 | 176 |
|  | 4 | 162 | 163 | 154 | 177 |
|  | 5 | 164 | 163 | 158 | 172 |
| **Hybrid Discretization** | 3 | 168 | 167 | 160 | 172 |
|  | 4 | 168 | 168 | 161 | 172 |
|  | 5 | 169 | 169 | 160 | 174 |
| **Desired Position** | 3 | 173 | 161 | 153 | 181 |
|  | 4 | 170 | 164 | 155 | 179 |
|  | 5 | 166 | 163 | 157 | 177 |

**Table 22.** Average time required by vessels to complete the process

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The results of this performance measure indicate that the *Hybrid Discretization* and *Desired Position* models record the maximum times, for vessels to complete the mentioned processes. Despite the negative aspects of those models, they both work in the best way when the queue policy *earliest due date* (EDD) is applied. The charts below highlight the advantages of using that precise policy, giving priority to vessels that have the tighter schedule. Choosing this queue policy results are quite lower. The same situation appears in the *Sub-berths* and *Fully Discretized* models, where the *earliest due date* (EDD) queue policy enables the shortest makespan. The latter models cut down the makespan of almost ten hours. The *biggest load* (BL) queue policy results to be always the less convenient and efficient; the spare ones instead do not diverge significantly and stand between the best and worst scenarios, for each model. Speeding up vessels does not minimally affect models and queue policies; indeed outcomes are, or almost, overlapped in the charts below. Then the possibility of speeding up does not affect significantly the average time and the number of queued vessels, as well as the total time needed by vessels to reach the port and be served.
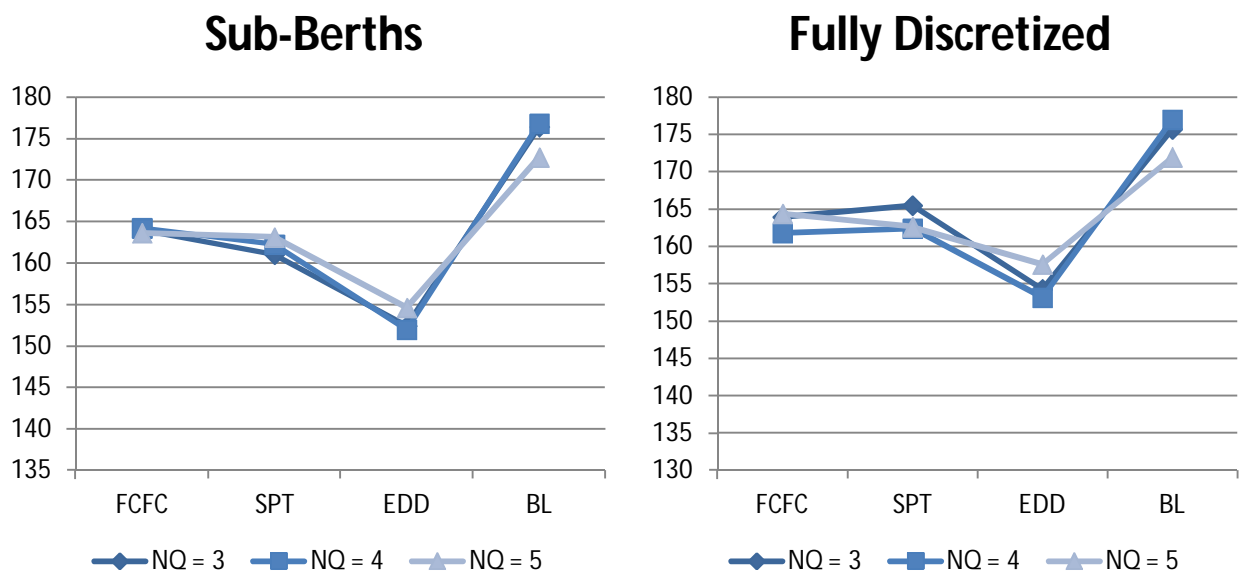


**Figure 32.** Average values necessary for vessels to be processed in the *Sub-berths* and *Fully Discretized* models
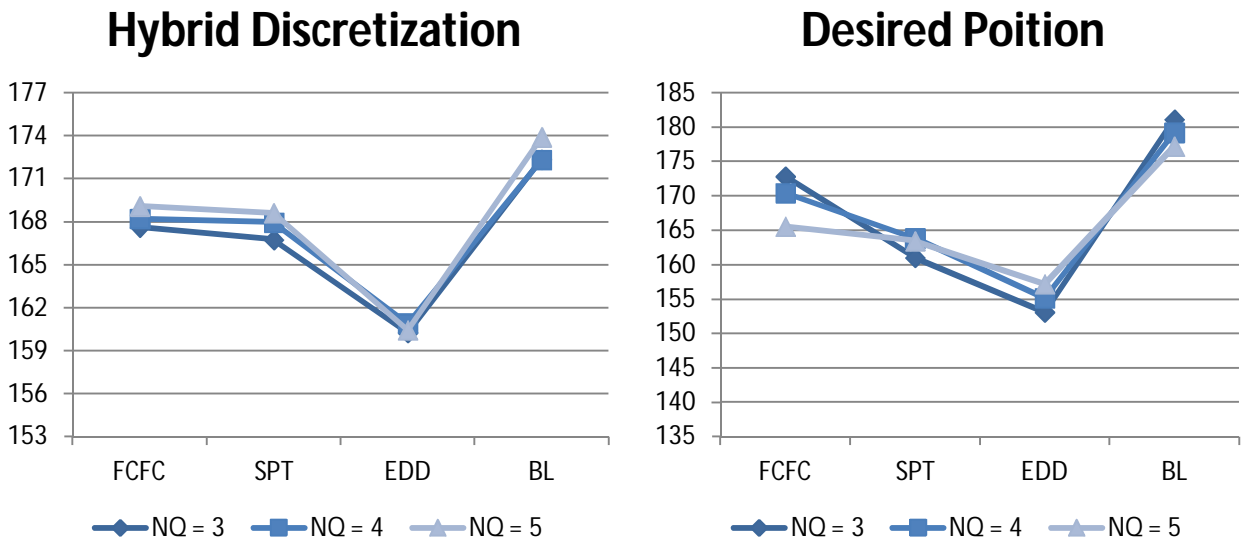
**Figure 33**. Average values necessary for vessels to be processed in the *Hybrid Discretization* and *Desired Position* model

The delay time is the lateness with which vessels leave the port, in respect to the expected time of departure (ETD). This parameter is function of the length of vessels, because it is directly proportional to the processing time of them. This measure records the ability of the port of handle vessels in order to make them leave accordingly to their schedule. If vessels are ready to leave the port before their expected departure, they wait in the port, in another specific area, till the time of departure. In the opposite case, if vessels are late respect to the schedule, they leave as soon as all the containers they can move are completely loaded or unloaded. The delay is recorded negatively, so the lower is the value, the worse the model, and related queue policy. It must be reminded that delayed departures of vessels cause high costs that are function of the length of vessels. Those costs increase with the length of vessels; so they must be minimized and the queue policy plays an extremely significant role. The average values collected during the simulations are shown in the table below.

