Impact of Mega-ships on the Performance of Port Container Terminals

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Abstract Following the advent of mega-ships, the performance requirements of container terminals have increased significantly, highlighting necessary changes in their layout, infrastructure and equipment. We focus on the impact of mega-ships on a terminal, within the port network of the Italian region of Liguria, in terms of its ability to manage the flow of imports from arrival to inland destinations. We use discrete event simulation techniques to analyze the operations of a terminal and evaluate the relevant performance indices in different scenarios, which vary as a function of the *call size* of the larger containerships. The possibility of guaranteeing a more balanced modal split (favoring rail transport) for the inland distribution of containers is also evaluated. Dwell times at the yard and turnaround times at the berth are considered, with the objective of achieving a modal split of inland transport consisting of no less than 40% rail. Our results show that this objective can be achieved if a higher dwell time for outgoing containers is allowed.

Keywords: Logistics; Maritime Container Terminal; Discrete Event Simulation; Performance Indices; Mega-ships.

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1. INTRODUCTION

The phenomenon of mega-containerships (hereafter mega-ships) is currently a theme at the core of the debate throughout the world. Containerships represent around a quarter of the global merchant fleet and are essential for the transportation of manufactured goods worldwide. One of the peculiarities of this phenomenon is the speed of the dimensional evolution process of containerships, much faster than those involving other types of ships. In fact, the growth rate of the size of containerships has accelerated since the start of the new millennium, from 3,400 Twenty Foot Equivalent units (TEUs) (average size for newly built ships between 2001 and 2008), to about 8,000 TEUs in 2015, and 21,000 TEUs today. The size of the current generation of containerships could potentially go up to 22,000 TEUs, with further optimization of ship designs and an increase in capacity. This has caused a series of consequences in terms of infrastructural adjustments in ports and Information Technology (IT) systems, for the organization of handling operations, the peaks of port congestion and the environment (see Haralambides 2017; 2019).

Critical issues of mega-ships concern a possible increase in costs paid by ports and their hinterland actors (including the opportunity costs of coastal and city land, and the external costs of pollution and traffic congestion in inland transportation networks), more than proportionally to the increase in ship sizes. It is therefore necessary to analyze these developments in terms of the trade-offs between the *benefits* of mega-containerships and their *cost* along the entire transport chain (Tran and Haasis 2015).

There are also issues concerning the routes to be chosen by carriers and the ports their ships will call. According to an analysis conducted by the Organization for Economic Co-operation and Development (OECD/ITF 2015), the most flexible and probably profitable vessels -in terms of their accessibility to ports and markets to be served- are in the range of 5,500 and 6,500 TEUs. To many, it becomes increasingly clear that the grown in containership sizes is dictated above all by economies of scale at sea, with disregard to operational matters and diseconomies in ports (Tran and Haasis 2015; Haralambides 2019). As regards operating costs, the estimated savings thanks to the achievement of greater economies of scale, between a 15,000 TEU ship and a 19,000 TEU one, is $50 per TEU, assuming a capacity utilization of 85%. In particular, it has been observed that, as ship sizes increase, from a 2,000 TEU feeder ship to a 20,000 TEU mega-ship, economies of scale decline constantly (Tran and Haasis 2015; Haralambides 2017 and 2019).

The drive towards bigger ships clearly implies commercial challenges, such as decreasing load factors and efficiency issues, as the time spent in ports reduces the number of trips and therefore ship capacity per unit of time, in terms of TEU-miles; in turn, this causes a push for increasingly rapid terminal operations and related technical issues involved in accommodating larger vessels. In particular, terminals must always guarantee an acceptable throughput, regarding loading and unloading operations, and an adequate level of service. In fact, mega-ships have led to critical infrastructures, as well as to a change in operations, both quayside and landside, generating the need to optimize management and minimize criticalities, given the amount of investment required. For those reasons, operations research and decision science tools are frequently used by terminal management, with a view to improve efficiency and productivity, by minimizing costs and improving performance indices, as they are imperatives of the current shipping market (Carlo et al. 2013; Carlo et al. 2014; Kaveshgar and Huynh 2015; Steenkeen et al. 2004; Stahlbock and Voß 2008).

In fact, the competitiveness of a container terminal is determined by a series of different factors: first of all is the ability to receive and serve the largest containerships, as well as to minimize the time spent in a port, and to maximize the number of TEUs handled in a certain amount of time, at competitive rates. Terminal operators, together with carriers and port authorities, are now investing in new technologies to improve the handling and operational efficiency of ports, according to the needs of the largest containerships, adapting as much as possible their infrastructure and equipment, and thus reducing access costs.

