ORIGINAL ARTICLE

Impact of megaships on the performance of port container terminals

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Abstract

Following the advent of megaships, the performance requirements of container terminals have increased significantly, highlighting necessary changes in their layout, infrastructure, and equipment. We focus on the impact of megaships 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 · Megaships

1 Introduction

The phenomenon of megacontainerships (hereafter megaships) is currently a core theme of debate worldwide. Containerships represent around one-quarter of the global merchant fleet and are essential for transportation of manufactured goods worldwide. One of the peculiarities of this phenomenon is the speed of evolution of the dimensions of containerships, which is much faster than for other types of ship. In fact, the growth rate of the size of containerships has accelerated since the start of the new millennium, from 3400 twenty foot equivalent units (TEUs) (the

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average size for newly built ships between 2001 and 2008), to about 8000 TEUs in 2015, and 21,000 TEUs today. The size of the current generation of containerships could potentially reach 22,000 TEUs, with further optimization of ship designs and an increase in capacity. This has a series of consequences in terms of infrastructural adjustment 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 megaships concern a possible increase in costs paid by ports and their hinterland actors (including the opportunity costs of coastal and city lands, and the external costs of pollution and traffic congestion in inland transportation networks), more than proportionally to the increase in ship size. It is therefore necessary to analyze these developments in terms of the tradeoffs between the benefits of megacontainerships 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 at which their ships will call. According to an analysis conducted by the Organisation 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 5500 and 6500 TEUs. To many, it is becoming increasingly clear that the growth in containership sizes is dictated above all by economies of scale at sea, disregarding operational matters and diseconomies at ports (Tran and Haasis 2015; Haralambides 2019). Regarding 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—would amount to US $50 per TEU, assuming capacity utilization of 85%. In particular, it has been observed that, as ship size increases, from a 2000 TEU feeder ship to a 20,000 TEU megaship, economies of scale decline constantly (Tran and Haasis 2015; Haralambides 2017, 2019).

The drive toward larger 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 thus ship capacity per unit 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, megaships 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 these 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 these are imperative in the current shipping market (Carlo et al. 2013, 2014; Kaveshgar and Huynh 2015; Steenken 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 port and 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 their infrastructure and equipment as much as possible, and thus reducing access costs.

Among decision sciences tools, simulation techniques have been widely used in recent literature on maritime logistics, mainly for evaluation of the performance 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 (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 aim to reduce the queue length and waiting times of container trucks, caused by traffic peaks; For example, Chen and Yang (2010) suggest the definition of temporal windows for truck arrivals of containers for export, 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, 2009). In particular, the work by Parola and Sciomachen (2009) presents a discrete event simulation model for evaluation of possible improvements to the 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 transfer of road traffic to a high-capacity railway link, on the already existing infrastructure.

Simulation has been used to analyze the accessibility of large ships to terminals and related costs (Sys et al. 2008). Qiang et al. (2017) formulate the operational 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 modeling, 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 required is justified by the achievable performance (Bielli et al. 2006).

This work presents the results of a simulation study, aimed at evaluating the impact of megaships 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 the authors' knowledge, very few simulation studies with this aim have been carried out. We thus focus on all the main operational areas of the container terminal under study: berth, yard, and inland connections.

The remainder of this manuscript 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. In the final section, some conclusions and suggestions for future work are presented.

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 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 modern megacontainerships, 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 draft 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 with the Middle East/India/Far East whose reference market extends from Northwestern Italy to Switzerland and Southern Germany.

The main challenge related to 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 farther than 500 m from the gate, before the containers continue to their final destination. To reach this goal, at least 18 freight trains per day are foreseen, each with length of about 500 m. 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 toward Genoa (50 km) and the other westbound toward France (107 km)

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 show a map of the geographic area where APT-VL is located.

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 only consider the analysis of the terminal performance regarding standard 20′ and 40′ containers arriving at the new platform for inland forwarding).

Fig. 1 Map of geographic area of APT-VL container terminal

The APM-VL project includes a 700-m quay, divided into two parts, one of which will have a depth of 22 m and will be the berth for ultralarge 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 depicts 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 seven rows, where containers are stacked in four-level tiers (Fig. 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 transshipment 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

Fig. 2 Layout of APT-VL container terminal

and unloading times and increasing the potential containerized flow that could be managed.[1]

3 Discrete event simulation model of the terminal

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 analyzes three main components, representing the operational processes of the terminal concerning the quayside, internal area, and 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 drive the simulation experiments.