**Delay Time**

| | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-Berths** | 3 | -22 | -23 | -10 | -36 |
| | 4 | -21 | -21 | -11 | -34 |
| | 5 | -20 | -22 | -12 | -31 |
| **Fully Discretized** | 3 | -18 | -21 | -10 | -29 |
| | 4 | -16 | -20 | -11 | -30 |
| | 5 | -19 | -19 | -13 | -27 |
| **Hybrid Discretization** | 3 | -25 | -25 | -16 | -34 |
| | 4 | -25 | -24 | -17 | -34 |
| | 5 | -27 | -25 | -14 | -33 |
| **Desired Position** | 3 | -27 | -22 | -13 | -38 |
| | 4 | -24 | -24 | -17 | -34 |
| | 5 | -22 | -23 | -15 | -36 |

**Table 23.** Average delay times caused by models in respect to the schedule

Models performance reflects the previous situations. The *Hybrid Discretization* model, assuming the discrete quay, and the *Desired Position* one, assuming the continuous quay, record the lowest value of delay, meaning that, independently from the queue policy applied, they are the less convenient and efficient as well as they boost costs , due to the high values of delayed departures of vessels. The *Sub-berths* and *Fully Discretized* models work better than the previous ones, reducing of five hours the average delay from the schedule of vessels. The most effective queue policy is the *earliest due date* (EDD) since it gives berthing priority to vessels that have to leave sooner the port; then delays are cutting down as expected, as well as the linked costs. The *biggest load* (BL) queue policy when applied triplicates the delays and the cost so it is not only the less productive policy but also the less advantageous and opportune, because vessels are enormously delayed and costs are maximized. The remaining queue policies result to have almost the same values, not as good as for the most efficient scenario but not even as bad as the less beneficial one. The possibility of speeding up more vessels once again does not influence visibly the results, as it is illustrated in the charts below where all gather in a small area and they do not extensively diverge.
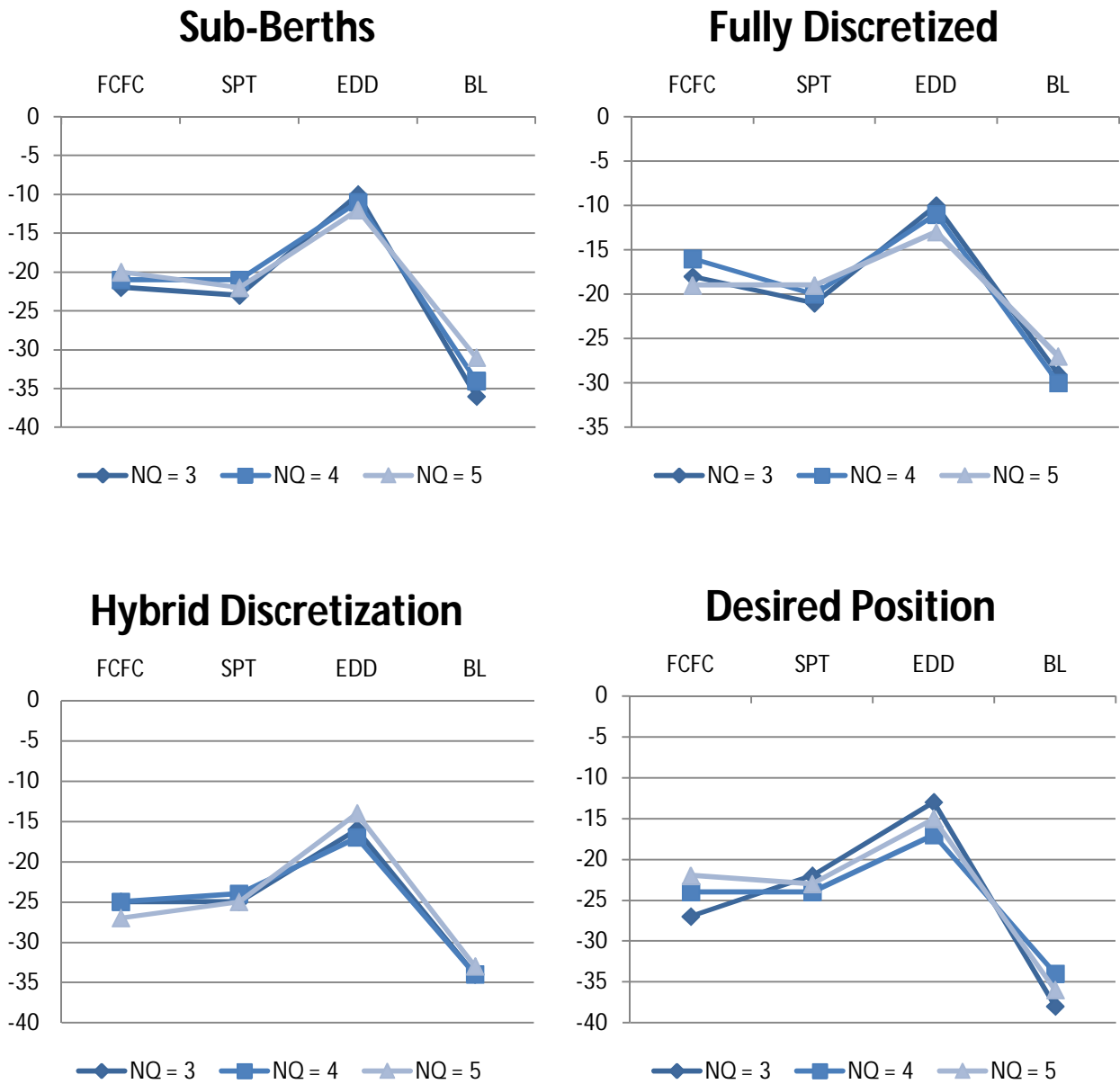
**Figure 34.** Delay values according on the expected time of departure for each model

The *cost function* is the results of all the previous performance indicators. In fact wharfs utilization defines the non-utilization cost; the average time and numbers of queued vessels determine the possible delays of vessels on their schedule, which cause he cost for delayed departures. Finally the *cost function* is completely defined by the fuel consumption of vessels that sail the last 500 nautical miles. The fuel consumption is function of the speed assigned to vessels, as already remarked. This performance indicator is no more equal to the one calculate in the pure berth allocation, but the fuel consumptions is introduced as third and last factor that affects this performance measure. The objective indeed is to minimize fuel consumption costs, as well as emission, while getting the same or higher port performance.

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As in the previous part non-utilization cost is calculated as the inverse of the wharf utilization times the cost of the wharfs utilization per day. This value is now set as fifty thousands of dollars per day, appositely increased to make it comparable with fuel consumption, as exposed in the expression below.

$$Wharf\ Utilization\ Cost\ =\ 50\ k\$\ per\ day \qquad (29)$$

The delayed departure is still calculated has the delay on the schedule of vessels times the cost, depending on the length of vessels. The values are changed and they are increased to make they have a higher impact on the total cost. The classification of vessels is Feeder, Medium and Jumbo, according to their length, defines the relative costs for delayed departures, as shown in the table below.

| Length of Vessels (m) | Delayed Departure Cost (k$) |
|---|---|
| 50 – 100 | 7 |
| 100 - 180 | 12 |
| 180 - 300 | 15 |

**Table 24.** Cost for delayed departure of vessels depending on the classification of vessels

In the four following tables the results for each of the cost and the final *cost function* are exposed. The wharfs non-utilization costs reflect the wharfs utilization; indeed the *Hybrid Discretization* model records the lowest cost, due to the highest utilization of the wharfs. It must be kept in mind that the assumptions formulated in the models that consider discrete the quay make an overestimation of the real wharfs utilization. The models that assume continuous the quay have higher non-utilization costs. The *Sub-berths* model has the lower cost among them, because it is a model that considers the quay quite similarly to the discrete scenario but with a more precise accuracy. The remaining ones record the lowest value, due to the consideration of the real length of vessels and then getting the most realistic scenario as well as the maximum accuracy. As already specified, neither the queue policies nor the speed assignment affect significantly the outcomes for the wharfs non-utilization cost. The cost derived for the delayed departures of vessels repeat the considerations remarked the delays on the schedule of vessels. The *Sub-berths* and *Fully Discretized* models minimize this cost, in particular when the *earliest due date* (EDD) and the *shortest processing time* (SPT) queue policies are applied. This queue policy implements the best

scenario possible, because it drops down the cost to half of the values collected with the *Hybrid Discretization* and the *Desired Position* models, which maximize the cost for each of the queue policies. When the *biggest load* (BL) policy is utilized models do not diverge in results and they are as inconvenient as when the *first-come-first-served* (FCFS) queue policy is used. The speeding up condition do not influence the results notably.

