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Full Length Article

The impact of container call size - evidence from simulation modelling

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A R T I C L E I N F O

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A B S T R A C T

We present an analysis of the impact of large container ship call sizes on the operational efficiency of container terminals as well as on hinterland modes of transport. We use standard container terminal simulation software, that can represent a realistic terminal operation. We include dynamic crane productivity, arrival time uncertainty, and deepsea vessel prioritisation in our model.

Our experiments investigate the impact of introducing larger call sizes of container ships, increasing the uncertainty in arrival times of deepsea ships, and the impact of the phenomenon of split calls that are employed by the largest container ships in certain regions in the world. We differentiate between the impact on terminal operations, land-based hinterland traffic, and hinterland traffic over water, through barges and feeder vessels.

Our results show that introducing large ships with large container call sizes comes with benefits and drawbacks. Benefits can be found in planning advantages for both the deepsea ships and barges and feeders handled in the terminal. Drawbacks occur as a result of operational peaks in subsystems such as the quay cranes, the stack and the land side gates. Higher uncertainty deteriorates the performance of the terminal, but the impact on the hinterland modes of transport is greater than on the large deepsea vessels. The impact of the split call is that it brings all the disadvantages of large vessels, but none of the benefits.

Our analysis shows the operational impact of large call sizes on terminal operations and hinterland transport operations, based on container terminal simulations with a higher degree of realism than previous work. In addition, we offer, for the first time, insights in the impact of split calls of container ships at container terminals.

1. Introduction

In recent years, the global container transport system has witnessed major price hikes, serious congestion of containers and ships at terminals, service interruptions such as in the Suez Canal (the Ever Given in March 2021, and Houthi attacks in early 2024), unstable services and very poor service performance. Much of this has been widely publicised not only in the specialised professional press, but also in mainstream media channels such as the Wallstreet Journal and the Financial Times.

Apart from these recent developments, the container shipping industry has also undergone a transition towards ever bigger ships. This development has also, in recent years, bridged the gap between academic literature (e.g. Rodrigue 2020) and mainstream business

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press (see FT 28 March 2021 ‘Too big to sail? The Debate over huge container ships’). This is a development that started with the introduction of the first fully cellular container vessels in the 1970s. While these early vessels could carry between 1000 and 2500 twenty foot equivalent container units (TEU), currently, the largest vessels measure more than 24,000 TEU.

The growth of the capacity of ships mirrors the growth in trade. Trade patterns have changed in volume but not much in terms of structure (see, for instance, Papadopoulos et al. 2023). The same ports and terminals are visited as about 20 years ago, but the numbers of containers loaded and unloaded in a visit have grown substantially. This is referred to in the container industry as the *call size*. Call size and ship size have thus grown in tandem over the years (see Park and Suh 2019, and also, for some industry wisdom, Mooney 2020).

The growth of the size of vessels and the call size have put increasing pressure on the port facilities, i.e. container terminals, to follow this development, and maintain their performance levels (Park and Suh, 2019). Large ships generate revenue at sea, so they demand to be served with priority in terminals, and the turnaround time should be kept as small as possible, to the detriment of other modes of transport that are served by the terminal. While in standard berth allocation problems this prioritization of ships has been studied (see, for instance Yıldırım et al., 2020), the consequences of vessel prioritization in a more integral terminal model, that includes hinterland transport, has not.

We also observe in practice that, in port systems where only a few ports can handle the largest vessels when they are fully loaded, one port will be designated as the main hub. This port will then be visited twice: for an unloading call, and after a journey to the other ports, again for a loading call, to be filled up to maximum capacity. This phenomenon has not been studied at all in the academic literature. We therefore also want to study the impact of this phenomenon of a so-called *split call* in this paper, as it is one of the more extreme results of the increase in container ships and their call sizes.

We perform our analysis in a terminal simulation environment that has proven its value in dozens of terminal design projects around the world. Our approach is based on an approach similar to Meng et al. (2017) with some advancements in terms of the way we deal with ship arrivals, deep sea ship prioritization and the uncertainty in ship arrival measured against an initial berth planning. In our model, we can generate and compare planned and actual arrival times of vessels. This allows us to study (uncertain) out-of-schedule arrivals of vessels and their impact on terminal operations.

This paper contributes to the literature in three ways. We explicitly analyse the effects of call size growth on terminal operations (quay crane operations, stack operations), in an advanced terminal simulation environment where we can model the ship arrival processes in a realistic way. Second, our analysis provides insights in how other modes of transport (feeder transport, barge transport, trucking) are impacted by the call size of ocean ships, and the current practice of offering priority handling to deep sea vessels. As a corollary of these contributions, we shed light, for the very first time, on a particular phenomenon in container shipping and ports that is called the *split call*.

