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Network Capacity Estimation of Vessel Traffic: An Approach for Port Planning

Xavier Bellsolà Olba¹; Winnie Daamen²; Tiedo Vellinga³; and Serge P. Hoogendoorn⁴

Abstract: Port capacity is an essential parameter for the assessment of port performance. In the literature, there is no unanimous capacity definition, which depends on each research goal. Vessel traffic in ports and the corresponding port performance indicators have been analyzed with different simulation models, but they generally do not include a method for determining a port's capacity. Guidelines or other studies using empirical data also have not addressed this important topic. The method developed in this paper estimates the port network traffic capacity (PNTC) by using vessel traffic data. The analysis and comparison of several indicators are used to identify meaningful relationships for estimating port capacity with generic applicability to any port design. The relation between the total number of trips in the port and the ratio of waiting time to service time seems to be the most suitable for identifying when the port reaches unstable flow situations, that is, when it reaches capacity. The method has been applied successfully in six scenarios with various berths, layouts, service times, vessel fleet types, and maneuvering times. Application of the method is useful during the port-planning phase, because with a few simulations, an indicative PNTC value for each design can be inferred, and thus, different scenarios can be compared. DOI: [10.1061/\(ASCE\)WW.1943-5460.0000400](https://doi.org/10.1061/(ASCE)WW.1943-5460.0000400). This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <http://creativecommons.org/licenses/by/4.0/>.

Author keywords: Network capacity; Port performance; Vessel traffic; Simulation model.

Introduction

World globalization and containerization have led to a significant increase in vessel traffic in most of the commercial ports around the world. Therefore, ports face growing demand for vessels and cargo handling that might lead to traffic congestion. The evaluation of port performance becomes more relevant for the efficient development of the whole maritime supply chain. Because of the growth in the numbers and sizes of vessels, traffic congestion can occur in some ports such that the port's capacity is a key indicator for identifying loss times or delays. Although port productivity is usually determined by terminal operations, port efficiency can be reduced by vessel traffic congestion.

Previous research focused on specific activities in a port, such as the ship arrival (Van Asperen et al. 2003), the ship–berth interaction (Dragović et al. 2006), and the anchorage (Huang et al. 2011). Moreover, extensive research on terminal operations

assessment and optimization has been conducted (Daganzo 1989; Stahlbock and Voß 2007), and specific research has studied the individual sailing behavior of ships in ports (Shu et al. 2013).

Port network capacity is a valuable indicator for port planning during the design of new ports or terminals and during the expansion of existing ones. Recently, a new method for estimating capacity of a port network was developed by Bellsolà Olba et al. (2015), called the *port network traffic capacity* (PNTC). The goal of this paper was to develop the PNTC estimation method on the basis of previous research that introduced this method (Bellsolà Olba et al. 2015) but did not present an accurate method for clearly identifying the PNTC value. Therefore, the PNTC value estimated was subjective, and this paper provides a detailed explanation of the way the method was developed and is applied in a generic way. By using a simulation model, a variety of scenarios, including extreme situations, are generated, and the results of each simulation provide a single representative value for a specific configuration (fleet composition, port infrastructure layout, etc.), while the underlying computation method provides insight into the critical port processes for estimating the PNTC. Any simulation model, or real vessel traffic data, could be used with the indicators introduced in the following sections to estimate the PNTC. This method allows the estimation of the capacity in any port network design, and the estimated value is useful for port planning because it can be used to compare the results of different designs or measures in relation to the maximum vessel flow.

This paper is divided into six sections. In the next section, port performance indicators from literature are presented. The third section describes the methodology used in this paper, including the indicators, the development of the PNTC estimation method, and the conceptual network-capacity model. The experimental setup is presented in the fourth section. The fifth section describes the setup, model, and results of the simulation. The last section presents conclusions and suggestions for future research.

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Literature Overview

The literature reveals an extensive variety of definitions for port capacity according to the way the definitions are used, such as terminal capacity (Ligteringen and Velsink 2012) and bottleneck approach (Fan and Cao 2000). In addition, many of the proposed indicators are not generic and have severe limitations in terms of their applicability. For example, the bottleneck approach defines port capacity on the basis of the most critical element of the network. However, there can be specific port networks that do not reach capacity despite having a critical bottleneck.

Despite the existence of these definitions, the port capacity definition considered in this research for a port network was recently proposed as “the maximum average vessel flow that can be handled by a port, with its specific infrastructure layout, vessel fleet, traffic composition and demand, satisfying the required safety and service level” (Bellsolà Olba et al. 2015, p. 45).

Past literature has not addressed the capacity of a port. However, there is research on how to evaluate port performance. Hence, the most relevant indicators related to port performance and some background information is summarized in this section.

Port performance and efficiency can be measured with financial and operational indicators, which have been extensively used for many years. For research purposes, like the previous research developed by Bellsolà Olba et al. (2015), the focus is on the operational level, and the most relevant indicators are presented in this section.

An early study assessed port performance based on traffic engineering with the following indicators: degree of occupancy (percentage of time that the total number of berths is occupied, recently called *berth occupancy*) and the degree of congestion (percentage of time that the number of ships exceeds the number of berths available) (Nicolaou 1967). The use of these indicators has some drawbacks. The degree of occupancy does not indicate how the occupancy is split; for example, the results would be the same whether one-half the berths were occupied during a certain period or all of them were occupied for one-half the time during the same period. Hence, this indicator alone does not provide enough information. Because the degree of congestion is dependent on the length of the port infrastructure, ports with longer waterways require more sailing time, and this indicator becomes higher without having a higher flow.

There are other indicators used for port efficiency. Researchers recently approached this topic by using the average turnaround time (Ducruet et al. 2014), which is the time spent by each vessel when performing all the operations inside the port (entering, berthing, loading and unloading, and departing). Although this indicator is a proper indicator for port performance, it will not be applied in this research because its main variations are caused by the terminal service time (the larger time). For the purposes of this study, the turnaround time would not be sufficiently representative because the sailing time is a small part of the total turnaround time.