## Wharfs non-utilization Cost

| | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-Berths** | 3 | 2460 | 2530 | 2487 | 2424 |
| | 4 | 2461 | 2529 | 2531 | 2440 |
| | 5 | 2466 | 2518 | 2480 | 2465 |
| **Fully Discretized** | 3 | 2566 | 2611 | 2615 | 2518 |
| | 4 | 2634 | 2622 | 2604 | 2528 |
| | 5 | 2626 | 2635 | 2546 | 2618 |
| **Hybrid Discretization** | 3 | 2133 | 2208 | 2251 | 2176 |
| | 4 | 2190 | 2179 | 2233 | 2176 |
| | 5 | 2197 | 2181 | 2207 | 2166 |
| **Desired Position** | 3 | 2652 | 2690 | 2669 | 2667 |
| | 4 | 2679 | 2656 | 2638 | 2649 |
| | 5 | 2658 | 2635 | 2647 | 2660 |

**Table 28.** Wharfs non-utilization cost in each model

## Delay Cost

| | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-Berths** | 3 | -1080 | -559 | -475 | -1398 |
| | 4 | -1004 | -606 | -396 | -1317 |
| | 5 | -917 | -518 | -571 | -1056 |
| **Fully Discretized** | 3 | -752 | -501 | -409 | -1113 |
| | 4 | -578 | -473 | -439 | -1089 |
| | 5 | -913 | -504 | -631 | -990 |
| **Hybrid Discretization** | 3 | -1400 | -622 | -793 | -1261 |
| | 4 | -1435 | -644 | -1037 | -1099 |
| | 5 | -1567 | -659 | -621 | -1183 |
| **Desired Position** | 3 | -1588 | -608 | -579 | -1299 |
| | 4 | -1269 | -559 | -992 | -1169 |
| | 5 | -1135 | -590 | -840 | -1218 |

**Table 25.** Cost for delayed departures of vessels in each model

The fuel consumption table below shows the costs caused by the real use of fuel during the miles sailed to reach the port. Most of the times the cost increases when more vessels are speeded, but in some cases when there are too many oncoming vessels the port congests and then the cost decreases. As expected the *shortest processing time* (SPT) queue policy makes every model to speed up more vessels than the other policies, for each model, and cost are boosted. He opposite scenario occurs when the *biggest load* (BL) queue policy is utilized, for the contrary considerations. The last table is just the sum of the three factors that compose the *cost function*. For discussion and comparison among models and queue policies, it is easier to analyze and compare the following histograms, which represent the four models, separately, considering the four different queue policies for every single speed assignment parameter.

## Fuel Consumption Cost

| | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-Berths** | 3 | 3585 | 3883 | 4085 | 3161 |
| | 4 | 3814 | 4283 | 4271 | 3174 |
| | 5 | 3862 | 4426 | 3991 | 3161 |
| **Fully Discretized** | 3 | 3732 | 4110 | 3977 | 3273 |
| | 4 | 4021 | 4420 | 3985 | 3264 |
| | 5 | 4186 | 4630 | 4211 | 3710 |
| **Hybrid Discretization** | 3 | 3502 | 3725 | 3645 | 2821 |
| | 4 | 3405 | 3880 | 3477 | 2820 |
| | 5 | 3495 | 4169 | 3980 | 2866 |
| **Desired Position** | 3 | 3442 | 3838 | 3766 | 2789 |
| | 4 | 3666 | 4242 | 3862 | 2862 |
| | 5 | 3739 | 4525 | 3866 | 2816 |

**Table 30.** Cost derived from the consumption of fuel in each model

## Cost Function

| | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-Berths** | 3 | 7126 | 6973 | 7047 | 6983 |
| | 4 | 7279 | 7419 | 7199 | 6931 |
| | 5 | 7245 | 7463 | 7043 | 6683 |
| **Fully Discretized** | 3 | 7050 | 7223 | 7001 | 6904 |
| | 4 | 7233 | 7515 | 7029 | 6881 |
| | 5 | 7726 | 7769 | 7388 | 7318 |
| **Hybrid Discretization** | 3 | 7036 | 6556 | 6689 | 6258 |
| | 4 | 7031 | 6703 | 6748 | 6096 |
| | 5 | 7260 | 7009 | 6809 | 6216 |
| **Desired Position** | 3 | 7683 | 7136 | 7015 | 6756 |
| | 4 | 7614 | 7457 | 7493 | 6681 |
| | 5 | 7532 | 7750 | 7354 | 6694 |

**Table 26.** Total cost as the sum of the three former factors for each model

It must be kept in mind that is quite hard to compare all the different scenarios, because the number of served vessels, which go through the system, diverge according to model and queue policy utilized. In fact even in the same model, changing queue policy can alter extensively the number of vessels processed and served. The *Sub-berths* model shows the highest costs when the *first-come-first-served* (FCFS) and *shortest processing time* (SPT) queue policies are applied, independently from the feasibility of speeding up more incoming vessels. Instead cost are quite reduced or halved when the *earliest due date* (EDD) and *biggest load* (BL) queue polices are respectively utilized. The *Fully Discretized* works similarly to the previous model, referring to the four different queue policies. In this scenario the more vessels are speeded up, the higher the costs.
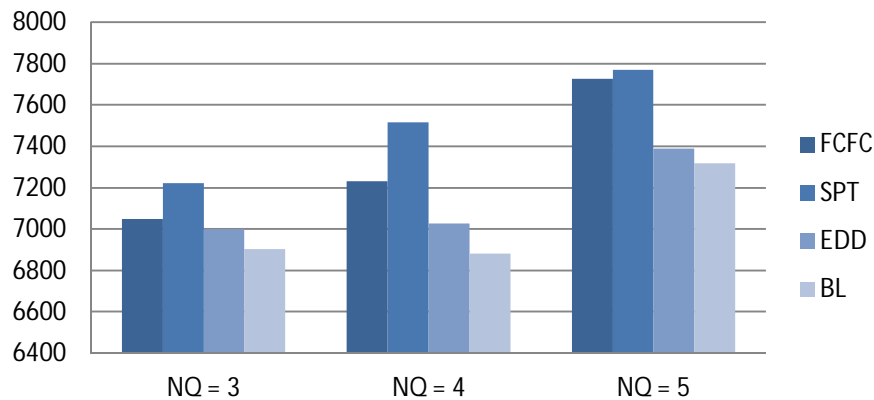
## SUB-BERTHS
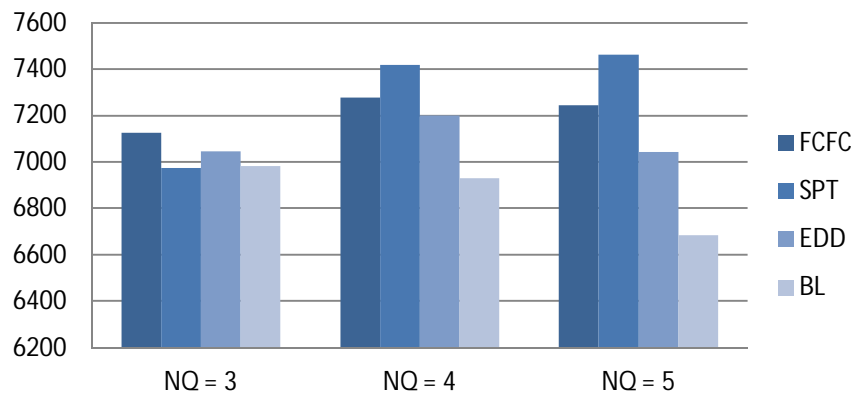


## FULLY DISCRETIZED



**Figure 35.** Total cost caused by the implementation of the *Sub-berths* and *Fully Discretized* models

The results of the *Hybrid Discretization* model float in the same way as the former models, and increasing the number of possible speeded up vessels does not affect importantly the outcomes of the sum of the three single costs. The spare model that assumes the quay continuous, results to be the most expensive one. The *Desired Position* model has the trend line alike the ones just introduced, regarding the queue policies and the speed assignment. Thus it is possible to state that the queue policy is extremely influent in the resulting costs of every single model, and then speeding up vessels does not get the results of reducing terminal container cost while increasing fuel consumption. The costs are boosted, due to the increasing speed assigned to vessels, but wharfs non-utilization cost and the cost of delayed departure of vessel are not drastically reduced to support the increased fuel consumptions.