The remainder of this paper is organised as follows. We briefly discuss previous work on the impact of large container ships and call sizes. We then discuss our simulation environment and the choices we have made for our model. This discussion results in the formulation of our research problems. After that, we introduce our base case definition and the experiments we have conducted. We then present our results and offer some conclusions and recommendations.

2. Size development in container shipping

The main enabler for the growth in call sizes at container terminals is the increase in container ship size. The basic economic driver for the continued increase of container ships is the existence of economies of scale at the level of the ship (Cullinane and Kanna 1999). For more recent discussions, see Haralambides (2019), Notteboom (2020) and Ge et al. (2021).

There has been much speculation about the biggest possible container ship size. Some years ago, McKinsey (2017) came out with a report that expects container ships to grow to 50.000 TEU in 2067. Wijnolst (1999) – a relatively early source - postulated that ships would not become larger than about 18,000 TEU (the so-called MalaccaMax). At the time, the largest ship was 6.200 TEU. This argument was made as much on the basis of the navigational limitations of the Malacca Straight around Singapore, as well as on logistical arguments. Some of the work on mega-ships, such as Park and Suh (2019) attempted to estimate the dimensions of, at the time of writing, non-existing, 24–25.000 TEU ships. They conjecture about the problems the increased length of these ships – beyond 400 m – would have on terminal operations. Much of this work has been superseded, however, when the actual 24.000 TUE ship came into use in 2022/2023 with a length overall of just below 400 m.

The International Transport Forum from IFT-OECD (2015) published a report that also puts the economies of scale in shipping in perspective. They outline negative economic impacts of mega-ships such as large infrastructural investments, investments in equipment that needs to keep pace with the bigger ships, and peaks in container traffic in ports. The report states that the introduction of a new large ship imposes costs on various parties in the chain: terminals, hinterland transport operators, port authorities, as well as a broad range of parties that might suffer from higher levels of congestion in the port.

Notteboom (2020), on the other hand, argues that ports and terminals have been remarkably flexible in accommodating larger ships and call sizes, and as a result, have prevented diseconomies of scale to materialize for shipping. Ports and terminal operators have had to invest heavily in cranes, yard space and advanced operating systems. This reasoning explains, to some extent, the development of the *split call* solution, for ships that are too large to be handled in almost all the ports they visit.

Much of the work on container terminals considers individual processes (or limited combinations thereof), and provides little insight in hinterland transport. See, for instance, the enormous body of literature in terminals operations that studies the Berth Allocation Problem (see, for a recent survey, Rodrigues and Agra, 2022). One of the few contributions that takes an integrated view to terminals is Daduna and Stahlbock (2020), who argue that the operational capacity of terminals can only be studied properly if both the sea-side ànd the land-sided networks are taken into account.

Moon and Woo (2014) connect efficient ship operations to efficient port operations, by considering the size of ships as a moderating variable. Their analysis indicates that bigger ships are more sensitive to efficient operations in terminals than smaller ships. In this paper, we are interested in the opposite: How do bigger ships impact the efficiency of terminals? We have already indicated above that we will include prioritization of deepsea vessels in our model. Another way large ships impact terminals, and possibly, hinterland traffic, is by generating uncertainty about their arrival times. This is inspired, among others, by Muñuzuri et al. (2020), who show that the availability of real-time information is essential for efficient operations in intermodal transport chains. We also now, from Veenstra and Harmelink (2021), that ETA information from ships is notoriously unreliable. Our simulation analysis should therefore shed some light on the interaction between deepsea vessels, terminal operations and hinterland transportation when arrival information is uncertain.

Musso and Sciomachen (2020) is one of very few sources that directly look into the impact of large ships or call sizes on terminals. They present a simulation study based on the APM Vado Liguria terminal. This is a (relatively small) 800,000 TEU/700 m quay/6 crane terminal that receives two types of deep sea vessels: 8000 TEU and 19,000 TEU. The largest ship generates a call size of some 5.700 TUE on average. In the simulation, Musso and Sciomachen (ibid) increase the number of 19,000 TEU vessels, while keeping the number of 8000 TEU vessels constant, and observe the impact in the yard and at the truck and rail gates. They observe improvement in utilisation of equipment and berths, but also increasing dwell times for containers, up to 7 days for the rail modality.