Other research presented several operational indicators directly related to productivity and to the operational performance of a port, such as the previous turnaround time, and others, such as waiting and service times (UNCTAD 1985). One of the most appropriate measures of the level of service of the port, quality of traffic service, is the ratio of waiting time of vessels to the total service time at the terminal, which has been shown to be below 30% (UNCTAD 1985). In reality, this factor will be conditional on the basis of specific rules and costs assigned to the waiting time, and according to port experts, the value should be below 20% (UNCTAD 2012). The information that this indicator alone provides can lead to an incorrect interpretation, because an

increase in the terminal service time results in a lower ratio without any performance improvement.

Many other indicators related to port throughput could be considered, such as tons per gang hour. However, their application is useful for assessing the terminal performance, and they do not contribute to the assessment of the vessel traffic performance in a port. Because none of the existing metrics are satisfactory, in this study, a new metric was developed and tested for robustness using simulation.

Port networks have not been analyzed from an aggregate point of view in terms of traffic. There is extensive research for road networks, and because there are similarities between port and road networks, similar approaches could be applied to create the new metric. Recent work on roads developed the concept of macroscopic or network fundamental diagram (MFD and NFD, respectively) (Geroliminis and Daganzo 2008; Keyvan-Ekbatani et al. 2012), where the relation between the total flow and the average density allows for identification of different traffic states. In the case of a traffic jam, the flow decreases with the density increase; however, this would not happen in a port because traffic regulations at the entrance prevent vessels from being queued inside the port. According to a concept similar to perimeter control in roads, the load on the waterway network is reduced, such that it will not exceed the capacity, so no congestion will occur in the port. However, the uncongested regime of the NFD could be related to unsaturated port operations. On the basis of the successful results in road traffic, analogous relations between port performance indicators were analyzed in this paper, exploring the possibilities for building and improving the previous PNTC estimation method (Bellsolà Olba et al. 2015).

Methodology

This section presents the indicators chosen to develop the method, describes the steps of the PNTC estimation method, and explains the conceptual network-capacity model.

Indicators

The indicators considered relevant to combine for estimating capacity on the basis of literature overview presented are

- Waiting time to service time ratio (WT/ST), considering the entire port including sailing time, describes the degree of port efficiency;
- Total trips (TTs), the average number of trips that vessels complete within a time interval, gives a reference for the vessel flow (entering or exiting the port is considered as one trip each, while each trip between terminals is considered another trip); and
- Berth occupancy (BO), the percentage of time that the total number of berths is occupied.

PNTC Estimation Method

A generic method to estimate PNTC was recently presented by Bellsolà Olba et al. (2015) and has proven applicable in different port setups and sailing characteristics with similar outcomes. As previously introduced, the previous research addressing this topic (Bellsolà Olba et al. 2015) did not define a PNTC value, which was subjective to the user interpretation. In this section, a comprehensive and detailed explanation of the PNTC estimation method is presented. The application of the method depends on the availability of a port simulation model or a data set from a port with traffic congestion that allows the calculation of the desired indicators. The different steps of the method are presented as follows:

- Calculate the indicators WT/ST, total trips (vessels per day), and berth occupancy.

- Set the values to define the desired port design and characteristics, such as infrastructure layout, terminals, service times, safety measures, and traffic rules.
- Estimate a demand interval to come up with a range of values for WT/ST and berth occupancy. To obtain values between 0 and (at least) 1.5 for the first indicator and between 0.25 and (at least) 0.80 for the second one, the authors recommend that the capacity from the relation between the two indicators be clearly defined.
- Run a sufficient number of simulations with different demands until values with stable and unstable conditions are obtained. These values are used as minimum and maximum demands.
- Find the average value of the maximum total trips, based on the WT/ST values greater than 1, to determine the PNTC value.
- The graphical representation of total trips versus WT/ST, and the exponential fitting, should lead to the graphical representation of the estimated curve, for which the limit value is the PNTC.
- Applying a reduction coefficient of 0.9 to the PNTC value, an acceptable flow for a specific port design can be obtained, and it can be used for the evaluation of port performance and for comparisons to other designs.

Conceptual Network Capacity Model

A conceptual capacity model is presented in Fig. 1. The capacity-influencing factors are directly linked to capacity and to each other. The macroscopic vessel flow is determined by the microscopic vessel behavior, which in turn, is determined by the different factors influencing the microscopic behavior.

As shown in Fig. 1, the indicators depend on the specific setup in each case, such as infrastructure design, fleet composition, and so forth, and on specific demand. The total number of trips (vessels/

day) has a close relationship with capacity, and it is one of the outputs from the simulation model. Although the outflow of the port was used in previous research (Bellsolà Olba et al. 2015), when trips between terminals are considered, the outflow indicator misses the effects of having interterminal trips; thus, it loses meaningfulness. The berth occupancy factor does not allow the identification of the location of the occupancy. Although it is not useful for drawing conclusions about certain problems in a port network, together with WT/ST this indicator is useful for an aggregate analysis of a network or for comparing different scenarios/.

From the combination of indicators and network capacity, some relationships are expected. An increase in demand might lead to different variations in the indicators. For example, this increase can lead to higher TT and BO values with the same or slightly higher WT/ST. This means that TTs and BO are improving, and the port was operating below capacity under the previous demand-level scenario. In an alternative situation, an increase in demand leads to a small increase in TTs and a moderate increase in WT/ST while BO decreases or remains the same. This situation might be the consequence of traffic congestion caused by limited wet infrastructure capacity. Because they find restrictions in the waterways, vessels are not able to reach the berths as expected and the BO decreases. Another possible scenario would emerge in which there is a limitation in the terminals. An increase in demand would not affect the BO (it would remain close to the maximum value for this configuration) while WT/ST would increase moderately and the TTs would not have a remarkable difference.