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

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 modeled in the system, which are the elements flowing throughout the terminal, are the ships and the containers.

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[1] For more information about the terminal, see https://www.portsofgenoa.com/it/terminal-merci/containers/vado.html.
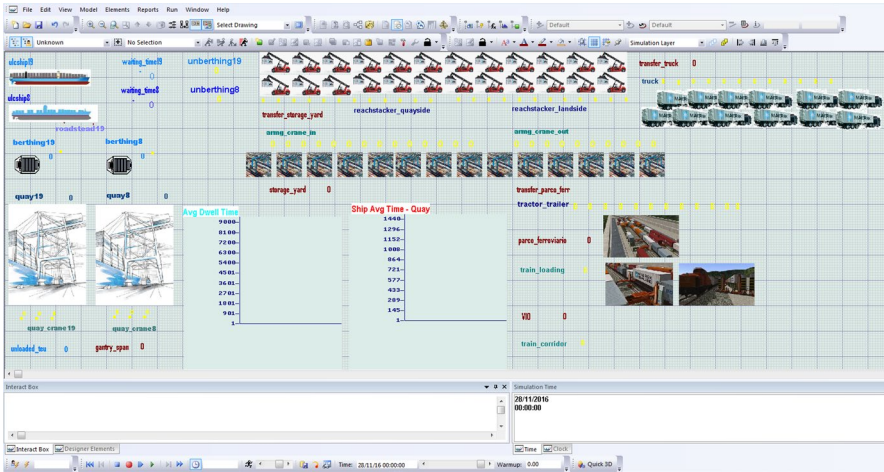
Fig. 3 Layout and main components of simulation model representing the container terminal under study

Buffers are all the zones of the terminal where parts wait to be serviced, such as roads and yards, while machines include all the equipment in 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 8000 TEUs (denoted by LS) and megacontainerships 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 interarrival times of ships are expressed by randomly generated variables, following a negative exponential distribution, with rate $\lambda = 2160$ and $\lambda = 4320$ min in case of LS and MS, respectively; this corresponds to the arrival of a large ship every 1.5 days and a megacontainership every 3 days on average.

Based on the projected data of the APT-VL platform and current ship sizes, two buffers, denoted berth19 and berth8 (according to the maximum ship size), representing the two berths, were created, assuming that the first had a draft of 22 m and a longer quay length, thus being able to receive ships of up to 19,000 TEUs. Instead, berth8 can only accommodate ships up to 8000 TEUs. Therefore, as ships enter the system, they 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 machines berth8/berth19, according to a uniform distribution in [min, max], where min and max correspond to 20% and 30% of the capacity of the ship, viz. 8000 or 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, whereas if it is 1, then it is a 40′ container.

Quayside operations start when the ship is at its assigned berth. At that time, a predefined number of cranes, modeled as machines, are assigned to the ship 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 are defined as batch machines, which take two parts from either berth8 or berth19 and return two parts in output, proceeding to their grounding in a buffer called the gantry span. The service time of the cranes is generated at each occurrence from a negative exponential distribution with mean value $\frac{1}{\lambda} = 2$ min 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 and 45 min, 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 the quayside and landside reach stackers. The quayside reach stackers 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 represent reach stackers by negative exponential variables with average service time $\frac{1}{\lambda} = 4$ min. Instead, the landside reach stackers are created because some of the containers are not transferred to the yard but proceed directly to the terminal gate. The exit rule for these containers complies with the APT-VL terminal policies; that is, 40% of them are sent to the inland terminal by train, while the rest are sent to the transfer terminal by truck. This dispatching rule guarantees the level of performance indicators required by the terminal, which includes a modal split of 60% to road and 40% to rail.

As far as yard operations are concerned, 24 yard cranes are created, having an average service time of 3 min. In particular, 14 cranes pick up the containers from the transfer storage yard and place them in the storage yard. Instead, ten cranes deal with the transport of containers from the yard to the transfer areas, i.e., either the truck transfer area or railway park.

On landside, as regards the exit of the containers from the system, two different machines (trucks and trains) are used, based on the transfer modality of the containers to the hinterland. First, 12 trucks with average service time of 5 min are used. In fact, it had been requested that about 1440 trucks a day will cross the terminal through the reversible lanes of the gate; each truck takes one or two containers at a time from the truck transfer area. Then, the containers leave the terminal. With regard to the exit of containers via train, the tractor trailer is used, which as reported in the project of the APT-VL platform, takes seven 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 30 min.