A second source is Meng et al. (2017), who develop a queuing and simulation model based on a terminal in Hong Kong to study the impact of mega-ships. This terminal model considers barges, smaller container vessels (feeders) as well as trucking as hinterland modes. The way they structure the ship-terminal system with ship size classes, and various stylised terminal processes, provides a good standard that is very similar to our modelling approach. Their focus is on the terminal operations, while modelling the ship arrivals in a fairly straightforward way: a Poisson arrival process into a queue to wait for a berth.

We extend on the work of Musso and Sciomachen (2020), and Meng et al. (2017) as follows. We present a study of the operational impact of large container ships on terminal performance, where we increase the degree of realism in the ship arrival and berth allocation process by including priority handling of deepsea vessels, and information uncertainty about the arrival of ships, compared to a scheduled arrival process. We employ the same complex model split as in Meng et al. (2017), but use a slightly smaller terminal of 2,5 mln TEU capacity and three berths of 400 m each. This is the standard size of container terminal modules in much of the European container ports, but also more or less the size of the individual development phases of the container terminal operation on, for instance, Yangshan, Shanghai in China, as well as in the TUAS port of Singapore, which are developed in steps of 3 berths at a time.[1]

In contrast to Musso and Sciomachen (2020), we choose to restrict the throughput volume in the terminal. We look at an optimized operation, where some smaller ships are replaced by fewer, bigger ships, keeping the total volume of containers constant. This is reflective of the current situation of limited growth in container traffic in a considerable part of the world. Meng et al. (2017) perform a similar analysis in some of their scenarios. This provides a cleaner look at the operational impact of larger ships and their larger call sizes on terminal operations, and offers a more appropriate perspective on the potential of terminal congestion resulting from the larger call sizes.

3. Simulation model

We are studying the impact of container call size on terminal and hinterland operations. For hinterland transport, we consider feeder transport, inland barging, and road transport. Our model will allow us to study the relationship between ship arrival processes, container operations on the terminal and hinterland transport operations. Transport operations include the arrival, waiting and berthing of all ships (deepsea, feeder and inland barge), as well as an integrated procedure for truck gate operations and loading and unloading.

The use of simulation models to analyse container ship and terminal performance has a considerable history. Since the advent of the large, semi-automated container terminals in ports like Rotterdam, container terminal simulation has been used to verify design decisions and performance expectations. Early contributions go back to the 1970s, see for instance, Dunford (1972). Extensive literature reviews are available in Angeloudis and Bell (2011) and Dragovic et al. (2017).

In all this literature, a container terminal has the basic structure as depicted in Fig. 1.

The quay side of the terminal contains processes such as ship arrival and quay crane operations. A standard terminal model then consists of a transfer system for containers from the quay cranes to the stack, and vice versa. In modern terminals, this would be done by automated guided vehicles, but other equipment such as terminal trucks or straddle carriers are also used. The yard, or stack, is a storage space for containers, that can be stacked up to 4 layers or higher. Then there is another transfer system to the land side gates and loading onto trains or trucks.

In our analysis, we use the terminal simulation model TRAFALQUAR, that was developed by TBA Consultancy, and currently exploited in its terminal advisory branch Portwise.[2] For more information on TRAFALQUAR and its simulation engine, see Saanen (2020) and de Waal and Saanen (2016). The model is very similar to the simulation model used in Meng et al. (2017), in terms of the level of abstraction, and the way different sizes of ships are included.

TRAFALQUAR is a strategic terminal simulation platform that models ship arrivals, berth allocation, and quay crane assignment. It

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[1] https://www.mot.gov.sg/news/press-releases/Details/enhancing-singapore-s-connectivity-securing-our-future

[2] See portwiseconsultancy.com

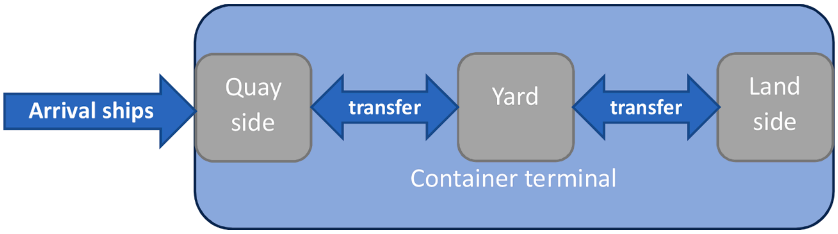

Fig. 1. Generic model of container terminal operations.