In this research, changes in the terminals and some parts of the wet infrastructure (layout) will help in identifying and assessing the effects on the network-traffic indicators and the applicability of the PNTC-estimation method in any port design. Because of their main influence in vessel traffic inside a port, several control variables were used in this research. In relation to the terminals, the service times and number of berths were changed for different

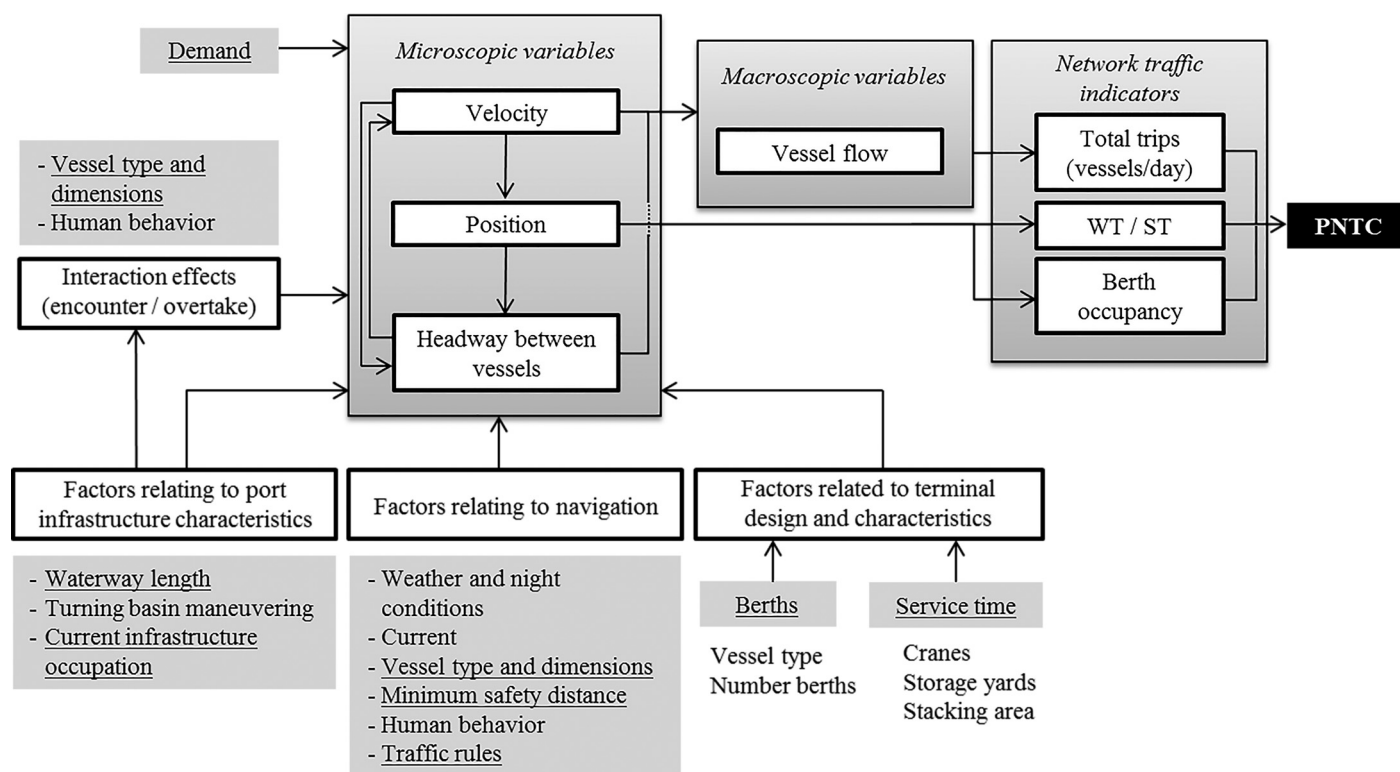


Fig. 1. PNTC conceptual model (Note: Factors underlined are included in the model) (adapted from Bellsolà Olba et al. 2015)

scenarios. With respect to the wet infrastructure, the lengths of the waterways and the maneuvering times in the turning basins were changed. The simulation setup presents all these possibilities.

Experimental Setup

This section describes the experimental setup used to validate the method. The first subsection presents the conceptual capacity model and indicators considered in the PNTC-estimation method. The subsequent two subsections present an overview of the port infrastructure layout considered and the data used for setting up each scenario.

Layout

The schematic of the port layout defined in the model used to simulate the different scenarios is presented in Fig. 2. It is the same one previously used by Bellsolà Olba et al. (2015). The infrastructure layout chosen includes the main parts of all port designs. There are several waterways and terminals as well as some turning basins and terminals. Any of these might become the bottleneck or otherwise influence vessel flows. The layout represents a complete port network infrastructure.

The port wet infrastructure is made up of an approach channel (L4) with a turning basin (B1), where vessels are separated. The vessels destined for Terminal 1 use the waterway L1, and the others continue through waterway L5. At the end of this waterway, there is a second turning basin (B2) that connects with two waterways. Vessels destined for Terminal 2 will sail through waterway L2 while vessels going to Terminal 3 sail through waterway L3.

Scenario Setup

To evaluate the relationships between the indicators, different scenarios were implemented with different control variables. The different setups allowed for the creation and comparison of different port designs, identification of the level of congestion in each case, and determination of port capacity.

The data used to build different scenarios are shown in Fig. 3. The control variables changed for the different scenarios are demand, layout, terminal service time, vessel fleet types, number of berths per terminal, and maneuvering time in turning basins. The changes in these parameters affected the traffic flow and port capacity, and they were used to apply and validate the method. Two layouts of different lengths were implemented (Table 1). As for the other parameters, changes in the lengths of different approach channels and basins will affect traffic because of different sailing times and, thus, have direct effects on the port performance and the resulting capacity. The authors chose demands according to each port configuration with the purpose of reaching congested traffic states in the port and estimating the PNTC.

Simulation Setup

Simulation brings the possibility of building different scenarios for analyzing and comparing results as necessary to implement the estimation method previously described. In this section the developed simulation model is first described. Then, the simulation setup with the characteristics of the scenarios implemented is presented, and finally, the results are presented and analyzed according to the PNTC-estimation method.