Among the decision sciences tools, simulation techniques have been widely used in the recent literature of *maritime logistics*, mainly for the performance evaluation of container terminals. In this area, most of the simulation models applied to real cases analyze container terminals with respect to their productivity and strategic planning (see, e.g., Gambardella et.al. 1998; Legato and Mazza 2001; Ballis and Golias 2004; Cartení and De Luca 2012).

Other works have dealt with the management of truck arrivals at the gate (Sharif et al. 2011; Veloqui et al. 2014). In particular, by attempting to optimize available terminal resources, these studies have had the aim of reducing the queue length and the waiting times of container trucks, caused by traffic peaks. For example, Yang et al. (2010) suggest to define temporal windows for truck arrivals of export containers, which can be optimized with heuristic methods.

Other relevant contributions of simulation studies have focused on the rail / road connections (see, among others, Rizzoli et al. 2002; Parola and Sciomachen 2005 and 2009). In particular, the work by Parola and Sciomachen (2009) presents a discrete event simulation model for the evaluation of possible improvements to modal split in favor of rail transport, departing from a container terminal in the Italian north-western port system. Their study proposes the introduction of a dry port, for better transferring road traffic to a high capacity railway link, on already existing infrastructure.

Simulation has been used to analyze the accessibility of large ships to terminals and related costs (Sys et al. 2008). Quiang et al. (2017) formulate the operation process at a container terminal in Hong Kong as a queuing network, and analyze a possible need to expand the berth area, in order to manage an increasing volume of containers. Dulebenets et al. (2015), using simulation modelling, evaluate the performance of two terminal configurations, based on the floater quay concept.

Finally, simulation has also been used to compare alternative terminal investment projects aimed at measuring terminal performance and economic impacts, thus attempting to assess whether the amount of capital to be used is justified by achievable performances (Bielli et al. 2006).

Our work presents the results of a simulation study, aimed at evaluating the impact of mega-ships on the operations and management of a container terminal located in the Italian region of Liguria. In particular, dwell times at the yard, and turnaround times at berth, are analyzed, with respect to a desired modal split of inland containers leading to a 40% share of rail. To the best of our knowledge, there are very few simulation studies with this aim. We thus focus on all the main operational areas of the container terminal under study, that is berth, yard and inland connections.

The work is organized as follows. Section 2 briefly describes the container terminal under analysis and its role within the multimodal supply chain in a strategic European corridor. Section 3 describes the main components and the routing rules of the discrete event simulation model of the terminal. Section 4 presents our main results in terms of performance indices, in relation to alternative scenarios that foresee different arrival processes of large ships. Finally, some conclusions and suggestions for future work are given.

2. OPERATIONAL ASPECTS OF MARITIME TERMINALS

Aiming at proposing a methodology potentially suitable for all marine terminals, our analysis focuses on a new terminal (still under construction) located in the port of Vado Ligure, belonging to the Port Authority of the Western Ligurian Sea, which also includes the ports of Genoa, Savona and Pra. The terminal is a part of the APM Terminals group (http://www.apmterminals.com/).

APM Terminals has chosen the port of Vado Ligure, as it meets the requirements necessary to accommodate the modern mega-containerships, namely adequate draft, good nautical accessibility and existing railway and highway connections with the hinterland, not requiring new infrastructures, as well as spaces available for all the required logistics operations. In fact, the new platform under construction, henceforth referred to as APT-VL, is located in a basin, naturally suitable to allow the entrance of larger vessels, having sufficient drafts along the access channel and near the berths. Further, the terminal will also be equipped with a rail system, integrated with quayside and landside operations. It is worth noting that the terminal belongs to the TEN-T network. It thus aims to attract the largest shipping companies operating in the Mediterranean and serve the trade between Middle East / India / Far East, whose reference market extends from North-Western Italy to Switzerland and southern Germany.

The main challenge of the terminal will be to shift 40% of its containerized traffic to rail. This traffic would be directed to an inland intermodal platform, located no further than 500 meters from the gate, before the containers continue to their final destination. To reach this goal, at least 18 freight trains per day are foreseen, with a length of about 500 meters. Further, the idea is to ship the containers along the following railway lines:

- two railway services to Turin (135 km) and Alessandria (93 km);
- two railway services along the Ligurian coast, one eastbound towards Genoa (50 km) and the other westbound towards France (107 km), respectively.