can deal with a mix of ship sizes arriving at its berth. This means that both deep sea, short sea and barge traffic can be included in the analysis. In addition, on the land side, both truck and train operations can be included. Given the strategic level of this model, operations in the stack, as well as quay to stack transport are not modelled in detail. Container dwell time in the stack is the result of design choices in the model. TRAFALQUAR allows us to model a terminal at a general level, without the need to make very specific equipment choices. For our purpose that is sufficient. We just need to specify assumptions on the duration and variation of certain processes to represent the time they take in the terminal. These processes will be represented by simplified triangular distributions, as is common in terminal simulation (see, for instance, Meng et al. 2017)

We model the ship arrival process by generating an initial arrival planning based on a variety of ship sizes. These ships come with a call size for loading and unloading, assigned cranes and a berthing location. In our ship size choice, we can also introduce very large ships with large call sizes. The planning assigns an estimated time of arrival (ETA) to each ship. The ships arrive at a so-called anchorage point, where they either wait for a berth, or proceed to the berth directly. This is in line with the way the standard berth allocation problem is modelled. In our model, however, we do not follow the regular first-in-first-out principle, but we allow deepsea vessels to ‘jump the queue’. Waiting time is the difference between the time of arrival at the anchorage point, and the berthing time, adjusted for the nominal time it takes to sail from the anchorage point to the berth.

We can also introduce uncertainty in the actual arrival of ships by adding a so-called ETA-deviation to each planned arrival. This is a standard triangular distribution around an average delay which can make this ship arrive late but also a little early. We will specify the parameters of this distribution below. We can influence the shape of the cumulative distribution of the ETA-deviation distribution in order to obtain a realistic differentiation of arrival time deviations across vessels.

This sophisticated arrival process results in realistic operational consequences in terms of waiting time for ships to berth, increasing waiting times for already waiting ships because of prioritization of deep sea vessels, shifting ships to other berths, and assigning a different number of quay cranes than expected. All these measures will allow us to record inefficiencies caused by the arrival pattern of deepsea ships on the operations of the terminal and the other modes of transport. The model also calculates berth occupancy, crane deployment and workload, stack occupancy and the utilisation rates of the truck gate. For simplicity, we did not include an active train operation in our model.

We have specified a generic terminal model, partly for simplicity reasons, but also partly to avoid reference to any specific container terminal. We have designed a terminal that can handle 2,5mln TEU per year in deepsea and feeder traffic. This standard, but realistic, terminal has a quay of 1200 m, which allows the berthing of three of the largest deepsea vessels at the same time. The hinterland modal split is 480,000 teu barge, 230,000 TEU feeder and the remainder truck traffic. On a weekly basis this translates into 30 barges, 4 feeders and 12 deepsea vessels of ‘normal’ call size that equals 5500 box moves per vessel. A large call would represent 8500 box moves per vessel. In this case, there would be only 7 deep sea vessels per week.

4. Benchmark simulation and experimental design

In this paper, we address three research problems. The first is that we aim to investigate the impact of introducing larger call sizes on terminal and hinterland operations. Within this context we also investigate the possible impact of uncertainty of information on the arrival of deepsea vessels. As a third research problem, we want to look at the phenomenon of split calls, which is a particular feature in the operation of large container ships. For this last topic, there is no previous literature at all. All our initial insights are therefore based on discussions with practitioners at large container terminals.

Our main approach in the simulation study is to compare a benchmark scenario with various scenarios in which we introduce larger deepsea vessels with larger call sizes. The benchmark model works on the basis of a planning for 12 deepsea vessels of varying size in classes DS1, 2, 3 and 4. These are ships with call sizes that vary from 1500 boxes to 5500 boxes per call. Two additional size classes represent barges and feeders. Their numbers, in the weekly planning, are 30 and 4, respectively. All ships come with a planned number of cranes they need to have deployed to achieve their target service level, and a designated berthing location. Deepsea vessels get priority when they arrive. We employ a maximum of 12 quay cranes with dynamic productivity. This means that the crane performance deteriorates with the number of cranes deployed, as follows: 1 to 8 cranes-100 %/9 cranes – 97 %/10 cr. – 94 %/11 cr. – 91 %/12 cr. – 88 %. Note that this is a bit more complex than the modelling of performance uncertainty in individual cranes, such as in Meng et al. (2017). In the base case, we introduce a mild deviation from the recorded estimated time of arrival of the vessel which follows a logistic distribution, where up to 20 % of vessels may arrive 6–12 h early, 65 % for deep sea ships and 75 % for feeders and barges arrive up to 24 h late, and the remainder may arrive more than 24 h late. These are realistic settings based on the pre-covid performance of container vessels (see, for instance, the container carrier service performance tracking by shipping consultant Drewry). We set an average dwell time in the stack of 7 days, with a maximum of 14 days. The total size of the stack of this terminal is in principle unrestricted. We run the simulation for 52 consecutive weeks. In the remainder of this discussion, we will refer to boxes and not containers to avoid confusion over the possibility that a container could be a 20 ft or 40 ft box. We will use the term *box* throughout.