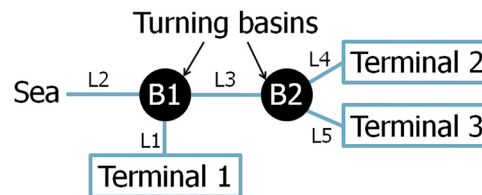


Fig. 2. Port network model layout (adapted from Bellsolà Olba et al. 2015)

		Scenarios					
		S1	S2	S3	S4	S5	S6
Expected demand [h]	Min.	10			x		
	30	x	x			x	x
	60			x			
	40				x		
	Max.	70	x	x			x
Layout	Design 1		x	x	x	x	x
	Design 2			x			
Service Time [h]	μ	5		x			
	10	x	x		x	x	x
	σ	0.5		x			
Vessel fleet types	1	x	x	x	x		x
	2					x	
Berths per terminal	5				x		
	10	x	x	x		x	x
Maneuvering turning basin time [min]	10	x	x	x	x	x	
	20						x

Fig. 3. Simulation setups

Table 1. Layout

Layout design	Waterway length (m)				
	L1	L2	L3	L4	L5
1	1,200	500	700	1,000	2,000
2	2,500	1,500	1,500	2,000	2,500

Simulation Model

To apply the PNTC estimation method, different data sets are needed for the different scenarios. The method is independent of the simulation model used but depends on the indicators. Any existing simulation could be used for this purpose, but the outcome would not provide the indicators required for the purposes of this study. Hence, a simulation model that provides the indicators required for applying the method is needed. In this research, the simulation model previously used by Bellsolà Olba et al. (2015) was enhanced. To represent reality as closely as possible, the vessel trips between terminals are implemented in the model, which allows for analysis of their effects. The port network traffic has been analyzed using a dedicated event-oriented simulation model developed in *MATLAB*. This microscopic model describes individual vessel dynamics within a port in a simplified way with time-step calculations. The basis of the simulation model is described.

When the simulation is started, a vessel generation module creates vessels according to the prespecified interarrival time toward each destination (terminal). Ships can sail directly to the destination and then leave the model, or ships can make a chain of trips with

intermediate destinations at different locations (terminals) in the port. The interarrival time was Poisson distributed, and each vessel gets a random speed. The considered speed is between a maximum and minimum range related to vessel length. After all vessels are generated, the vessel module, including three submodules (sailing, turning basins, and terminals), does the required computational calculations. The sailing submodule is built for each stretch of the port and stores and updates vessel positions for each of the waterways and basins. The turning basins submodule includes all basins from the port infrastructure and stores and updates the time spent by each vessel in them. Finally, the terminals submodule includes all the berths and terminals available and stores the service time of each vessel moored in each of the berths. Each of the submodules elements store and update each vessel position at every time step. When a vessel has completed the trip in one of the submodules, the vessel will wait in the current submodule until the next submodule has space to allocate more vessels. Once the simulation time, defined by the user, is reached, the vessel module stops and all data are stored.

Although ports usually have an anchorage, which provides vessel queuing and reordering possibilities, the port layout considered in the simulation model does not explicitly include it. The model considers the port entrance as the location where vessels can reorder in cases of different terminal destinations and current availabilities as if anchorage was used.

The model implementation includes several assumptions to simplify the complex port network and the sailing behavior of vessels, and thus, to build and compare different scenarios in a reasonable time. Built on the assumptions presented by Bellsolà Olba et al. (2015), those considered for this study were

- Sailing characteristics:
 - Vessels sail in a one-dimensional movement with no interactions between vessels in head-on and no overtaking situations;
 - Random vessel speeds are generated between 4.5 and 10 knots ($\sim 3.1\text{--}5.1$ m/s) with speed range varying according to vessel length; and
 - Each vessel speed assigned is a constant unless the safety distance with the predecessor reaches a minimum in which case the vessel sails at the predecessor's speed.
- Vessel destinations:
 - Vessel destinations and trips between terminals are predetermined when vessels are generated; and
 - Vessel entrance to the port is contingent on berth availability within sailing time such that once a vessel visits different terminals, a berth is reserved in the next terminal while the vessel is served in the current one, but if no berth is available, vessels have to wait outside.
- Maneuvering and operations:
 - The turning-basin maneuvering is defined as a fixed time period equal for all vessels; and
 - Neither berthing operations nor loading and unloading processes are detailed in the model, but these operations are included in the service time, which is described by a normal distribution.
- External conditions:
 - No weather conditions, tidal windows, or night effects are included.

None of these assumptions has a severe effect on the indicators considered in the capacity-estimation method, and they are considered reasonable for the purpose of this research. However, the authors acknowledge that for a more advanced model that considers, for example, two-dimensional vessel movements, the influence

in speed and path while encountering other vessels moving in the opposite direction and the availability of tugs to help large vessels maneuver in turning basins would provide an estimated capacity closer to reality. Moreover, the model could also relate vessel speed to vessel size and the effects of the infrastructure over a dynamic path, as developed in recent research for a unique vessel (Shu et al. 2015). Hence, for the application of this method in a real port, an advanced model would provide more realistic results. However, the research purpose is to develop the PNTC method, and the model is used only to validate the capacity-estimation method.

Simulation Setup

The different simulation setups for each scenario are summarized in Fig. 3. Each demand is gradually increased within a range between minimum and maximum values to gradually overload the system, and each simulation includes 30 different demands equally distributed between the two extreme values. Gradually increasing demand provides increasing values of each indicator when reaching capacity. Once demand is over capacity, indicators should reveal that the operations in the port network are unstable.

The model includes the possibility for vessels to make a trip chain within the port. For this research, 20% of the entering vessels will make interterminal trips, and the rest of the vessels will just visit one terminal.

Because the model is stochastic, 10 runs for each scenario were carried out, resulting in a total of 300 values per scenario. To make the scenarios comparable, an average value over the 10 runs was considered. The simulation time was 5 days with a warming-up period of 1 day.