## HYBRID DISCRETIZATION
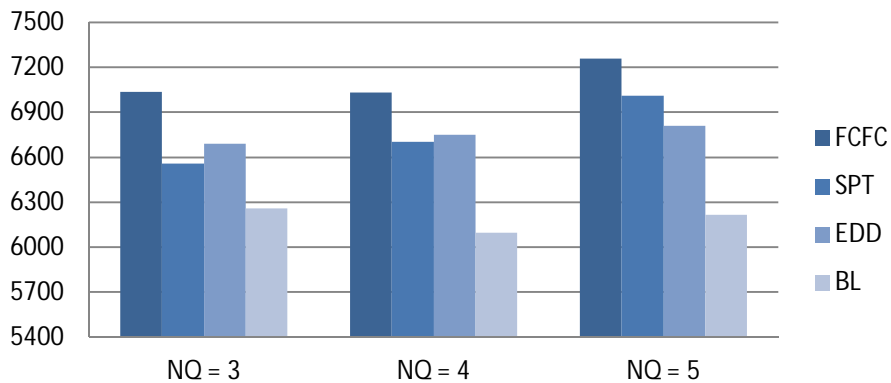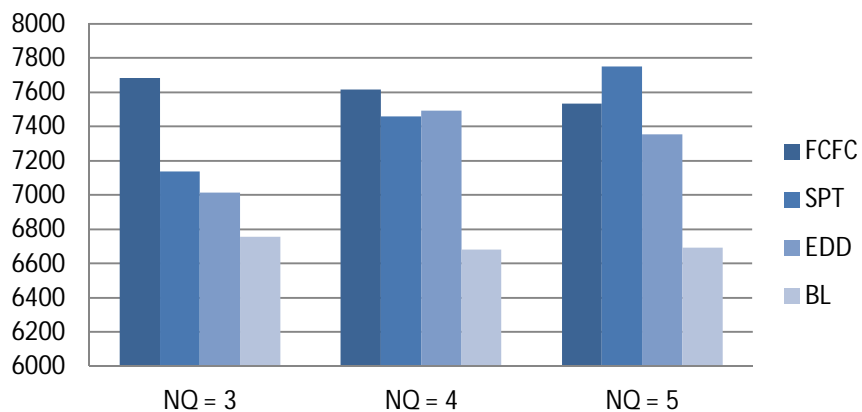


## DESIRED POSITION



**Figure 36.** Total cost caused by the implementation of the *Hybrid Discretization* and *Desired Position* models

The pie charts below describe the impact of the three cost factors on the total cost. Those are four average scenarios, according to queue policies and speed assignment, thanks to the fact that costs are not completely divergent in the various cases. As mentioned before, the fuel consumption has the highest influence, which is around the 50 %. Then the wharfs non.-utilization cost is around the 40 % and finally the delayed departure cost affects the total cost for about 10 %. Each model has different percentages, but averagely they can be summarized with the pie charts below. Indeed changing queue policy or speeding up condition results are not affect significantly and outcomes do not drastically differ from the represented ones.
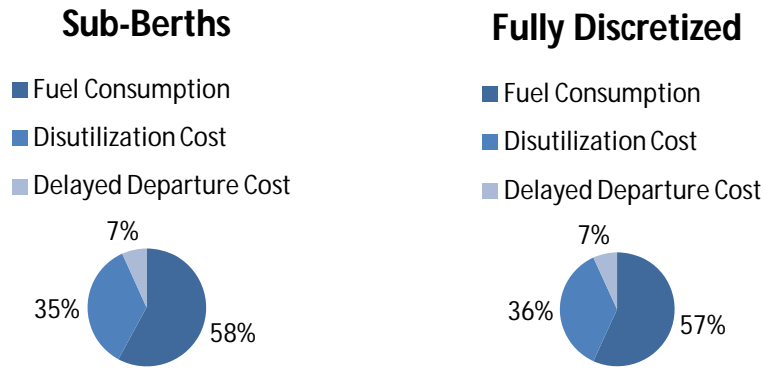
**Figure 37.** Cost incidence on the total cost for the *Sub-berths* and *Fully Discretized* models

It is possible to notice and highlight that the models above, *Sub-berths* and *Fully Discretized*, reduce the cost for delays on the schedule of vessels, while the wharfs non-utilization cost is averagely equivalent in every single model. In the models below, *Hybrid Discretization* and *Desired Position*, the fuel consumptions is decreased, affecting the expected departures of vessels, but keeping constant the wharfs non-utilization cost.
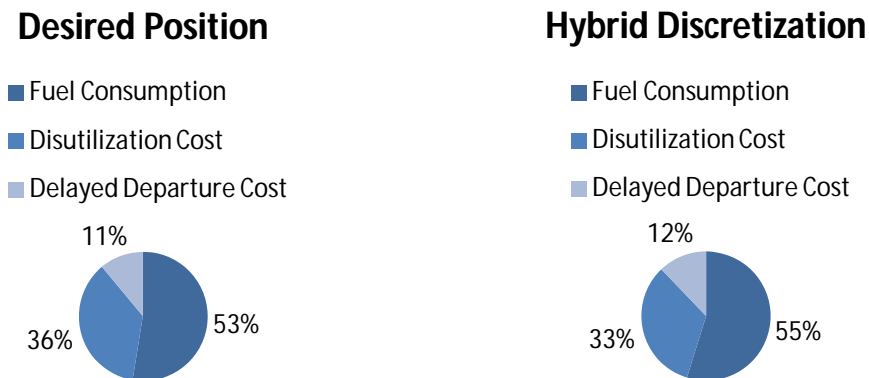


**Figure 38.** Cost incidence on the total cost for the *Hybrid Discretization* and *Desired Position* models

Thus the number of vessels served, during the one month of simulation, is essentially to be exposed and commented. In fact models performance indicators rely on the number of berthed, handled and served vessels, which go through the port in one month. The more vessels are served and processed, the higher are the containers moved and the higher are the benefits, for the port. The results of models, queue policies and speed assignment are illustrated in the table below.

**Number of Vessels Served**

| | NQ | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
| **Sub-berths** | 3 | 138 | 137 | 140 | 122 |
| | 4 | 135 | 140 | 138 | 119 |
| | 5 | 135 | 137 | 140 | 120 |
| **Fully Discretized** | 3 | 136 | 137 | 139 | 118 |
| | 4 | 133 | 139 | 141 | 118 |
| | 5 | 135 | 137 | 141 | 122 |
| **Hybrid discretization** | 3 | 130 | 132 | 129 | 108 |
| | 4 | 126 | 129 | 129 | 104 |
| | 5 | 127 | 131 | 130 | 106 |
| **Desired Position** | 3 | 132 | 137 | 138 | 108 |
| | 4 | 132 | 139 | 137 | 108 |
| | 5 | 133 | 142 | 135 | 111 |