The port of Vado Ligure is also connected to the northernmost part of Italy via the A6 Savona-Turin highway, and to the Brenner highway via the A33 Cuneo-Asti, as well as the A10 coastal highway. Figure 1 present the map of the geographical area where the APT-VL is located.

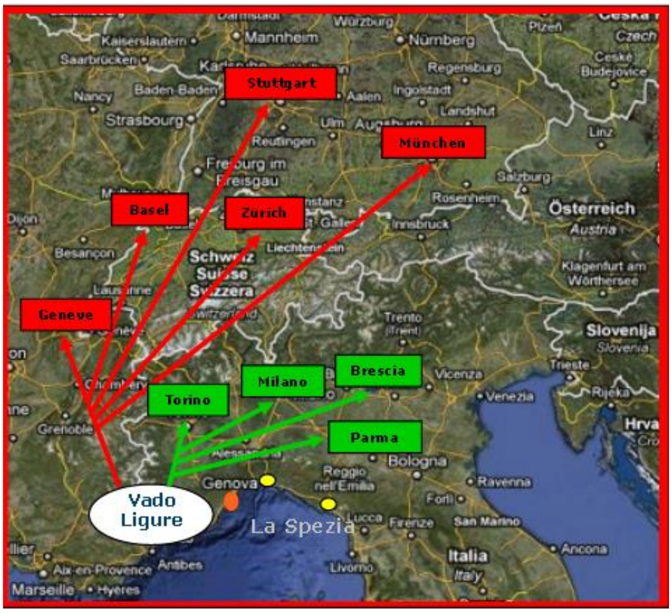

Figure 1. The map of the geographical area of the container terminal APT-VL

The annual throughput of the terminal is expected to be about 800.000 TEUs and it will be integrated with the already active Reefer Terminal at Vado Ligure, which presently has a capacity of 275.000 TEUs (here, however, we are only concerned with the analysis of terminal performance regarding standard 20’ and 40’ containers, arriving at the new platform for their inland forwarding).

The APM-VL project includes a 700-meter quay, divided into two parts, one of which will have a depth of 22 meters and will be the berth for the ultra large containerships. The quay will be equipped with six latest-generation cranes, capable of handling two 40'containers at a time, and performing 30 handling operations / hour. Figure 2 reports the layout of the terminal.

Six vehicle lanes will depart from the apron to allow trucks and reach stackers to lift up to two 20', or one 40', containers at a time, from the quay to the yard where there will be 40 blocks for stacking 20' containers (or 20 blocks for stacking 40' containers) in the longitudinal direction, consisting of 7 rows, where containers are stacked in four-level tiers (see Figure 2).

The gate is located under the planned office structure and consists of 15 reversible lanes. Trains will arrive and depart from the new railway park, located inside the port area. Containers will be loaded and unloaded with the Metrocargo system, a technology that uses electric cranes which allow modal change to wagons by longitudinal trans-shipment using specialized shuttles and turrets mounted on special lift trucks. This system avoids the composition and decomposition of trains and the need to move the wagons out of the terminal, thus reducing loading and unloading time and increasing the potential containerized flow that could be managed.[1]

Figure 2. The layout of the container terminal APT-VL

3. THE DISCRETE EVENT SIMULATION MODEL OF THE TERMINAL

[1] For more information about the terminal, see https://www.portsofgenoa.com/it/terminal-merci/containers/vado.html.

Since the aim of the present study is to evaluate the capability of the APT-VL terminal to manage large volumes of import containers arriving by ship and leaving the terminal by truck or train, our simulation analyses three main components, representing the operational processes of the terminal concerning the quayside, the internal area and the landside. These activities consist of the unloading of ships, the location and repositioning of the containers in the yard, and the loading of the containers onto either a truck or a train and their successive exit from the terminal.

The dwell time of the containers at the terminal, the yearly throughput and the berthing time of the ships are the performance indices that drove the simulation experiments.

Figure 3 shows the graphical representation of the layout and the main elements of the APM-VL container terminal, implemented by using the discrete event simulation software environment Witness (Lanner Group 2017; Waller 2012) which is also used for the computation and analysis of our performance indices.