Results and Analyses

The simulation results for the different scenarios are analyzed in this section. Because the results from all scenarios follow the same trends, Fig. 4 shows only the results for the different capacity indicators for scenarios S1 and S4.

Fig. 4(a) shows the relationships between each demand and TTs each day. S1 and S4 show a parabolic relationship between the demand and TTs, which flattens at higher demand levels. The initial linear relationship for lower demands disappears at a specific demand value, approximately 40 vessels/day for S1 and approximately 18 vessels/day for S4, and there is a dispersion of results. Previous research showed that, not considering internal trips, the outflow reached a maximum with a stable value (Bellsolà Olba et al. 2015). However, in this case, allowing vessels to make trips between terminals created unstable situations exceeding the capacity level. This is reflected by some points with high demands resulting in fewer TTs because of congestion. This pattern does not clearly reflect the situation when the capacity of the port is reached.

Fig. 4(b) shows the relationship between BO and TTs, and it can be seen that above 0.7 of BO, there are some drops in TTs, which can be related to the excess demand over capacity and the congestion level of the port. When the congestion in some areas of the port is high, there might be situations where the port network cannot process as much traffic as it did before. Fig. 4(b) also shows a high density in the right part of S4, and some TT values were lower at the same BO, which means that, increasing demand even further, BO reached its limit and TTs could not be higher. Hence, we can see that number of berths and the distribution among different terminals can be limiting factors in planning the port waterway network. However, for S1 between 0.7 and 0.9 BO, there is a high point density, which implies that if there is congestion, the limiting factor is

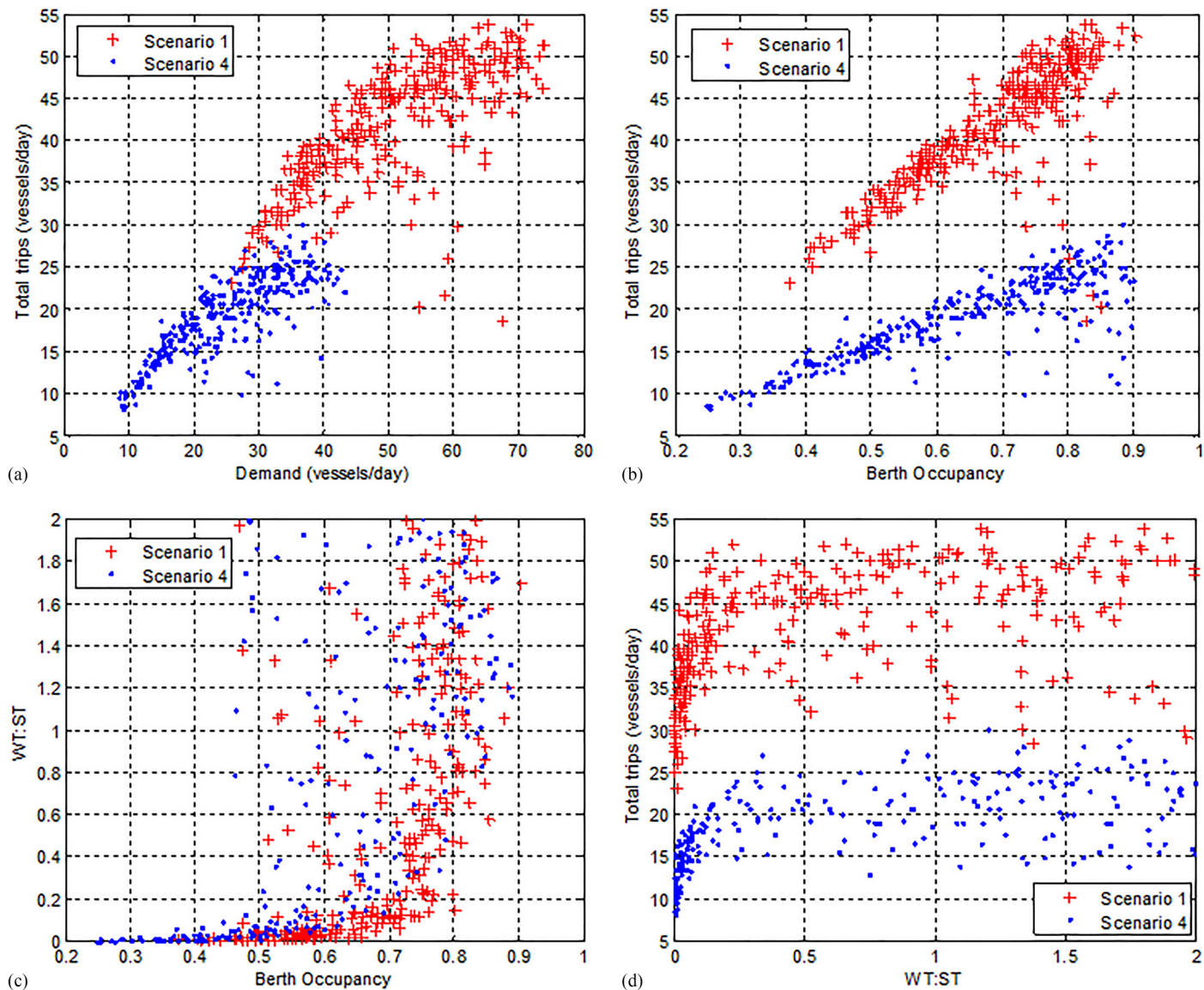


Fig. 4. Simulation results for S1 and S4 (total of 10 different simulations each scenario): (a) TT versus D; (b) WT/ST versus BO; (c) TT versus BO; (d) TT versus WT/ST

partly the result of the wet infrastructure design and not only the number of berths.

The relationship between WT/ST and BO [Fig. 4(c)] shows that WT/ST increases following an exponential distribution with respect to BO with a high dispersion above a value between 0.6 and 0.75 of WT/ST. This comparison proves that above a certain BO value, any increase in demand will produce only an increase in waiting times while the service time remains the same. Therefore, the port might be crowded with increasing levels of congestion and the efficiency may decrease. It should be mentioned that previous research using queuing theory proved that this relationship follows a similar trend (Groenvelde 2001); thus, the model output fits realistic trends previously studied. In addition, the scatter results above a certain WT/ST show the influence of congestion on the stability of the network. In this case, even with increasing demand, the resulting BO is lower than it is under lower demands when the situation is stable.