This benchmark simulation generates the following results.

In Table 1, the first three percentages indicate for how many ships the waiting time exceeded 8 h: for deep sea vessels only 4 %, and for feeders and barges 25 % and 21 %, respectively. This difference is the result of our prioritization of deepsea vessels. The average berth occupancy means that the berths are in use 63 % of the time. Crane peak deployment is measured as the share of the time more than 10 cranes are employed. In the base case this is 30 % of the time. A balanced workload is the active use of 5 to 10 cranes. This occurs 49 % of the time. We measure peak storage volumes in the stack as the maximum number of boxes in the stack. This was 28,180 in the base case. For the peak load at the trucking gate, we look at the 98 % busiest day threshold. This provides a slightly more realistic measure for gate peak load than the absolute largest number. This KPI, 2170 boxes, means that in 2 % of the days in our simulation, the load at the trucking gate was higher than 2170 boxes. We measure the deviation of cranes per shift in the absolute difference between the initial planned number of cranes, and the actual number of cranes employed when the vessel berths. This is 2.25 in our benchmark case. Similarly, we record the maximum absolute difference between planned and actual number of cranes. This number is 4 in this benchmark. Finally, since we have an initial planned berthing location in our planning, we calculate the distance between that berthing location and the actual berthing location where the ship is eventually moored. This difference is 226 m. These last three indicators illustrate inefficiencies in the operation of the terminal due to the way it receives and treats vessels.

As our **first experiment**, we will compare the base case with a scenario where we replace 5 deepsea vessels with three very large vessels: two with a call size of 6500 boxes and one with a call size of 8500 boxes.

Our expectation is that these large call sizes will reduce the operational performance of the terminal, because the terminal will have to process more boxes with its quay cranes and in its stack, and this will result in tighter availability of resources, and more peaks.

As a **second experiment**, we look at the impact of uncertainty in the arrival information of vessels. We introduce a significant increase in the ETA uncertainty of deepsea vessels: a doubling of the uncertainty to 48 h for a significant set of vessels, and an extreme scenario of possible delay up to 5 days. These scenarios are based on experiences during Covid, when such delays were actually witnessed in practice.[3]

Our expectation is that this will result in significant performance loss for the terminal, but also for the other, smaller, ships that the terminal serves. The uncertainty in the planned arrival of the large deepsea vessels is expected to result in higher waiting times for all vessels and deviations in crane assignments and berth locations.

Finally, as our third experiment, we look at the so-called split call. This is a phenomenon where the very large vessels visit a key port in a certain region twice: first to off-load a considerable number of containers, after which the vessel will do a tour to some other ports that are not as easily accessible. The second call, at the end of this tour is then a loading call, where the ship is loaded to maximum capacity before commencing its inter-continental journey. We implement this by splitting a large vessel in the planning into to sub-vessels, each with half the call size. This means that the arrival uncertainty of this ship is also increased: the second arrival is again uncertain. We look at the impact of only one vessel per week with a split call, and two vessels per week with a split call.

This split call phenomenon has not been studied yet. We therefore have only anecdotal evidence of its possible impact: it is again expected to reduce the performance of the terminal, because one-directional calls are generally less efficient than combined unloading and loading calls.

5. Results

5.1. Experiment 1: large call sizes

We present the results for the first experiment: the introduction of large ships with large call sizes. The base case outcome is represented in the column 'Benchmark Measures'. See the results in Table 2.

We observe that the outcome of this experiment is mixed: some elements of the performance improve as the result of larger call sizes, and some do not. In particular, the waiting time for the various ship types all improve: for deepsea and feeder vessels the percentage waiting time larger than 8 h is more than halved. We attribute this to the fact that planning is in fact easier when the units (ships, calls) in the planning are large. Around the large blocks in the planning, plenty of small gaps remain where feeders and barges would fit. The berth occupancy and berth deviation problems also improve with large call size, because vessels can berth closer to their planned locations.