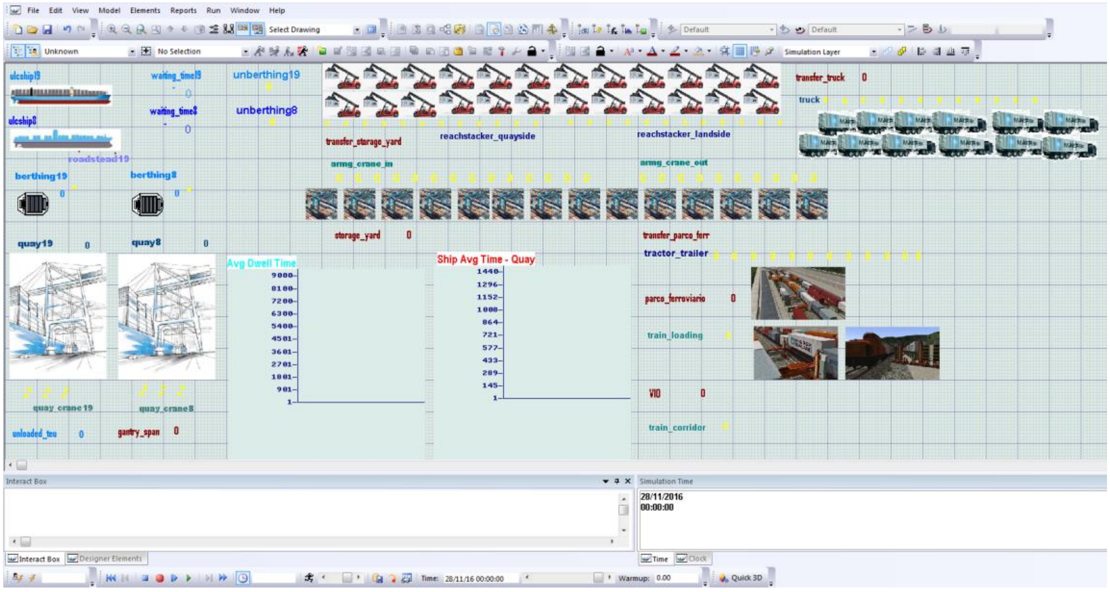

Figure 3. The layout and the main components of the simulation model representing the container terminal under study

The model was implemented by defining and detailing in advance the three main types of elements that constitute a general discrete event simulation model; i.e., parts, buffers and machines. The dynamic parts modelled in the system, which are the elements flowing throughout the terminal, are the ships and the containers. Buffers are all the zones of the terminal where parts wait to be serviced, such as road and yard, while machines include all equipment of the terminal performing cargo handling or transport activities.

In particular, two types of parts, representing the ships, are considered; namely, large containerships of up to 8,000 TEUs (denoted by LS) and mega containerships of up to 19,000 TEUs (denoted by MS). In order to be properly represented in the model, for each type of ship, the distribution of the arrival times and the routing followed within the system, from the quay to the gate, must be defined. The inter-arrival times of ships are expressed by randomly generated variables, following the negative exponential distribution, with rate λ = 2160 and λ =4320 minutes in case of LS and MS, respectively; this corresponds to the arrival of a large ship every one and half day and a mega-containership every 3 days on average.

Based on the project data of the APT-VL platform and the current ship sizes, two buffers, denoted by berth19 and berth8 respectively (according to the maximum size of the ships), representing the two berths, were created, assuming that the first had a draft of 22 meters and a longer quay length, thus able to receive ships of up to 19,000 TEUs. Instead, berth8 could only accommodate ships up to 8,000 TEUs. Therefore, the ships enter the system and are routed to the corresponding buffer. Then, as soon as a ship, either LS or MS, reaches the berth, parts representing containers are generated by using an ad hoc function. In particular, containers named cont8 / cont19 are randomly generated by machine berth8 / berth19, according to a uniform distribution in [min,max], where min e max correspond to the 20% and 30% of the capacity of the ship, respectively, that is 8,000 and 19,000 TEUs. Each container part has an attribute used to define its size, i.e. 20’ or 40’; this attribute is a binary value that is randomly generated in such a way that if the value is 0, the generated container is a 20’ one; if it is 1, it is a 40’ container.

Quayside operations start when the ship is at its assigned berth. At that time, a predefined number of cranes, modelled as machines, are assigned to it for the unloading of the containers. Then the containers thus generated are put on berth8 / berth19 to be picked up, one by one, by a crane for their unloading. Each berth is served by three cranes equipped with a double spreader; for this reason, they have been defined as *batch machines*, which take two parts from either berth8 or berth19 and return 2 parts in output, proceeding to their grounding in a buffer called gantry span. The service time of the cranes is generated at each occurrence from a negative exponential distribution with mean value $\frac{1}{\lambda} = 2$ minutes, that is equal to 30 moves/hour, although their productivity, based on technical data, could reach 40 moves per hour.

