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Estimating Port Network Traffic Capacity

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Abstract

Port capacity is a relevant parameter to estimate the expected performance of a port facility. Many simulation models have been used to predict traffic in ports and waterways, but they do not include provisions for estimating the port's capacity. The innovative method presented here determines a Port Network Traffic Capacity (PNTC) based on simulation. This method estimates PNTC given the configuration and processing characteristics of the port. It can be a useful tool to apply while designing ports, because only a limited number of simulations are required to estimate of the capacity of the infrastructure under consideration.

Introduction

Port performance is a key to the efficient functioning of a maritime supply chain. Nowadays, the increased pressures of vessel traffic and cargo handling time cause congestion. Terminal operations normally have the lowest capacity rate and determine the productivity of the system, but no method currently exists to estimate the vessel traffic capacity in a port, in order to quantify its traffic efficiency. Most research on ports focuses on terminal operations performance (Daganzo, 1989; Stahlbock and Voß, 2007) or the performance of individual parts of a port, such as anchorage (Huang, Hsu and He, 2011), ship-berth interaction (Dragović, Park and Radomilović, 2006), or ship arrivals (Asperen et al., 2003), among others.

Due to technological improvements and resultant increases in operational efficiency, the vessel traffic inside a port has increased to levels that might become problematic. There is a need to be able to quantify the maximum traffic flow that a specific waterway network can sustain, given a specified level of service, adequate safety provisions and acceptable waiting times. Hereafter, the metric will be referred to as the port network traffic capacity (PNTC). This paper proposes a method to determine PNTC from the results of a computer simulation. As we will show, the PNTC represents a single value that fairly summarizes a port's throughput, while the underlying computation method provides insight into the critical processes determining the PNTC value.

Background

Despite the fact that there are several different published port capacity definitions, based on different computational approaches, such as terminal capacity (Ligteringen and Velsink, 2012) and bottleneck approach (Fan and Cao, 2000), there is no standard, broadly accepted, definition of the capacity of a port as a waterway network. In general, the network capacity cannot be defined by the most critical part or element (bottleneck approach), because each element in the network is dependent on the rest of the infrastructure. In the context of port capacity, this dependency includes also factors related to demand and the composition of the fleet. Because of these considerations, port capacity was defined 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"*.

Two issues were reviewed during the development of the current metric for PNTC: (A) previous evaluations of port performance and its primary determinants, and (B) metrics developed to estimate the capacity of highway networks. Highway networks were studied because of the obvious similarities between networks of roads and waterways, and because waterway networks had received so little study in the past.

A. A literature review of port performance indicators

The importance of the efficiency and performance of a port has been recognized for many years. The performance of ports has been measured by two types of indicators, financial and operational. This study focuses on operational indicators of port performance.

One of the first studies addressing this topic defined two metrics from the field of traffic engineering: “occupancy,” the percentage of time that all berths are occupied (“berth occupancy rate”); and “congestion,” the percentage of time that the number of ships in port exceeds the number of available berths (Nicolaou, 1967). The first indicator has the drawback of not describing how occupancy is distributed over time. For example, 50% berth occupancy is as true of a situation in which half of the berths are always occupied and half are always empty, as it is of all berths being occupied half of the time. These clearly different scenarios point out the need for an additional indicator. The second indicator described above, congestion, does not quite meet the need because large ports encompassing long sailing distances can accommodate more sailing vessels than berths without technically being congested. Another study proposed different operational indicators, most of which were related to the productivity of cranes and tons of cargo loaded/unloaded hour. Others, such as waiting time, service time and turn-around time, are more directly and comprehensively related to the operational performance of the port (UNCTAD, 1976).

The ratio of waiting time to service time has proven to be an appropriate measure of timeliness of service of the terminal. Generally, acceptable values for this ratio are 30% and below (UNCTAD, 1985). The significance of this ratio is, however, determined by specific rules, and by the costs associated with waiting. Moreover, the use of this indicator alone can result in misleading information if a very low wait-to-service ratio is caused by a very inefficient service team.

Other indicators related to throughput from, for example, berths or cranes are useful from some perspectives, but they are related to terminal performance, and not specifically to port *traffic* performance.

B. Prior work on network capacity

Compared to the work on ports and waterways, road traffic has been extensively researched in relation to network capacity, and several ways have been proposed to quantify it. These studies were in fact the point of reference for the method developed in this paper. Having carefully reviewed all potentially useful approaches, we will restrict all further discussion to approaches deemed relevant to ports and waterways.

Several theories describe vehicular traffic movement in cities at an aggregate level. Traffic dynamics follow a specific pattern, given a certain demand, its increase does not produce higher flows. This is the basis of the Macroscopic Fundamental Diagram (MFD) (Geroliminis and Daganzo, 2008), which shows that if the traffic data from detectors is aggregated over an area (network), a relation between accumulation (i.e., average density per roadway length) and production (i.e., average flow of vehicles per time unit) exists. The MFD was evaluated as a network indicator to evaluate accessibility in a neighborhood. Later, more research was done in relation to MFD, and other networks were integrated into this concept (Knoop, Hoogendoorn and Lint, 2012).