What does not improve is the peaks in the stack, at the truck gates, and in the quay crane deployment. Also deteriorating are the deviations in crane assignments, and the quay crane balanced workload: the terminal works more often with a high number of deployed cranes (peak deployment is higher) and less often with an average number of cranes (balanced workload is lower).

In other words: handling larger vessels has some advantages for both shipping company and terminal. At the same time, it creates peaks in the workload in various subsystems. We observe that this outcome is in line with the discussion in the industry, where shipping lines nor terminals complain about the large call sizes. The complaints come from other transport operators (barge operators,

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[3] https://www.marineinsight.com/maritime-law/causes-and-consequences-of-vessel-delays-in-container-shipping/

Table 1
Benchmark performance results.

KPI	Measure	Remark
Deep sea vessel waiting time	4 %	Waiting time exceeding 8 hrs
Feeder vessel waiting time	25 %	Waiting time exceeding 8 hrs
Barge vessel waiting time	21 %	Waiting time exceeding 8 hrs
Average berth occupancy	63 %	
Quay crane peak deployment	30 %	%of time >10 cranes active
Quay crane balanced workload	49 %	%of time 5–10 cranes in operation
Peak storage occupancy	28,180 bx	
Peak gate workload	2170 bx/day	98 % busiest day threshold
Average deviation of required vs planned number of crane per shift	2.25	
Maximum deviation of required vs planned number of cranes per shift	4	
Average deviation planned berth position	226m	

Results based on benchmark simulation run in TRAFALQUAR terminal simulator.
‘hrs’ stands for hours; ‘bx’ stands for box (referring to a container); ‘m’ stands for metre.

Table 2
Results experiment 1.

KPI	Experiment 1 results ‘large call size’	Benchmark Measures	Gap
Deep sea vessel waiting time	1 %	4 %	↑
Feeder vessel waiting time	8 %	25 %	↑
Barge vessel waiting time	14 %	21 %	↑
Average berth occupancy	56 %	63 %	↑
Quay crane peak deployment	36 %	30 %	↓
Quay crane balanced workload	37 %	49 %	↓
Peak storage occupancy	28,540 bx	28,180 bx	↓
Peak gate workload	2,220bx/day	2170 bx/day	↓
Average deviation of required vs planned number of crane per shift	2.36	2.25	↓
Maximum deviation of required vs planned number of cranes per shift	6	4	↓
Average deviation planned berth position	154 m	226 m	↑

Results based on benchmark simulation run in TRAFALQUAR terminal simulator.
‘hrs’ stands for hours; ‘bx’ stands for box (referring to a container); ‘m’ stands for metre; ↑ means an improvement, ↓ means a reduction.

trucking companies) and shippers, because they are impacted by the peak loads in cranes and gates.

5.2. *Experiment 2: increased ETA uncertainty*

Fig. 2 represents the various ETA distributions we have used in our analysis of this experiment.

Observe in this figure that we distinguish different distributions: the two left-most distributions were employed in the benchmark simulation, for feeders/barges and deepsea vessels, respectively. The two distributions on the right hand side are the two alternative scenarios for arrival uncertainty that represent a large deviation (double the deviation in the benchmark case) and an extreme deviation of up to five days (120 h).

In Table 3, we present the results of the experiment, both for the base case and the large call size simulation. The ETA deviation experiment should be compared to the base case, and the ETA deviation for large call sizes, against the benchmark results of the large call size.

From these results, we conclude that uncertainty in the ETA of ships generally increases waiting times for all ships. The waiting times for feeders and barges run up faster for the larger call size. This means that the situation with very large ships and large call sizes is more sensitive to ETA uncertainty. This confirms the findings in Moon and Woo (2014). For the more extreme ETA uncertainty, the waiting times and other performance indicators also deteriorate, but not proportionally. Apparently, if the uncertainty is already large, an even larger uncertainty is not going to lead to much more performance loss. We take this to mean that it is useful to not only prevent large ETA uncertainty, but to aim for any improvement that can be realised. Relatively small uncertainties can already result in considerable negative operational impact.

5.3. *Experiment 3: split calls*

In this third experiment, we distinguish between one split call and two split calls. We perform this experiment in the large call size scenario. The option with two split calls allows us to verify if more split calls results in a more pronounced effect or not. In a split call, a large deepsea vessel is planned twice, with related calls: one primarily for unloading and one primarily for loading. Both ship arrivals are uncertain. Deepsea vessels still have priority when they arrive. Observe the simulation results in Table 4.