In the gantry span buffer, whenever a container is generated, a counting variable, initialized to zero, is incremented in order to update the number of unloaded containers.

At the end of the unloading operations by the quayside cranes, the ship leaves the quay buffer and is processed by a machine having an average service time uniformly distributed in [30,45] minutes, expressing the time necessary for the ship to leave the port.

The internal handling operations start when the containers are taken from the gantry span by quayside and landside reach stackers. The reach stackers quayside move containers from the quay to the yard, taking them from the gantry span, where they are positioned by the quay cranes, waiting in the transfer storage yard for an automated electrical crane. Based on historical data, we have represented reach stackers by negative exponential variables with an average service time $\frac{1}{\lambda} = 4$ minutes. Instead, the reach stackers landside have been created because part of the containers is not transferred to the yard but proceeds directly to the terminal gate. The exit rule of these containers complies to the APT-VL terminal policies, that is 40% of them is sent to the inland terminal by train, and the others are sent to the transfer terminal by truck. This dispatching criterion guarantees the level of performance indicators required by the terminal, among which a modal split of 60% to road and 40% to rail.

As far as yard operations is concerned, 24 yard-cranes were created, having an average service time of 3 minutes. In particular, 14 cranes pick up the containers from the transfer storage yard and place them in the storage yard. Instead, 10 cranes deal with the transport of containers from the yard to the transfer areas, either in transfer truck area or transfer park rail.

On landside, as regards the exit of the container from the system, two different machines (trucks and trains) are used, based on the transfer modality of containers to the hinterland. First, 12 trucks with an average service time of 5 minutes were used. In fact, it had been requested that about 1,440 trucks a day will cross the terminal through the reversible lanes of the gate; this truck takes 1 to 2 containers at a time from the transfer truck area. Then, the containers leave the terminal. With regard to the exit of containers via train, the tractor trailer was used which, as reported in the project of the APT-VL platform, takes 7 containers of 20’ at a time and transfers them to the nearby railway park having a maximum capacity of 400 TEUs. The average service time of this tractor trailer is set to time 30 minutes.

As said in Section 2, in the railway park, the loading of containers on trains is carried out using the Metrocargo technology; this service is represented in the model by a train loading function. The park receives 80 containers as input and assembles them into a single train, with an average service time of 80 minutes, assuming that at least 18 freight trains are organized per day, according to the Port Authority's objective. Finally, this train later sends the containers to the inland intermodal terminal, connected to APT-VL. This is a buffer area from where the containers are taken and forwarded to the train corridor, which represents the output of the containers from the system.

Two counters, associated with the modal split attribute of the container parts, were created in order to check the number of outgoing containers with the different transport modes.

4. ANALYSIS OF THE CONTAINER TERMINAL PERFORMANCE

The goal of our computational experiments was to evaluate the ability of the APT-VL terminal to manage high volumes of containerized flows from mega vessels.

All the simulation runs have been performed within the experimental framework of the software environment Witness. We eliminated sampling of the results of the model by considering a warm-up period of one month; then, statistics of one year of operation of the terminal were collected.

Note that, according to the practice of the APM Terminals group, we have considered every day of the year, apart from Christmas Eve, Christmas Day, New Year's Eve and New Year's Day, when the terminal is assumed to be closed. Further, based on the timetable of APM Terminals, operations take place 24 hours per day; only the gate is closed every week from Saturday 3 p.m. to Sunday 3 p.m.

For validation purposes, we first run the model using the data described in Section 3, representing the base scenario (Scenario I). Starting from the base scenario, 4 others were subsequently hypothesized, assuming an increase in the arrival frequency of 19,000 TEU mega ships. In this way, we were able to analyze the management of the terminal in the event of the so-called mega-peak arrivals. Table 1 shows the inter-arrival times (in minutes) of the ships in all scenarios. Note that in scenarios II and III, the number of LS having capacity of 8,000 TEUs has been kept constant, while an increase of the inter-arrival times of MS has been considered in Scenarios II and III up to a frequency of one ship every two days.

Table 1. Ship inter-arrival times under different scenarios

Inter-arrival times (min)		
	LS	**MS**
Scenario I	2160	4320
Scenario II	2160	3600
Scenario III	2160	2880
Scenario IV	1800	2880
Scenario V	1440	2880

As in any simulation study, independent replications for each scenario were executed to estimate the average values of the various performance measures. By using the T-Student confidence interval test, ten replications were found to be sufficient, as the average standard deviation was less than the corresponding coded value (Law 2007).