**Table 27**. Average number of vessels berthed and served in each model

The most effective solutions are represented by the *Sub-berths* and *Fully Discretized* models, underlining the great advantages that the continuous berthing space can enable, compared to the lower value of the discrete berthing space, embedded by the *Hybrid Discretization* model. This scenario indeed results to be the most efficient one, because the minimum values of served vessels are collected. The *Desired Position* model, despite is relies on the continuous wharfs, it is not as efficient as the others, but it is anyway as productive, and in some case even more, as the model that assume discrete the berthing space. The queue policies affect distinctively the results of the total vessels served. The *biggest load* (BL) queue policy is the one that has to be avoided; indeed the vessels handled and processed are 30 % less when this policy is utilized. The *first-come-first-served* (FCFS) queue policy gives higher outputs than the former one, but not as efficient as the two remaining policies. The *shortest processing* time (SPT) and the *earliest due date* (EDD) allow having the highest number of vessels berthed and served, maximizing benefits. The outputs just declared are graphically shown in the histograms below. The number of vessels served is a performance indicator extremely significant, because it expresses the capability of ports to manage an undefined number of vessels incoming and it means also working with a high level of organization and coordination in the port, as well as of efficiency and productivity.
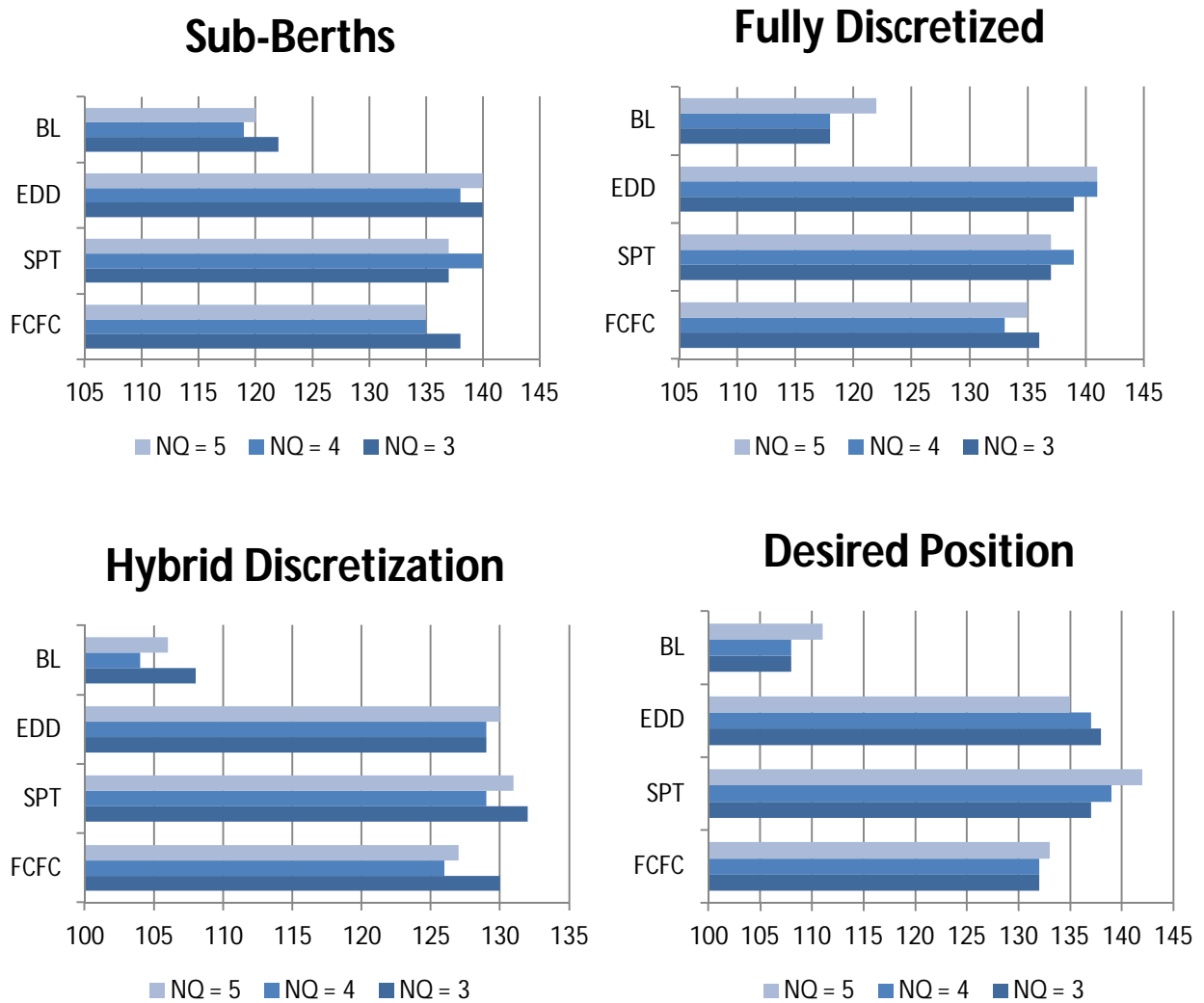
**Figure 39.** Average number of vessels berthed and served in each model and scenario

## 6.3   Outputs analysis for result validation

Verification and validation of computer simulation models is conducted during the development of implemented models with the ultimate objective of producing an accurate and credible model, due to the increasing utilization of simulation software to solve problems and to support in decision-making. In fact simulation models are approximate imitations of real world systems and they never exactly imitate the real life system; thus models should be verified and validated to the degree needed for the models intended purpose or application. Verification of a model is the process of confirming models are correctly implemented with respect to the conceptual model, meaning that they match specifications and assumptions deemed acceptable for the given purpose of application.

During verification models are tested to find and fix errors in their implementation to ensure that simulations are a correct and appropriate representation of the real life modeled system.

The validation phase checks the accuracy and precision of the representation of the real system by the simulated models. In order to perform the required validation, the implemented models have to be a reasonable imitation or interpretation of a real world system, thanks to the assumptions necessary to build them which can be structural or data assumptions. The former ones are made about how the system operates and how it is physically arranged. Data assumptions allow building as close as possible to reality models with a sufficient amount of appropriate data available. Lack of appropriate data is often the reason attempts to validate a model fail; or a typical error is assuming an inappropriate statistical distribution for the data. The validation test consists of comparing outputs from the system under consideration to model outputs for the same set of input conditions.

In order to validate the results collected from the simulation of the models it is necessary to perform a statistical analysis. The outcomes analysis must focus on the number of replications, set for run simulations, to verify that it is the correct number to consider statistically valid the results, to check the half width, which is the dispersion of values, and the confidential interval.

All the previous values, illustrated and described above, are average values. They come from all the data collection of models, and each of them has a maximum and minimum value and a half width. So according to the number of replications, set as a parameter for simulations, values change; increasing the number of replication it is possible to refine the outputs average value, as well as their half width, meaning that the accuracy increases and the confidence interval decrease too, which is the double of the half width. It is significant to find the correct number of replication in order to prove that the data collected can be validated, used and compared among analyzed models or compared with other solutions.

It is necessary to get the smaller half width possible to get the highest precision, so the average value can be considered the expected value and the one that enables the best solutions.

Since all the previous outputs considered are average values, it is approximately true to use the *central limit theorem* (CLT), which states that: "given certain conditions, the arithmetic mean of a sufficiently large number of iterates of independent random variables, each with a well-defined expected value and well-defined variance, will be approximately normally distributed".

In statistic and probability theory the normal distribution, or Gaussian, is a continuous probability distribution immensely useful and applied in many results and methods. The normal distribution can be defined by explicating two important parameters: the mean value and the standard deviation. The mean value is the expected value or expectation of the distribution and it is the most likely value of the population. The standard deviation shows the variation or dispersion from the average

value, in a statistical population. A low standard deviation indicates that the data are quite close to the mean value; a high standard deviation means that the data are spread out over a large range of values. The standard deviation is frequently used to measure confidence in statistical conclusions and comparisons, by calculating the margin of error in the results if the variables are collected multiple times. The margin of error is a statistically expresses the amount of random sampling error in the results of a survey. The larger the margin of error, the less confidence there is that results are close to the probability distribution expectation. So in researches the standard deviation of experimental data defines how much further data can fall in the confidence interval, in order to point out the values that are statistically significant.

The confidence interval (CI) is a type of interval estimate of a population parameters and it is used to delimit the values that are reliable. Confidence intervals consist of a range of values where it is possible to find the value of an unknown parameter. The confidence level of a population indicates the probability that the confidence range captures the population parameters, according on a distribution of samples. This value is expressed in percentage and it refers to the percentage of values which are represented by the distribution in the interval. In this study, as in applied practice, confidence intervals are typically stated at the 95%, meaning that we cut out the 5% of values which deviate too much from the mean value and so they are not statistically significant. It is important to find out the confidence interval and validate the assumption of choosing a specific number of iterations for simulate the models. The half width, of the collected results, and the confidence interval are functions of the mean value, the standard deviation, the number of replications, the critical value from the tables of the Student distribution and the half width. Then to calculate either parameter the following expressions can be used.

$$Confidence\ Interval\ (CI) = X \pm \frac{t_{n-1,1-\frac{\alpha}{2}}*s}{\sqrt{n}} \qquad (30)$$

$$Half-width\ (h) = t_{n-1,1-\frac{\alpha}{2}} \times \frac{s}{\sqrt{n}} \qquad (31)$$

Where the symbols are:

X = mean value

$t_{n-1,1-\alpha/2}$ = critical value from t tables

n = number of replications

s = standard deviation

Since it is not possible to control the critical value of the Student distribution and the standard deviation, with the purpose of reducing as much as possible the confidence interval, and then the half width, the number of iterations must be increased from an initial value. The right number of times to iterate models is hard to estimate and some approximations are required.

Solving the previous correlation and setting the half width, it is possible to find out an initial value for the number if replications.

$$n = t^2_{n-1,1-\frac{\alpha}{2}} \times \frac{s^2}{h^2} \qquad (32)$$

Then if the critical value of the Student distribution is replaced with the critical value of a normal distribution ($z_{1-\alpha/2}$) and it is pretended that the current standard deviation will hold for larger samples, an easier and approximated value of iteration can be determined. The initial value of number of iteration can be updated to a more precise and accurate one, once the first statistical population of results is collected, and it is possible to set a correlation between number of replications and half width.

$$n = z^2_{1-\frac{\alpha}{2}} \times \frac{s^2}{h^2} \qquad (33)$$

$$n = n_0 \times \frac{h_0}{h} \qquad (34)$$

Where the symbols are:

$z_{1-\alpha/2}$ = critical value of the normal distribution

$n_0$ = initial value of the number of replication for simulate models

$h_0$ = initial value of half width, by setting the number of iteration equal to $n_0$

From the previous expressions it is explicit that the number of replications $n$ grows quadratically as the half width $h$ decreases, considering as constant value the other parameters.