As mentioned in Sect. 2, in the railway park, the loading of containers onto 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 average service time of 80 min, assuming

Table 1 Ship interarrival times under different scenarios

Interarrival time (min)		
	LS	MS
Scenario I	2160	4320
Scenario II	2160	3600
Scenario III	2160	2880
Scenario IV	1800	2880
Scenario V	1440	2880

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, are created to check the number of outgoing containers via the different transport modes.

4 Analysis of container terminal performance

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

All the simulation runs are performed within the experimental framework of the Witness software environment. We eliminated sampling of the results of the model by considering a warm-up period of 1 month; then, statistics for 1 year of operation of the terminal were collected.

Note that, according to the practice of the APM Terminals group, we consider each 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 h per day; the gate is only closed each week from Saturday 3 p.m. to Sunday 3 p.m.

For validation purposes, we first run the model using the data described in Sect. 3, representing the base scenario (scenario I). Starting from the base scenario, four others were subsequently hypothesized, assuming an increase in the arrival frequency of 19,000 TEU megaships. In this way, we analyze the management of the terminal in the event of so-called mega-peak arrivals. Table 1 presents the interarrival times (in minutes) of the ships in all scenarios. Note that, in scenarios II and III, the number of LS having capacity of 8000 TEUs is kept constant, while an increase of the interarrival times of MS is considered in scenarios II and III, up to a frequency of one ship every 2 days.

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
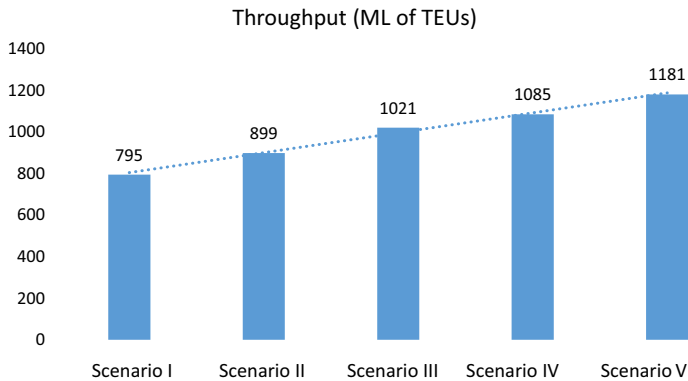
Throughput (ML of TEUs)

Fig. 4 Throughput values of APT-VL terminal in all scenarios

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

Equipment	Scenario I		Scenario V		Δ% improvement	
	No. operations	% Busy	No. operations	% Busy	No. 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

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

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

Instead, in the following scenarios, the increased frequency of ship arrivals results in an increased utilization rate of all types of crane, in line with the increase in the number of operations and in terminal throughput (Fig. 4). These increased values are reported in columns 4 and 5 of Table 2, while columns 6 and 7 show the percentage variation in the number of operations and the utilization rate.
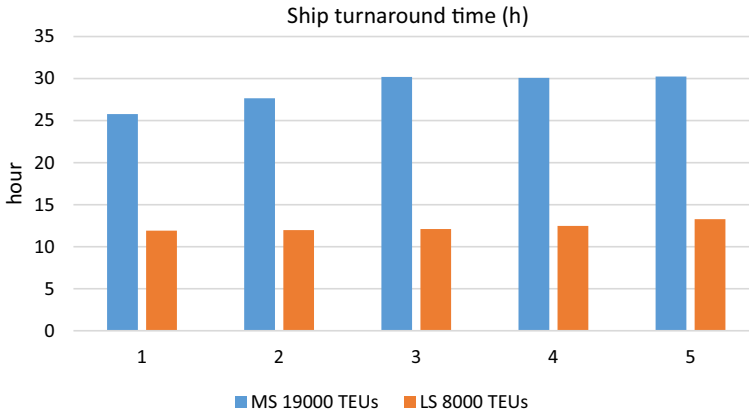
It also emerges that:

Fig. 5 Turnaround times of LS and MS ships

– Investments in efficient quay cranes allow one to manage megaships quickly and to keep an average ship turnaround time of about 1.2 days;
– A higher berth productivity is possible, as the utilization rates of quay and yard cranes are 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, via both road and rail; while values resulting from scenarios IV (one 19,000 TEU ship every 2 days and one 8000 TEU ship every 1.25 days) are still acceptable, the dwell times in scenario V jump to 6 days for rail and 5 days for road, which seem far too longer compared with current terminal productivity standards.