As foreseen in the APM Terminals objectives, fixing the expected throughput of the APT-VL platform at 800,000 TEUs in the base scenario (Scenario 1), the results of our simulation experiments returned a value of 795.071 TEUs of shipped containers, corresponding to the yearly throughput.

Figure 4 shows the throughput values obtained in all scenarios (note the linear growth trend in all cases).

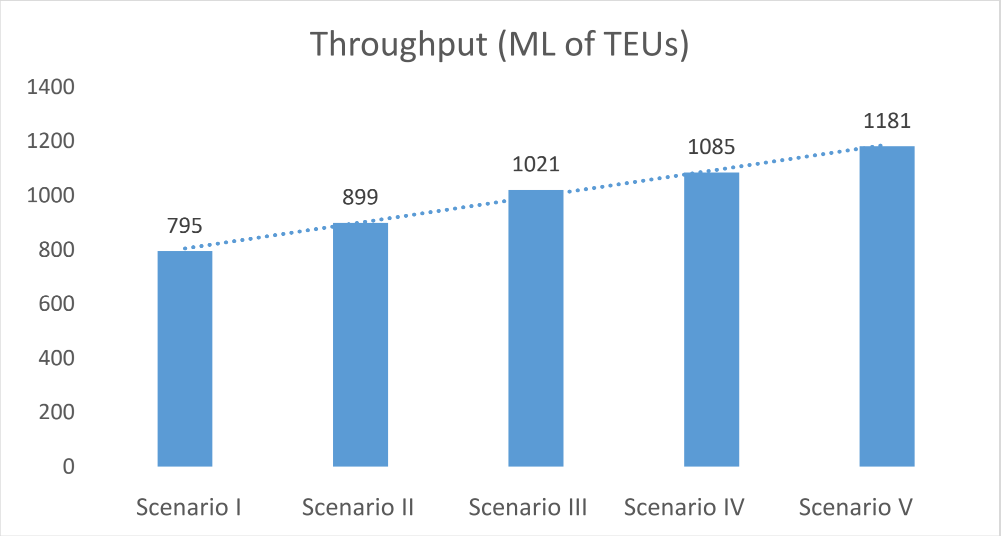

Figure 4. Throughput of the APT-VL terminal in all scenarios

However, it is necessary to point out that, in view of the more than satisfactory results related to the terminal throughput, in the simulation experiments of the base scenario we observed a low utilization of terminal resources, in particular of the quay and yard cranes. The resulting data are shown in the first columns of Table 2. It can be noted that the blocking states detected in the operation of the cranes are irrelevant, equal to 0.36% on average.

Table 2. Percentage of utilization of the equipment of the APT-VL terminal in the first and last scenarios

	Scenario I		**Scenario V**		**Δ % Improvement**	
Equipment	**N. operations**	**% Busy**	**N. operations**	**% Busy**	**N. operations**	**Busy**
quay_crane19	212.800	27,25	325.775	41,72	53,09	53,10
quay_crane8	184.740	23,70	264.806	34	43,34	43,42
armg_crane_in	397.481	16,37	592.962	24,37	49,18	48,87
armg_crane_out	401.240	23,16	597.687	34,43	48,96	48,70

Instead, in the following scenarios, the increased frequency of ship arrivals resulted in an increased utilization rate of all types of cranes, in line with the increase in the number of operations and in terminal throughput (see Figure 4). These increased values are reported in columns 4 and 5 of Table 2, while columns 6 and 7 show the percent variation in the number of operations and in the utilization rate.

It also emerges that:

- Investments in efficient quay cranes allow one to manage mega-ships quickly and to keep an average ship turnaround time of about 1.2 days;
- A higher berth productivity is possible, as the utilization rate of quay and yard cranes is still quite low (the utilization rate of cranes grows proportionally to the increase in throughput);
- The number of outgoing trucks increases by 46% from scenario I to scenario V, given an increase in throughput of 49%;
- The most critical issue is the increased dwell times for outgoing containers, both for road and rail; while values resulting from scenarios IV (one 19,000 TEU ship every 2 days and one 8,000 TEU ship every 1.25 days) are still acceptable, the dwell time in scenario V jumps up to 6 days for rail and 5 for road, which seems far too long compared to current terminal productivity standards.