Fig. 4(d) presents the relationship between TTs and WT/ST. Both scenarios follow the same trend: They have a linear increase up to a certain point where the WT/ST keeps increasing with a large

fluctuation of TTs. This finding proves that the port has reached capacity (maximum number of TTs) for a certain port configuration.

As the TT value becomes unstable above a specific demand level, the maximum traffic is reached for the port, and the value of TT between stable and unstable situations is considered the PNTC. The estimation of the PNTC can be obtained as the average value for WT/ST above 1 (PNTC = c ; Table 2). In addition, because all scenarios have a similar pattern for the relationship between TTs and WT/ST, a best fit of functions was performed (Fig. 5), revealing that this pattern follows an exponential distribution, shown in Eq. (1) as follows:

$$f(x) = a \cdot e^{bx} + c \quad (1)$$

Using the PNTC obtained for each scenario as c in Eq. (1), the parameters a and b of the exponential distributions are obtained as shown in Table 2. All scenarios had moderate correlations to the data on the basis of the R-squared value obtained for each of them,

Table 2. Exponential Fit and Capacity Estimation

Parameter	Scenario					
	S1	S2	S3	S4	S5	S6
a	-14.23	-14.78	-24.73	-10.29	-15.39	-14.05
b	-14.69	-16.21	-25.87	-10.74	-17.33	-13.38
$c = \text{PNTC (vessels/day)}$	44.75	44.81	69.72	21.64	44.95	43.68
R^2	0.38	0.45	0.42	0.51	0.45	0.53

Note: PNTC = port network traffic capacity.

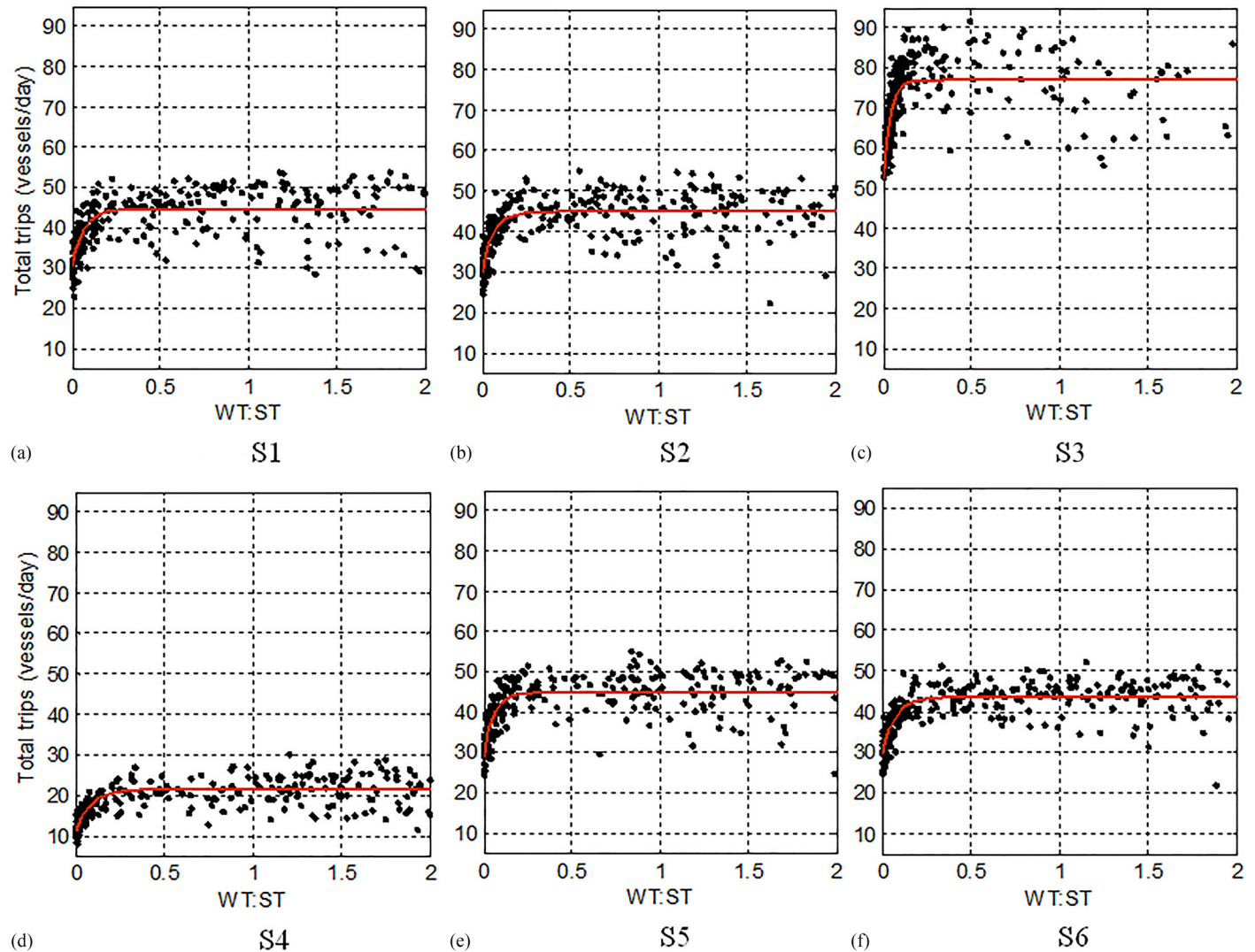


Fig. 5. Exponential fit to data for each scenario: (a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6

and Fig. 5 shows the graphs of the exponential fittings for each scenario. The dispersion of results above a certain value is attributable to the stochasticity of vessel arrivals and trips between terminals. Although for each scenario a higher TT than PNTC value can be observed, these values are mostly in the unstable situation, in which increasing demands lead to higher increased WT/ST than TTs, and the situation is unstable.