Observe from the results that a single split call increases waiting time compared to the large call size outcome for both feeders and barges, but not for deepsea vessels. Looking at the terminal efficiency related KPIs (crane deployment, berth deviation, and so on),

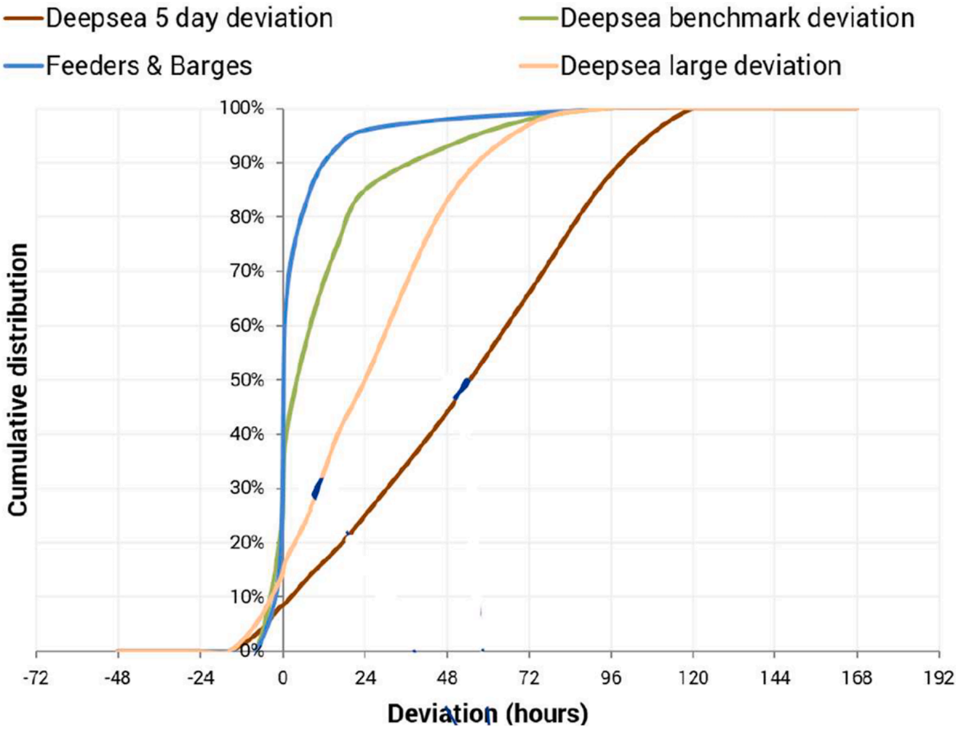

Fig. 2. Estimated time of arrival deviation distributions.

Table 3
Results experiment 2.

				Benchmark Measures	
KPI	Extreme ETA deviation large call size	ETA deviation large call size	ETA deviation benchmark	Results 'large call size'	Base case
Deep sea vessel waiting time	8 %	4 %	7 %	1 %	4 %
Feeder vessel waiting time	18 %	16 %	35 %	8 %	25 %
Barge vessel waiting time	27 %	23 %	30 %	14 %	21 %
Average berth occupancy	58 %	58 %	64 %	56 %	63 %
Quay crane peak deployment	40 %	40 %	33 %	36 %	30 %
Quay crane balanced workload	29 %	30 %	42 %	37 %	49 %
Peak storage occupancy	28,500 bx	28,500 bx	28,150 bx	28,540 bx	28,180 bx
Peak gate workload	2370 bx/day	2280 bx/day	2210 bx/day	2220 bx/day	2170 bx/day
Average deviation of required vs planned number of crane per shift	3.22	3.19	2.48	2.36	2.25
Maximum deviation of required vs planned number of cranes per shift	7	7	6	6	4
Average deviation planned berth position	235m	209m	256m	154m	226m

Results based on benchmark simulation run in TRAFALQUAR terminal simulator.
'hrs' stands for hours; 'bx' stands for box (referring to a container); 'm' stands for metre.

there is limited effect on terminal performance.

If we look at the situation with two split calls, we notice that again waiting times are increased, but now for all vessels. Performance of the terminal, for instance the peak storage occupancy and the deviation in the number cranes deployed, now also worsens considerably. We attribute this to the increased uncertainty of the two connected vessel calls. We already knew from experiment 2 that uncertainty reduces the performance of the terminal. With split calls this is also the case.