Because of its successful application to vehicular traffic on highways, relevant relationships between various MFD indicators (see *Experimental Design* section) were investigated here in an attempt to develop a good PNTC estimator.

Simulation model

An event-oriented simulation model to represent a port network was developed in the course of the attempt to develop an improved PNTC metric. This model describes the dynamics of each individual vessel as it moves through the port, updating the current situation at each time step, which will, in turn, condition the next time step.

After starting the simulation, all variables are initialized and loaded, including the network layout. The vessel generator creates vessels randomly, with arrival times based on a Poisson distribution, adjusted to reflect impacts of by the effects of vessel type and demand, with random speed and destination time at the terminal. Once this step is completed, the vessel module starts all computational steps, including three sub-modules controlling sailing, turning basins, and terminal. These three elements update their content in each time step. Whenever the next sub-module has insufficient space for additional vessels, the vessel remains in place until it becomes the current vessel.

Once the simulation time is reached, this module stops and all data are stored.

The model implementation includes assumptions to simplify a complex network and the complex sailing behavior of vessels, and thus, to build and compare different scenarios in a reasonable time. The assumptions are:

- Vessel movements are one-dimensional, lacking the overtaking and interaction or influence between vessels in head-on and maneuvering situations.
- Vessels are allowed to enter the port when, within their required sailing time, there will be a berth available. On the contrary, they have to queue outside.
- Vessels have fixed speeds that are reduced to the predecessor's speed whenever speeds are too high to maintain proper safety distances.
- Destinations are fixed and trips between terminals are not allowed.
- Sailing speeds are randomly generated between 5 and 8 knots (~2.6–4.1 m/s).
- Maneuvering in turning basins is considered to occur over a fixed time interval.
- Berthing operations, cranes available and loading/unloading processes are not modeled and they are considered as part of the service time, which is cribbed as following a normal distribution.
- No weather conditions or night effects are included.

Experimental design

The experimental design describes the simulation setup, as well as the data and indicators used to implement different scenarios and to provide data for the estimation algorithm. Subsection A described the conceptual relationships between capacity and the indicators used to define the PNTC. Subsection B gives an overview of the layout, while subsection C shows the data used to build each scenario.

A. Conceptual relationships between capacity and indicators

Figure 1 presents the factors that affect port capacity in the conceptual model. Different factors related to microscopic vessel behavior influence macroscopic vessel flow. As mentioned in the previous section, the simulation model does not consider all the factors, according to the assumptions. Changes of some of them included factors allows to assess their influence on capacity.

The literature review summarized in the Background section indicated that the following factors are the primary determinants of capacity:

- The Waiting Time to Service Time ratio (WT / ST): The ratio of waiting to service time, for the whole time a vessel is in port, inclusive of sailing time, reflects the degree of efficiency of the port.
- Outflow (O): The average number of vessels leaving the port per time period reflects the