In order to find out all the previous correlations, the standard deviation must be calculated, with the following expression.

$$Standard\ Deviation\ (s) = \sqrt{\frac{\Sigma(X - x_i)^2}{N-1}} \qquad (35)$$

Where the symbols are:

$x_i$ = value of a single replication

N = number of iterations

This value is calculated for a specific performance measure, which is the wharf utilization for the models considering continuous the berthing space; instead the berth utilization is assessed while dealing with the model which consider discrete the berthing space. Indeed it is scientifically correct to validate results for one performance indictor to extend the outcome analysis to all the recorded measures. Once all the value are collected for each model with every policy and speed changing condition, the confidence interval and the number of replications are calculated and they are illustrated in the following tables. While evaluating the pure berth allocation, the half width of the indicators under consideration is, for each one, equal to *0, 00*. This situation points out that all the values have the highest precision and accuracy possible; the mean value is not only the expected one, but it is surely and precisely the value that represent the implementations. This condition is obtained thanks to the huge number of vessels simulated in the systems. Then iterate 20 times all models can be considered a reasonable solution that leads to statistically significant outputs. In fact with the previous expression it is not possible to find it out because the half width makes it goes to an infinite number. The results of the confidence interval are exposed in the table below.

**Confidence interval and Number of Replications**

|  | n | FCFC | SPT | EDD | BL |
|---|---|---|---|---|---|
|  | 20 | CI | CI | CI | CI |
| **Sub-Berths** | 20 | 0,6212±0,00191 | 0,6208±0,00201 | 0,6213±0,00198 | 0,6221±0,00195 |
| **Fully Discretized** | 20 | 0,5983±0,00257 | 0,5935±0,00183 | 0,5937±0,00183 | 0,5944±0,00212 |
| **Hybrid Discretization** | 20 | 0,8439±0,00189 | 0,8418±0,00851 | 0,8433±0,00894 | 0,8459±0,01006 |
| **Desired Position** | 20 | 0,5831±0,00452 | 0,5832±0,00485 | 0,5835±0,00498 | 0,5833±0,00447 |

**Table 28.** Number of iteration equal for each models and the confidence interval for every single scenario

The speed assignment connected to the berth allocation problem is simulated differently from the pure berth allocation problem, as mentioned before, so again it is necessary to validate the outputs, focusing on the confidence interval and the number of replications. The previous expressions are used to find the values. The outputs of the confidence interval illustrated in the following table.

| | Confidence Interval | | | |
|---|---|---|---|---|
| NQ | FCFC | SPT | EDD | BL |
| **Sub-Berths** 3 | 0,63068±0,01471 | 0,61915±0,01748 | 0,62906±0,01915 | 0,64165±0,01738 |
| 4 | 0,63418±0,01487 | 0,62390±0,02229 | 0,61836±0,02005 | 0,64355±0,01491 |
| 5 | 0,64196±0,01187 | 0,62679±0,01911 | 0,62338±0,01868 | 0,63480±0,01663 |
| **Fully Discretized** 3 | 0,60429±0,01544 | 0,61006±0,0144 | 0,60130±0,01587 | 0,62543±0,01906 |
| 4 | 0,59428±0,01691 | 0,59674±0,01841 | 0,60724±0,01735 | 0,62184±0,01507 |
| 5 | 0,50504±0,01355 | 0,60130±0,01777 | 0,61720±0,01494 | 0,60132±0,01836 |
| **Hybrid Discretization** 3 | 0,82234±0,01904 | 0,79321±0,02621 | 0,77617±0,02362 | 0,80659±0,03131 |
| 4 | 0,80244±0,01706 | 0,79600±0,03351 | 0,77265±0,02423 | 0,80558±0,02861 |
| 5 | 0,80512±0,02697 | 0,79227±0,02373 | 0,78226±0,02291 | 0,80323±0,02701 |
| **Desired Position** 3 | 0,57200±0,01541 | 0,56268±0,01441 | 0,56407±0,01317 | 0,57122±0,01726 |
| 4 | 0,56898±0,01528 | 0,57583±0,01163 | 0,57043±0,01257 | 0,57283±0,01429 |
| 5 | 0,57163±0,01663 | 0,57712±0,01074 | 0,57124±0,01061 | 0,56310±0,01828 |

**Table 29**. Confidence interval for the speed assignment models

Once the results of the confidence interval are determined, the numbers of replication for every single model, queue policy and speed assignment are defined. Using the expressions above it is possible to get the outputs shown in the table below.

| | Number of Replications | | | | |
|---|---|---|---|---|---|
| | NQ | FCFC | SPT | EDD | BL |
| **Sub-Berths** | 3 | 37 | 13 | 16 | 13 |
| | 4 | 38 | 21 | 17 | 38 |
| | 5 | 24 | 16 | 15 | 12 |
| **Fully Discretized** | 3 | 10 | 36 | 11 | 15 |
| | 4 | 12 | 14 | 13 | 9 |
| | 5 | 32 | 13 | 39 | 14 |
| **Hybrid Discretization** | 3 | 15 | 13 | 24 | 19 |
| | 4 | 12 | 21 | 25 | 15 |
| | 5 | 14 | 24 | 23 | 14 |
| **Desired Position** | 3 | 10 | 36 | 30 | 13 |
| | 4 | 10 | 23 | 27 | 35 |
| | 5 | 12 | 20 | 19 | 14 |

**Table 30**. Number of replications for the speed assignment implementation of models

The table above shows the required number of iterations as results of the function that depends on the standard deviation, the half width and the critical value of the normal distribution. In average the optimal number of iterations required by models to get significant values is twenty times. So it can be considered definitely reasonable and statistically significant to implement all the models with twenty iterations. This number of replications can be considered as the appropriate and correct number for getting relevant values that prove the real life application of the studied an described models. A greater number of iteration leads to a higher accuracy that does not differ substantially from the collected and analyzed outputs. Vice versa a lesser number reduce significantly the precision and accuracy of the outcomes and leading to misleading results which cannot be considered validate for real life application because they do not imitate reasonably and correctly the modeled and studied system.

The outputs analysis provided by the implemented, analyzed and compared models proves that the results are verified, validated and statistically significant both for the pure berth allocation problem and for the speed assignment linked to the berth allocation.

# *Conclusion*

In this research the simulation modeling approach is developed to analyze and compare, initially, the pure berth allocation problem in a continuous quay with a discrete one, and afterwards the berth allocation is modeled and studied with the problem of the speed assignment, to check out and try to reduce fuel consumption, as well as emissions.

The berthing space is no more considered as made of multiple berths placed one next the other, but a continuous and single berth is assumed, where vessels can be moored anywhere. The objective is the comparison of the continuous quay with the discrete one, through four different models and policies, in order to get a more accurate and realistic measure of the utilization of the wharfs and to collect different key performance indicators to compare and assess models and find the best solutions that can apply in real life port to get the highest efficiency and competitiveness. The four models are named in distinctive ways to magnify the features of each one. Indeed three models out of fours are based on the continuous berthing space; instead the last one uses the discrete berthing space, in order to compare it with a different berthing policy and point out the correlate disadvantages. The four models are called the *Sub-berths*, *Fully Discretized*, *Hybrid Discretization* and *Desired Position*. Among the performance measure collected, the most significant ones are the average wharfs utilization, the average number of vessels waiting in the queue, before being berthed, the average time they have to wait in the queue, the makespan and the *cost function*. The last measure is an indicator of the cost required if a precise model is applied, as direct response of the other measures; it is set appositely in this research to compare costs, possible savings among models, and so possible benefits, as well as efficiency and productivity. Due to the fact that the queued vessels that wait in the appropriate zone of the port is a quite important indicator of the efficiency of ports, this study presents also different queue policies to decide and regulate the order with which vessels have to leave the special area where are temporary moored before being served and processed. Four queue policies are implemented and they are named the *first-come-first-served* (FCFS), *shortest processing time* (SPT), *earliest due date* (EDD) and *biggest load* (BL). The first one set the berthing order according on the sequence of arrival of vessels at the port; the others instead allow berthing vessels according on their length and processing time, if it is either minimum or maximum. Indeed, according to the length of vessels, the longer the vessel the longer the processing time takes and the looser the expected time of departure (ETD) is. This models and

queue policies are simulated both in the pure berth allocation and in the speed assignment connected with the berth allocation. In the latter scenario another condition is added to each model. In fact speed of vessels is changed to follow the port efficiency and the changing condition which triggers the speed alteration is the number of queued vessels already moored in an appropriate area at the port. Vessels are then speeded up or slowed down according to the mentioned constrain. This fixed parameter is changed three times to evaluate the response of ports when more vessels are speeded up and the system is stressed.