Fig. 5 shows that although the resulting limits are different for each scenario, all scenarios show the same trend, with a limit at capacity (PNTC). When the TT value reaches PNTC, relating it to road traffic concepts, this would be the congested state. A port

cannot operate at that state of high demand for a long period because the waiting times are unacceptable. Hence, the threshold value that determines an efficient port operation has to be below the PNTC.

In addition, the PNTC is different for each scenario because of their different setups. Assuming S1 as the basic case for comparison [Fig. 5(a)], Fig. 5(b) shows that S2 has almost the same TT values without much influence from the longer sailing distances through the port. S3 [Fig. 5(c)] considers a service time of 5 h, one-half that of S1. In this case, the PNTC results are almost twice as high as the one estimated for S1, which shows that the port infrastructure, the

inclusion of internal trips, and the sailing time influence the TTs. In Fig. 5(d), S4 has one-half the berths of S1, and the PNTC estimation is below one-half that of S1. S5 [Fig. 5(e)] considers two vessel fleet types, and the final result is almost the same as the previous scenarios, which means that this is not an influential parameter in this analysis. On the basis of the traffic point of view, this finding shows that the only factors that change among ship types are lengths and speeds and, as a consequence, so do safety distances. Further research should examine the influence of different maneuvering times. Finally, in Fig. 5(f), S6 was implemented with double maneuvering time in turning basins (20 minutes), and therefore, the result shows that the PNTC values are slightly lower than for S1, although the influence is really limited.

When comparing the results for different port designs, we can conclude that the control variables with strong effects on the PNTC were the service time and the number of berths in each terminal. The rest of the control variables had small effects.

The comparison between scenarios showed that, despite the different configurations, the indicators for estimating PNTC follow the

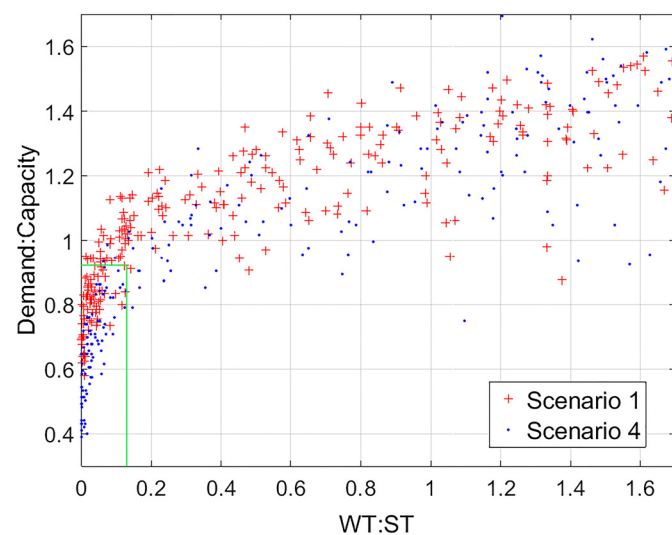
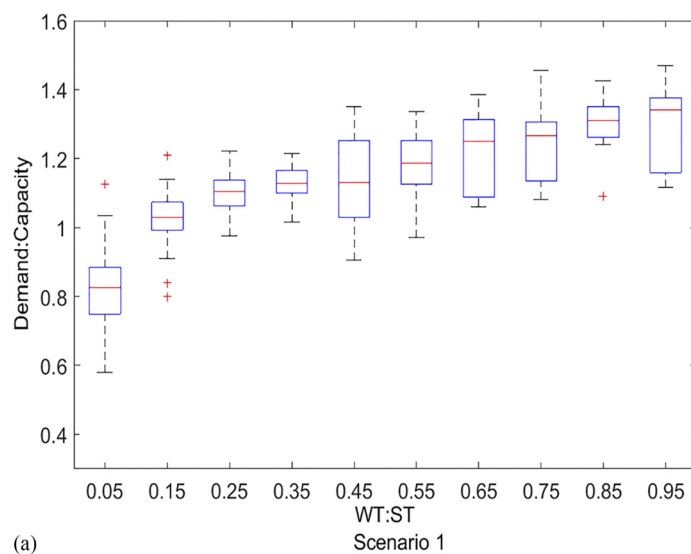
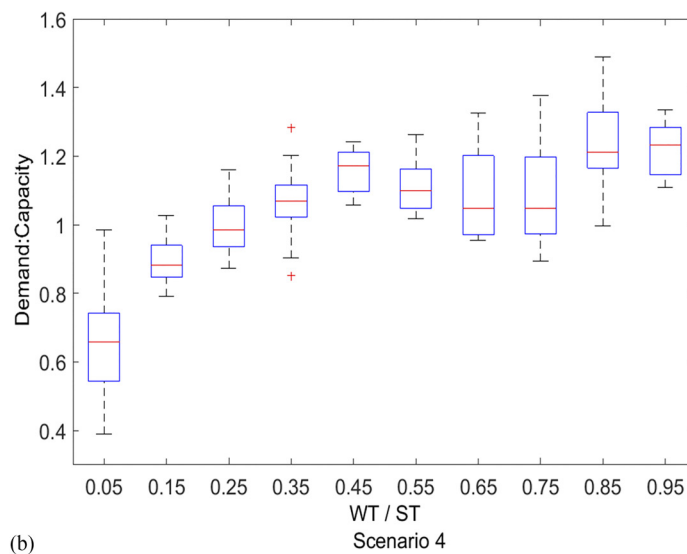


Fig. 6. Demand/capacity ratio versus WT/ST



(a)

Scenario 1



(b)

Scenario 4

Fig. 7. Boxplot representation of demand/capacity ratio versus WT/ST: (a) Scenario 1; (b) Scenario 4

same trends, and the PNTC can be estimated for any scenario. To guarantee acceptable congestion and WT/ST values, the point that determines the threshold of an acceptable operation with a specific port design should be below the PNTC. By following a similar approach used for road traffic, as described in the *Highway Capacity Manual* (Transportation Research Board 2010), in which different levels of service have been related to the traffic situation, a value of 0.92 volume/capacity is found for the level D threshold, which approaches unstable flow, corresponding to a maximum delay for freeway designs. The next level in this scale, E, corresponds to unstable flow. Fig. 6 shows the relationship between the demand/capacity ratio with respect to the WT/ST. Setting a demand/capacity ratio of 0.92 as the upper limit of stable flow [see line in Fig. (6)], as happens in vehicular traffic, congestion leads to more dispersed results than does stable flow. Furthermore, WT/ST is below 0.2, which is, as mentioned already, the maximum acceptable value for ports. Hence, after estimating PNTC, this value could be used as a reference value to assess new port designs or extensions.