The waiting time outcomes of the two split calls looks similar to the benchmark outcome that has no large call sizes (apart perhaps from the feeder waiting times). At the same time the drawbacks in terms of peaks in the yard, crane deployment and gate remain. Our simulation experiment shows that split calls result in all of the drawbacks of large call sizes, but do not offer any of the benefits we identified in experiment 1. Split calls, as a final consequence of the large ships with their large call sizes, is therefore not a good development for terminals and other, hinterland, transport modes.

Table 4
Results experiment 3.

KPI	2 Split Calls	1 Split call	Results 'large call size'	Benchmark Measures
Deep sea vessel waiting time	3 %	1 %	1 %	4 %
Feeder vessel waiting time	15 %	12 %	8 %	25 %
Barge vessel waiting time	20 %	17 %	14 %	21 %
Average berth occupancy	59 %	57 %	56 %	63 %
Quay crane peak deployment	36 %	35 %	36 %	30 %
Quay crane balanced workload	36 %	38 %	37 %	49 %
Peak storage occupancy	29,600 bx	28,700 bx	28,540 bx	28,180 bx
Peak gate workload	2260 bx/day	2220 bx/day	2220 bx/day	2170 bx/day
Average deviation of required vs planned number of cranes per shift	2.56	2.49	2.36	2.25
Maximum deviation of required vs planned number of cranes per shift	6	5	6	4
Average deviation planned berth position	189m	170m	154m	226m

Results based on benchmark simulation run in TRAFALQUAR terminal simulator.
'hrs' stands for hours; 'bx' stands for box (referring to a container); 'm' stands for metre.

5.4. Conclusions and recommendations

Our analysis sheds light on the impact of container vessels with large call sizes on terminal operations. We run a simulation study on a generic container terminal model, which is driven by a weekly planning of ship arrivals, and that can take into account deepsea vessel priority policies, uncertainty in the arrival information and split vessel calls at the terminal. We look at the impact in an integral way, combining terminal and hinterland operations.

Our experiments show that introducing vessels with large call sizes has both positive and negative effects. A planning with some larger vessels is 'easier' resulting in lower waiting times for all vessels, but the larger calls result in peaks in all the operational subsystems of the terminal: quay cranes, yard and landside gate.

The second experiment concerns the impact of arrival time uncertainty. Our results show that this uncertainty increases the waiting times for all vessels but deepsea vessels are the least hit. This is caused by our prioritisation policy that offers direct service to deepsea vessels as soon as a location is available, just as this is done in reality. Our results also show that small uncertainties in arrival estimates already result in considerable performance losses. These results provide insight in how uncertainty, essentially created by the deepsea vessels, impacts the other ship types handled at the quay, as well as the land traffic. While, from a logistics point of view, the terminal is a decoupling point in the container chain, our results also make clear that the terminal functions as a conduit for uncertainty from one transport mode to another.

The third experiment shows that the impact of split calls are similar to the results of the arrival time uncertainty. Especially for a situation with more than one split call, waiting times for all vessels increase. In fact, in the case of two split calls in the large call scenario, we obtain results where the benefits of having large call sizes (lower waiting times for all vessels) disappear, while all the drawbacks remain. We therefore conclude that split calls are not only a negative phenomenon for the terminal, but also for the other transport modes that are facilitated by the terminal.

In terms of recommendations for further research, we suggest, as a next step, to model a real terminal operation, based on actual data. While we have shown the existence of the mechanisms, this would provide actual measures of the negative impact of the largest deepsea container vessels in ports around the world.

Our results are relevant for the various parties involved in international container transport chains, since they show how the operational behaviour of one party impacts the performance of other parties. Our analysis shows that local port related business ecosystems will not be able to solve congestion problems in their ports by themselves, without including the deepsea shipping companies in their approach. Eventually, these businesses need to reconsider split calls as an operational model, as well as the strict prioritization of deepsea vessels to the detriment of all other parties in the port ecosystem. Finally, our results also provide a further justification of the so-called Just-In-Time programme of the International Maritime Organization. Implementing this programme might reduce the impact of arrival prioritization of deepsea vessels and thus reduce the negative impact on terminal operations and hinterland modes.

CRediT authorship contribution statement

Albert Veenstra: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Arjen de Waal:** Writing – review & editing, Visualization, Validation, Supervision, Software, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Co-author Arjen de Waal is employed by the terminal consultancy and simulation company Portwise that developed the simulation software for the work in this paper. The work for this paper was part of a larger project, for which partial funding was provided by the Dutch Topsector Logistics, the Convergence Program of the Erasmus University Rotterdam and Technical University

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