As a further comment on the values reported in Table 2, note 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 is to evaluate the capability of the terminal to manage high volumes of import containers, due to the phenomenon of megaships. 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 occurred; rather, too high a period of inactivity occurs, compared with the performance that this equipment could guarantee.

Also in reference to the performance of the quay, turnaround times of both LS and MS ships are evaluated (Fig. 5). As can be easily inferred from Fig. 5, the resulting 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
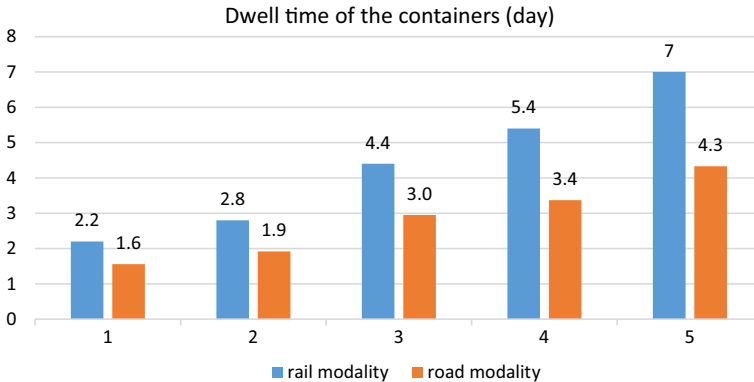
Fig. 6 Dwell times of containers in APT-VL terminal

the terminal, since the average turnaround time of a megaship is about 28 h, i.e., just over 1 day. Therefore, it can be said that, based on our simulation results, the ship turnaround time does not increase significantly as the throughput increases.

However, this is not true with regard to the dwell time of the containers in the terminal. The corresponding value (Fig. 6) is computed by considering the average time spent by the containers in all buffers in the model, viz. the yard and the truck transfer area and railway park, respectively, for the rail and road modalities, assuming a modal split of 40% by rail. In Fig. 6, the dwell times of the containers transported outside the terminal by both truck and rail increase as the throughput increases, that is, with an increase in the arrival frequency of megaships. 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. However, the dwell time obtained in scenario V is longer 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 too high compared with the required productivity standards.

As a final analysis in the present simulation study, we attempt to determine the number of operations performed by the truck machines, which transport one or two containers at a time, 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 are associated with an average fixed cost for their use, set at €2.5 per truck, based on estimates made by the OECD on congestion caused by import containers at 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 with an increase in throughput of around 49%, from scenario I to scenario V.
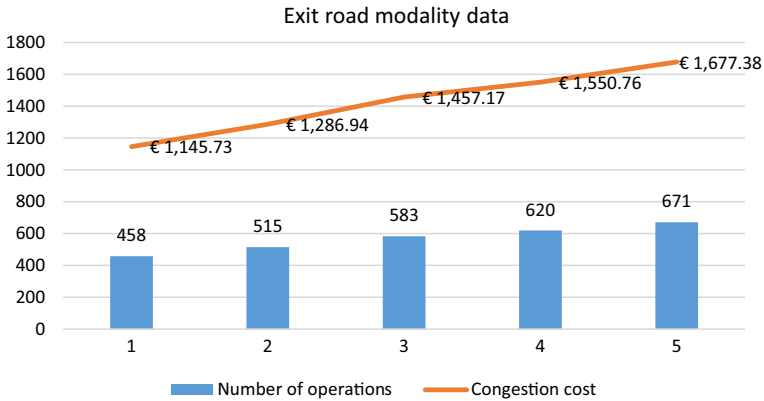
Fig. 7 Number of truck operations and related costs

5 Conclusions

We analyze the impact of megaships on the operational performance of a maritime container terminal. The analyses are performed by developing a discrete event simulation model and successively executing different runs, up to steady-state condition, evaluating five scenarios.

We focus our analysis on a container terminal, still under construction, located in the Region of Liguria. Our aim is to assess possible criticalities due to large-sized containerships, in such a strategic location within the Mediterranean and Reno Alps TEN-T corridor.

The simulation results confirm the estimates made by the owner of the terminal concerning its main performance indices. In particular, it is shown that investments in efficient quay cranes allow fast handling of megaship arrivals, guaranteeing a ship turnaround time of just over 1 day. However, the main critical factors are the hinterland connections, since the dwell times of containers are higher than the desirable value, for both the rail and road modalities.

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