As results of the pure berth allocation, all the performance measures show a higher efficiency in the continuous quay case, respect to the discrete one, pointing out the higher productivity granted by using the former approach. Wharfs utilization is lower in the continuous scenario, because they get a more realistic and accurate evaluation of the real utilization, avoiding the overestimation of the discrete case, where berths are completely seized even if they are partially used. Despite the lower but more precise value of wharfs utilization, causing a higher non-utilization cost of wharfs, the continuous berthing space reduces drastically the cost deriving from the delayed departures of vessels. Thus the total cost results to be way lower in the continuous case, meaning that savings are higher when the continuous quay is applied, for each model analyzed and for all the queue policies implemented. Precisely the best solutions and outcomes are collected when the *Fully Discretized* models, which most effectively represents the continuous quay case, is applied with the *shortest processing time* (SPT) queue policy, which allows to get the highest performance measures, cutting down cost as well as total required time to complete the process.

When the speed is modify to see the possible benefits to the berthing process, once again, the *Fully Discretized* model is the best solution, in term of accuracy and precision of results as well as efficiency and productivity, applying both the *shortest processing time* (SPT) and the *earliest due date* (EDD) policies. All the key performance indicators point out that the continuous quay is definitely better than the discrete one and, among the models studied, the most efficient is indeed the one that assume to berth vessels one next to the other, when constrains are fulfilled, according to their real length, and erasing boundaries between adjacent berths. The most important indicators that must be highlighted are the number of vessels that can be berthed and served at the port, during the month of simulation, and the correlated cost that results from use of a specific models and queue policy. The best scenario in the continuous quay, represented by the *Fully Discretized* model, is implemented when the *earliest due date* (EDD) queue policy is applied. In fact this model allows getting the highest number of vessels served with the lowest costs and then it is the most competitive solutions that can be applied to real life ports. In fact, among models, the solution just quoted grants to minimize the total cost per vessel, finding the most convenient and efficient

situation that grants to serve the maximum number of vessels, during the simulation span, at the minimum cost.

Then this research can be considered as a starting point for future works connected to this study or as an extension of it. First of all there is the possibility to study and simulate the berth allocation with the quay cranes assignment and scheduling, sea side activity strictly linked to the berthing process. The approximation that quay cranes are always available independently from the berthing position can be modeled and analyzed, in order to find the most suitable cranes to assign to vessels according on the schedule of incoming vessels. Thus all the terminal activities can be simulated with the berthing process to find the best scenario to improve and maximize efficiency and productivity of ports. The following step stands in the optimization of best simulated scenario, finding the optimal case that can cut down costs and improve current situation, keeping in mind that it is necessary to increase benefits and productivity. As far as the speed assignment is concerned, it is possible to modify the current simulation and find a better scenario that can allow achieving a more precise and accurate assessment of which is the right speed to assign to vessels. The trigging condition can be set according on time intervals, changing condition in the port, such as a vessel that arrives at the port or that leaves it, or a queue change. Then there is the possibility of applying a different queue policy that does not differentiate and choose anymore the right order to berth vessels, but tries to find the most convenient vessel to moor, according on an appropriate cost function. This approach is called *Simulation Annealing* (SA) and aims to find the global minimum of a precise variables, which can be a cost function or any other parameters that is to be minimized, and not just a relative minimum, with the objective of minimizing costs and maximizing productivity. Since it is not so easy to assess the results of the speed assignment, because the number of vessels processed changes according on models and queue policy, it can be associated to each type of classified vessels, Feeder, Medium or Jumbo, the relative possible revenue for the port, if it is served, coming from the number of vessels that can be transported by every single type of vessels. Then once revenues and cost are known it is reasonable to find out the profits that ports can gain from applying a precise model and queue policy. Then all the performance indicators can be support by showing clearly the cost and the profits, which can highlight and makes a model more reasonably interesting and competitive for real life applications.

# *Appendix*

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# Analisi Simulativa delle Attività Logistiche in un Container Terminal Integrato

I terminal container sono impianti di stoccaggio e movimentazione per container, sia pieni che vuoti, dove quest'ultimi possono essere conservati per periodi anche lunghi, in attesa di essere caricati, su un'apposita nave, per essere trasferiti in un altro porto, o ,in attesa, del cambio di mezzo di trasporto, per essere colocati al di fuori del terminal stesso. Infatti i terminal container, nella maggior parte dei casi, sono integrati con mezzi di trasporto terresetri, quali mezzi su rotaia o su gomma, per la movimentazione dei container da o per il porto. I terminal container rappresentano il fulcro del trasporto dei container e giocano un ruolo decisivo e significativo nelle vie di comunicazione nazionali ed internazionali. Per questa ragione, i terminal sono situati in prossimità di specifiche, adatte e importanti città. Il trasporto marittimo di container, attraverso apposite imbarcazioni, ha visto una crescita esponenziale, che tutt'ora prosegue ininterrotta, grazie alle potenzialità e ai benefici offerti, ma anche grazie ai continui miglioramenti e perfezionamenti che vengono ottenuti ogni anno. Nell'ambito della gestione portuale la coordinazione delle attività che si susseguono all'interno dello stesso risulta estremamente significativa per la massimizzazione dell'efficienza e della produttività. Le principali attività in un container terminal si dividono in attività riguardanti il lato banchina e quelle che avvengono all'interno del porto. Le prime sono quelle correlate alla gestione e all'esecuzione dei processi e servizi relativi alle navi da container; le attività interne invece, sono relative alla movimentazione e stoccaggio dei container all'interno del porto, nonché quelle relative all'entrata o all'uscita dei container dal terminal stesso, attraverso i mezzi su gomme o rotaia. Tra le attività dedite alla gestione delle navi svolge un ruolo rilevante , nella funzionalità del terminal, l'attività che prende il nome di *berth allocation probelm* (BAP). Questo processo definisce la modalità con cui le navi devono essere ormeggiate e ancorata alla banchina. L'obiettivo di questa attività è quello di minimizzare i tempi di servizio e, allo stesso tempo, massimizzare l'utilizzo delle risorse impiegate, come ad esempio le gru di banchina che vengono assegnate ad ogni imbarcazione in modo da servire in maniera precisa, efficiente e veloce le navi, evitando complicazioni o rallentamenti dovuti alla presenza di altre altre navi ormeggiate, in fase di carico o scarico dei container. Tutte le  attività che si svolgono all'interno del terminal risultano correlate le une con le altre perché un guasto o un rallentamento si riflettono sulle performance delle attività successive e quindi sull'efficienza del terminal stesso. Per questo motivo

la simulazione delle attività portuali e i programmi di simulazioni hanno trovato largo impiego in questo campo, poichè la ricerca ha un ampi spazi di diffusione e garantisce un continuo miglioramento nelle performance dei terminal. In questo studio il programma utilizzato per le implementazioni è il software di simulazione Arena, della Rockwell Automation.