As a further comment on the values reported in Table 2, we can say that, even in the last scenario, crane utilization is still quite low. These results are justified by the fact that in all the performed simulation experiments, all the available (six) quay cranes were used. In fact, the objective of this simulation experiment was to evaluate the capability for the terminal to manage high volumes of import containers, due to the phenomenon of mega-ships. Therefore, based on the data and assumptions made in the development of the simulation model, and the successive analysis of the scenarios, we observe the possibility of a potential increase in the productivity of the quay, as no relevant blockages have occurred, but a period of inactivity which is too high, compared to the performances this equipment is able to guarantee.

Also in reference to the performance of the quay, ship turnaround times of both LS and MS ships have been evaluated (Figure 5). As it can be easily seen looking at Figure 5, the resulting values of ship turnaround times in all scenarios tend to be stable; this is because the quay operations are always efficient. Further, it is worth noting that the values obtained in our simulation experiments are perfectly in line with the objectives of the APMT group. The results also confirm the productivity standards of the terminal, since the average value of the turnaround time of a mega ship is about 28 hours, that is just over a day. Therefore, it can be said that, based on our simulation results, the ship turnaround time does not increase significantly as the throughput increases.

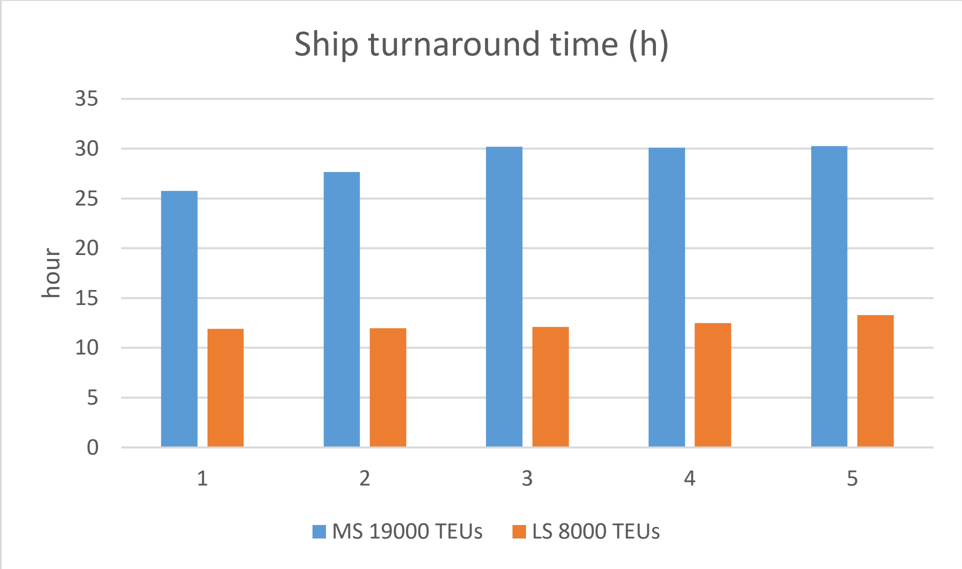

Figure 5. Ship turnaround time of the LS and MS ships

This is not true with regard to the dwell time of the containers in the terminal. The corresponding value, reported in Figure 6, has been computed by considering the average time spent by the containers in all buffers represented in the model, which are the yard and the transfer truck and park rail, respectively, for the rail and road modes, assuming a modal split of 40% by rail. In Figure 6, the dwell time of the containers transported outside the terminal by both truck and train increases with increases in throughput, that is with an increase in the frequency of arrivals of mega ships. The reported values can be considered acceptable up to Scenario IV, corresponding to an arrival frequency of one MS ship every 2 days and one LS ship every 1.25 days. Instead, the dwell time obtained in Scenario V is greater than 6 days in the case of containers departing from the terminal by train, and about 5 days for those departing by truck; these values seem to be too high compared to the required actual productivity standards.