Fig. 7(a) shows the boxplots for Scenario 1 and Fig. 7(b) shows them for Scenario 4. The results of both scenarios, and the others, follow the same pattern, and it can be seen that the demand/capacity ratio reaches 1 at approximately 0.15 of WT/ST for Scenario 1 and approximately 0.20 of WT/ST for Scenario 4. Moreover, the average values show that the demand/capacity ratio increases slightly more than the WT/ST ratio for high demands because of the capacity limitations of the port designs assessed.

Conclusions

This paper presented the PNTC estimation method, which provides the capacity value that can be sustained by a port network (Bellsolà Olba et al. 2015). The method allows for the identification of trends and relationships between indicators in a port from aggregated data for estimating its capacity. These indicators can be obtained from any simulation model with the required output. To show the applicability of the approach, vessel trips were implemented between terminals in a simplified simulation model, generated data for a range of situations and also through which extreme situations can be compared. The results revealed a trend that relates TTs with WT/WS. At

a particular point, PNTC, the system becomes unstable and the results become more dispersed. The capacity can be reached because of berth limitation or traffic congestion.

This methodology focuses on the traffic assessment of the port network and does not consider costs or restrictions with respect to waiting times. It can be applied during the port-planning phases to identify the optimum design in relation to vessel traffic. The application of this method allows port planners to estimate the capacity of different port designs while they are comparing feasible scenarios. On the basis of these results, planners can evaluate and compare the respective PNTC values, and use them as reference values for choosing between the options.

The approach presented is part of a methodology for making an assessment of a complete port while taking into account other indicators, such as risk and costs. In an additional step, other indicators will be included to improve this estimation method. Moreover, the implementation of different port configurations and extra functionalities can show the influence of other limiting factors, such as pilot and tug availability, the infrastructure design on capacity, among others. The results of the estimation method presented for real port networks directly depend on the level of simplification of vessel navigation and port infrastructure. The more a model accurately represents the most relevant factors in navigation, the closer to reality the results will be. On the basis of this method, further research might lead to defined levels of service in ports.

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References

- Bellsolà Olba, X., Daamen, W., Vellinga, T., and Hoogendoorn, S. P. (2015). "Estimating port network traffic capacity." *Sci. J. Marit. Univ. Szczecin*, 42(114), 45–53.
- Daganzo, C. F. (1989). "The crane scheduling problem." *Transp. Res. B: Methodol.*, 23(3), 159–175.
- Dragović, B., Park, N. K., and Radmilović, Z. (2006). "Ship-berth link performance evaluation: Simulation and analytical approaches." *Marit. Policy Manage.*, 33(3), 281–299.
- Ducruet, C., Itoh, H., and Merk, O. (2014). "Time efficiency at world container ports." *Int. Transport Forum Discussion Paper No. 2014-08*, Organisation for Economic Cooperation and Development, Paris.
- Fan, H. S. L., and Cao, J.-M. (2000). "Sea space capacity and operation strategy analysis system." *Transp. Plan. Technol.*, 24(1), 49–63.
- Geroliminis, N., and Daganzo, C. F. (2008). "Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings." *Transp. Res. B: Methodol.*, 42(9), 759–770.
- Groenvelde, R. (2001). *Service systems in ports and inland waterways*, VSSD, Delft, Netherlands.
- Huang, S. Y., Hsu, W. J., and He, Y. (2011). "Assessing capacity and improving utilization of anchorages." *Transp. Res. E: Logist. Transp. Rev.*, 47(2), 216–227.
- Keyvan-Ekbatani, M., Kouvelas, A., Papamichail, I., and Papageorgiou, M. (2012). "Exploiting the fundamental diagram of urban networks for feedback-based gating." *Transp. Res. B: Methodol.*, 46(10), 1393–1403.
- Ligteringen, H., and Velsink, H. (2012). *Ports and terminals*, VSSD, Delft, Netherlands.
- Nicolaou, S. N. (1967). "Berth planning by evaluation of congestion and cost." *J. Waterw. Harb. Div.*, 93(4), 107–132.
- Shu, Y., Daamen, W., Ligteringen, H., and Hoogendoorn, S. (2013). "Vessel speed, course, and path analysis in the Botlek area of the Port of Rotterdam, Netherlands." *Transp. Res. Rec.*, 2330, 63–72.
- Shu, Y., Daamen, W., Ligteringen, H., and Hoogendoorn, S. (2015). "Vessel route choice theory and modeling." *Transp. Res. Rec.*, 2479, 9–15.
- Stahlbock, R., and Voß, S. (2007). "Operations research at container terminals: A literature update." *OR Spectr.*, 30(1), 1–52.
- Transportation Research Board. (2010). *Highway capacity manual 2010*, Washington, DC.
- UNCTAD (United Nations Conference on Trade and Development). (1985). *Port development: A handbook for planners in developing countries*, New York.
- UNCTAD (United Nations Conference on Trade and Development). (2012). "The capacity in container port terminals." *Ad hoc expert meeting on assessing port performance*, New York.
- Van Asperen, E., Dekker, R., Polman, M., and Swaan Arons, H. D. (2003). "Waterway, shipping, and ports: Modeling ship arrivals in ports." *Proc., 35th Conf. on Winter Simulation: Driving Innovation*, Winter Simulation Conference, New Orleans, 1737–1744.