In questa ricerca il *berth allocation problem* (BAP) viene inizialmente studiato e simulato per un qualsiasi porto con alcune precise caratteristiche. L' argomento viene studiato in maniera diversa da come è usualmente affrontato. Infatti la banchina può essere considerata come formata da un susseguirsi di ormeggi, virtualmente separati con limiti che non possono essere sovrapposti da navi, e con il vincolo che le navi possono essere ormeggiate solo se la lunghezza, singola o complessiva di più navi, è inferiore a quella dell'ormeggio; eventualmente, in caso di sovrapposizione, la nave deve essere ancorata all'ormeggio successivo. In questo studio la banchina viene considerata come un ormeggio continuo, non più discreto, dove le navi possono essere ancorata in qualsiasi punto, se le condizioni stabilite vengono soddisfatte. Le uniche limitazioni stanno nello spazio fisico di ormeggio e nella disponibilità delle gru che sono necessarie per servire le navi nelle fasi di carico e scarico dei container. Il caso sotto studio è denominato *continuous berth allocation problem* (CBAP), contrapposto al *discrete berth alloation problem* (DBAP). Questo problema viene successivamente affrontato simulando la possibilità di modificare la velocità delle imbarcazioni che stanno raggiungendo il porto, precedentemente considerata fissa e costante, durante tutto la tratta di navigazione. La velocità delle navi viene cambiata solo dopo che queste raggiungono la distanza di 500 miglia nautiche dal porto, ma è successivamente aggiornata ripetutamente, in modo da rifletterne l'efficienza e la produttività del porto stesso. Infatti la condizione che porta ad assegnare alle navi una velocità diversa da quella con cui navigano è il numero di navi che sono già ancorate al porto, non per essere servite, ma bensì in un'apposita area, in attesa che si verifichino le condizioni necessarie di ancoraggio alla banchine per il successivo trattamento. Queste due simulazioni, il singolo processo di ancoraggio e l'ormeggio con possibilità di cambiare la velocità delle imbarcazioni, sono studiati facendo delle assunzioni riguardo la disponibilità della gru nel porto preso in considerazione. Infatti il generico porto studiato è considerato composto da due moli, nei quali sono disponibili rispettivamente due e tre gru. Quindi, indipendentemente dalla posizioni, i moli possono servire contemporaneamente due e tre navi; quelle che sono in attesa posso essere ormeggiate solo una volta che una gru diventa disponibile, cioè quando finisce di servire un'imbarcazione precedentemente ancorata, e se lo spazio è sufficiente per l'ormeggio, cioè quando non causa sovrapposizioni con navi già ancorate. Queste simulazioni sono implementate tramite quattro diversi modelli, nominati diversamente in modo da evidenziare le loro peculiarità. Tre di questi modelli si basano sull'assunzione che la banchina è continua; l'ultimo invece considera la

banchine come somme di ormeggi adiacenti e è quindi definita discreta. L'obiettivo di questa ricerca è infatti quello di simulare, analizzare **e** comparare i vantaggi dell'uso della continuità, al posto della discretizzazione, nella banchina di un container terminal. Infatti nonostante le semplicità di studio garantite nella formulazione del caso discreto, lo scenario continuo permette di avere delle misure più realistiche e precise che non sono causa di sovrastima, ma di una precisa riflessione della realtà, assicurando un'efficienza più elevata nonché prestazioni più promettenti nel porto. L'analisi comparativa tra i modelli si basa su degli indicatori chiave di performance, definiti *key performance indicators* (KPIs), i quali permetto di provare e giustificare l'efficienza o l'inefficienza di un modello rispetto ad un altro, suggerendo quale politica scegliere per massimizzare i benefici e minimizzare i costi. Queste misure di prestazione, collezionate durante le simulazioni, sono essenzialmente la percentuale di utilizzazione dei moli, il tempo e numero medio di imbarcazioni temporaneamente ancorate nell'apposita area del porto prima di essere ormeggiate, anche il tempo totale richiesto per compiere tutti i processi e infine, il costo che ogni modello comporta, se applicato, definito e calcolato secondo precise modalità. Le prestazioni di un container terminal sono quindi fortemente condizionate dal numero di navi e dal tempo in cui restano momentaneamente ancorate nell'area apposita del porto prima di essere ormeggiate sulla banchina del molo per essere servite. Per questo motivo oltre alle varie politiche dei modelli per l'implementazione della fase di ormeggio, per ognuno di questi vengono anche simulate quattro differenti politiche per definire l'ordine con le quali le imbarcazioni in attesa devo essere ancorate, sempre con il fine ultimo di massimizzare la produttività e minimizzare costi e inefficienze. Queste quattro metodologie, nuovamente denominate in modo da essere distinte, sono dipendenti o dall'ordine temporale con cui le navi raggiungono il porto o dal tempo necessario perché queste siano servite. Infatti il tempo di servizio delle navi è un parametro dipendente dalla lunghezza delle stesse e che va a influenzare anche la data stimata di partenza nella quale le imbarcazioni devono lasciare il porto. Queste diverse modalità di simulazioni sono ulteriormente incrementate nella seconda parte della ricerca, dove la velocità delle navi è presa in considerazione, con la possibilità di una eventuale modifica. La velocità con la quale le imbarcazioni si dirigono verso il porto è quella minima, che permette quindi la massima economia; ma questa può essere aumentata alla velocità massima, che porta però a consumi ed emissioni maggiori. L'aumento o la diminuzione della velocità dipende da una condizioni che viene ripetutamente controllata mentre le navi si stanno avvicinando al porto, una volta che le imbarcazioni si trovano a meno di 500 miglia nautiche dal porto, e la velocità viene quindi modificata in modo da limitare consumi di carburante ed emissioni, ma anche evitare situazioni compromettenti per la funzionalità e le prestazione del porto, quali congestioni o inefficienze e inattività delle risorse disponibili nel terminal .

Indipendentemente dalla possibilità o meno di controllare la velocità delle imbarcazioni, la banchina considerata come continua, che consente di ancorare le navi in qualsiasi punto del molo, permette di ottenere prestazioni decisamente superiori, rispetto a quella discreta, in qualsiasi misura di performance considerata, eccetto la percentuale di utilizzazione dei moli che risulta minore, poiché la sovrastima di questa misura sta alla base del modello discreto. Anche i costi, diversamente considerati e calcolati nelle due fasi della simulazione, risultano inferiori. Nel *pure berth allocation problem*, la politica più conveniente ed efficiente risulta quella che permette di ormeggiare e poi servire le navi più corte, tra quelle che sono in attesa di essere servite, e quindi che hanno bisogno di un minor tempo per le fasi di eventuale carico o scarico dei container. Tutte le misure di prestazione risultano minimizzate con un significativo aumento della produttività e dell'efficienza del processo di ormeggio, nonché del container terminal stesso. Quando alla fase di ancoraggio viene affiancata la possibilità di alterare la velocità delle imbarcazioni, la politica precedente viene superata in prestazioni dalla politica che opta nel servire prima le navi che devono lasciare il porto prima delle altre, secondo un programmazione predefinita. Infatti la data stimata della partenza delle navi, *time of expected departure* (ETD), viene assegnata alle stesse a seconda della lunghezza, e quindi in dipendenza del tempo richiesto dalle ultime per essere servite, una volta ancorate al porto. È importante inoltre notare che le varie condizioni di modifica della velocità delle navi non trovano un sostanziale miglioramento o peggioramento delle condizioni, facendo oscillare le prestazioni in un intervallo ristretto, specialmente nella condizioni più efficienti appena menzionate. Risulta quindi quasi completamente inefficace la scelta di aumentare il numero di imbarcazioni che possono essere accelerate, perché questo incremento porta solamente ad un aumento dei consumi di carburante, non giustificato dall'aumento di prestazioni dell'attività portuale pressoché costanti, o leggermente oscillanti, che non ritrovano un riscontro effettivo per un consumo così sproposito in termini di efficienze e produttività nel processo di ancoraggio, e per ultimo nel container terminal. Quindi la scelta di usare una banchina continua, invece che quella discreta, per la fase di ancoraggio delle navi in un porto qualsiasi composto da due moli serviti rispettivamente da tre e due gru, si dimostra sicuramente più efficace e conveniente, permettendo una produttività del porto e una sua efficienza decisamente più elevata e significativa, riflettendo precisamente le prestazioni dello stesso ed eliminando la sovrastima e le limitazioni del caso discreto, nonché abbattendo i costi e massimizzando i benefici del suo utilizzo. Risulta perciò giustificata la possibilità di riprodurre in un porto reale la situazione simulata in questa ricerca che permette di ottenere il massimo delle prestazioni e il minimo dei costi, facendo sì che il porto di diventare fortemente competitivo in un mercato in continua crescita, dove le possibilità di miglioramento, perfezionamento e successo sono estremamente necessarie e richieste.

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