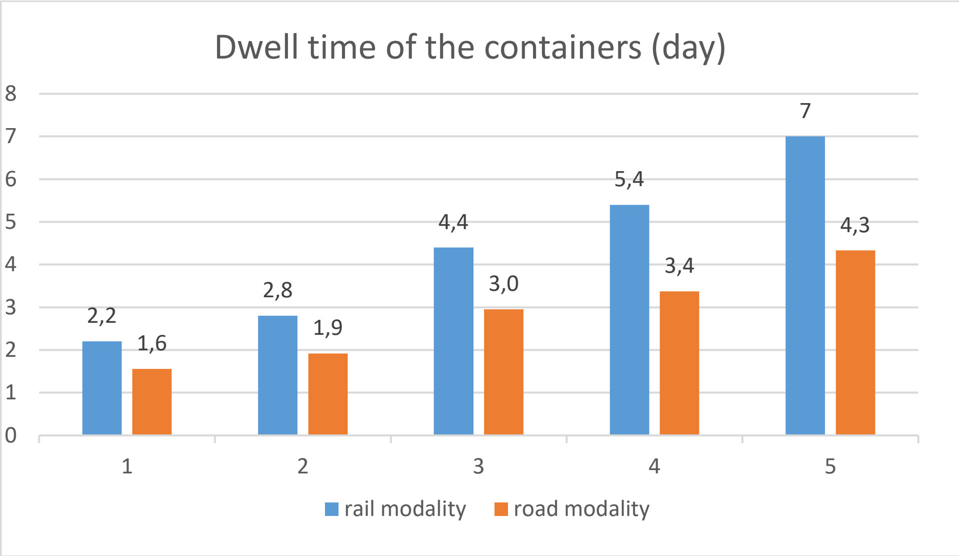

Figure 6. Dwell time of the containers in the APT-VL terminal

As a last analysis in the present simulation study, we have attempted to determine the number of operations performed by the truck machines, which transport one or two containers at a time, so as to determine the number of trucks leaving the gate. In this way, one might be able to evaluate the environmental impact of road traffic departing from the terminal. Trucks have been associated with an average fixed cost for their use, set at 2.5 € per truck, based on estimates made by the OECD on the congestion caused by import containers in maritime terminals (Maibach et al. 2008).

Figure 7 shows the increasing number of truck operations and the corresponding estimated congestion cost. There is an increase in congestion of 46%, compared to an increase in throughput of around 49% from Scenario I to Scenario V.

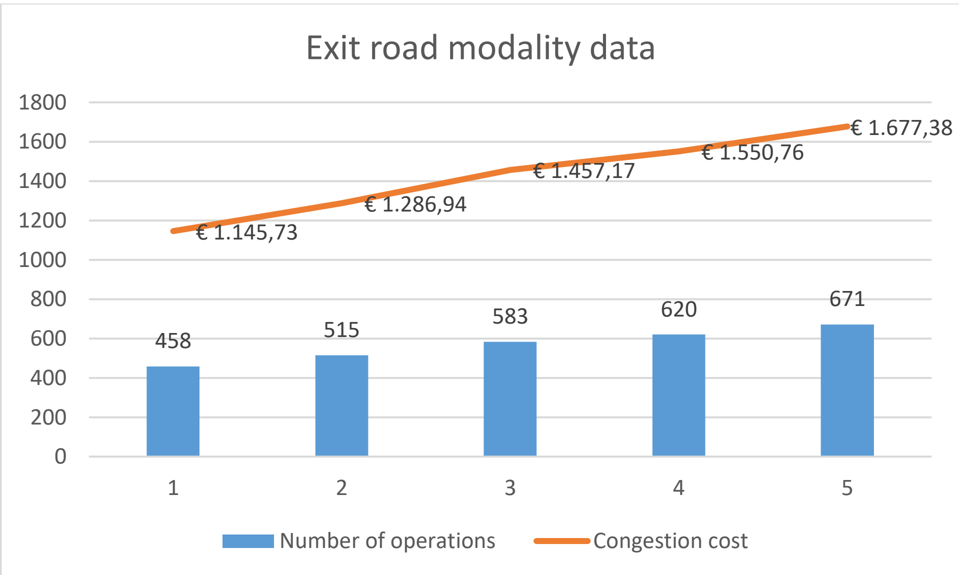

Figure 7. Number of truck operations and related costs

CONCLUSIONS

We analyzed the impact of mega-ships on the operational performances of a maritime container terminal. The analysis have been performed by developing a discrete event simulation model and successively executing different runs, up to the steady state condition, by evaluating five scenarios.

We focused our analysis on a container terminal, still under construction, located in the Liguria county. Our aim was to assess possible *criticalities* due to the large size containerships, in a such strategic location within the Mediterranean and Reno Alps TEN-T corridor.

The simulation results confirmed the estimate made by the owner of the terminal concerning its main performance indices. In particular, it has been shown that the investments in efficient quay cranes allow the fast handling of mega-ship arrivals, guaranteeing a ship turnaround time of just over a day. However, the main critical factors are the hinterland connections, since the dwell time of the containers is higher that the desirable value, both for the rail and road modalities.

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