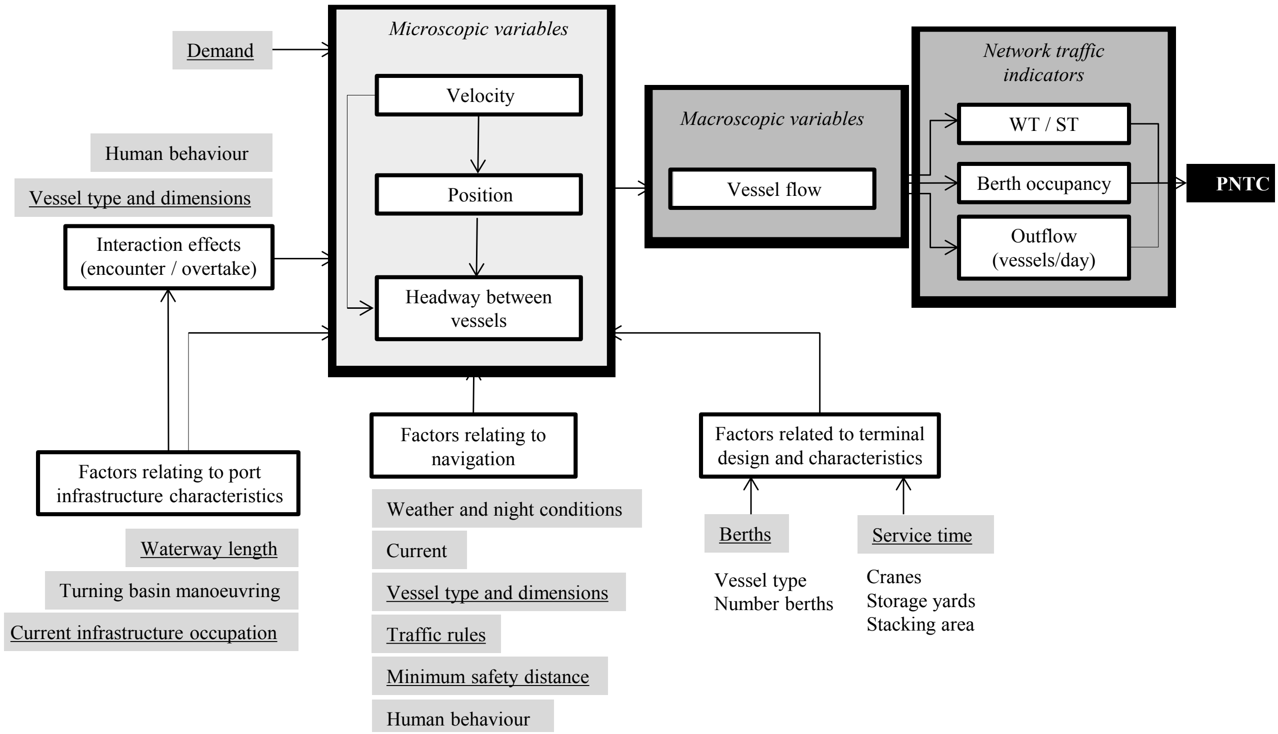

Figure 1. The various types of factors that interact to determine Port Network Traffic Capacity

vessel flow rate for a waterway network subjected to a specific demand (D).
- Berth Occupancy (BO): The percentage of time that all available berths are occupied.

These indicators are directly influenced by vessel demand and therefore are also related to the capacity value. Capacity is directly related to outflow (vessels/day), which is the final result of the simulation for each demand and gives the average number of vessels per day that are going out from the port. Thus capacity as previously defined can be related to the outflow that determines capacity under a given demand. Although BO has the previously cited drawback, it is considered a useful indicator

Table 1 presents relations between the indicators and the probable cause of congestion of the network. An increase in D can have different effects on different indicators, but between them, they are implicitly linked. First, an increase in D that leads to higher O and BO with the same or slightly higher WT / ST ratio. This means that O and BO are improving, and the port is operating below the capacity associated with the previous demand. Another possible scenario includes an increase of D leading to a small increase in O and a moderate increase in the WT / ST ratio, while BO decreases or remains the same. This situation might be caused by traffic congestion caused by limited “wet infrastructure.” When vessels encounter restricted waterways, they are unable to reach their assigned berths and the BO rate decreases. A third possible scenario would occur when there is a limitation in the terminals. An increase in demand would keep the same BO (around the maximum value for this configuration), while the WT / ST ratio would increase moderately and the outflow would not have a remarkable difference.

Table 1. Relations demand – indicators

Demand (D)	Indicators			Limitations
	Outflow (O) (vessel/day)	WT / ST	Berth Occup. (BO)	
+	++	+ or 0	++	D below capacity
+	+	++	– or 0	Wet infrastructure
+	+	++	0	Terminal limitation

++ = Moderate Increase; + = Minor Increase; – = Decrease; 0 = Equal.
Increase relative to the previous results with lower D

For this research, changes in the terminal and the wet infrastructure will be allowed to assess the effects on capacity. In relation to the terminals, the service times and number of berths will be changed for different scenarios. In terms of wet infrastructure, the length of the waterways will change, but not the capacity of turning basins.

B. Layout

The layout used to build the different scenarios is schematized in Figure 2. The structure of the port is composed of an approach channel (L4) with a turning basin (B1), where vessels heading toward Terminal 1 will leave via a separated waterway (L1), and the rest will continue through another waterway (L5). At the end of this path, there is another turning basin (B2), which divides vessels with destination Terminal 2, through a waterway (L2), and the ones going towards Terminal 3, through the last waterway (L3).

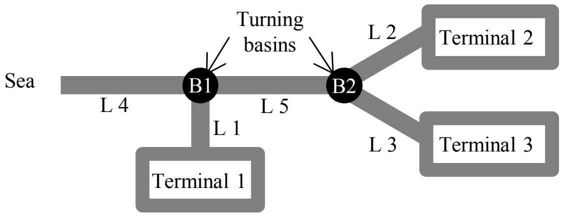

Figure 2. Port network model layout

A simplified layout, like that proposed in Figure 2, allows changes in the lengths of the approach channels or inner basins, as well as in the service times (ST) of each terminal. Thus, effects and patterns of different setups on resulting capacity can be compared.

C. Scenario data

Several scenarios have been analyzed to compare the effects of different layouts on capacity. The parameters in these scenarios include expected demands, service times, vessel fleet and berths per terminal. These different setups reflect different plausible scenarios in a port.

Two different layouts with the lengths summarized in Table 2 were analyzed. A change in the lengths of the different approach channels and basins shows the effect of traffic on port performance, and the resulting impacts on capacity. The results here show that longer channels can cause traffic congestion without complete terminal utilization.

Table 2. Layout Data (I)

Layout	Waterway length [m]				
	L1	L2	L3	L4	L5
1	1200	500	700	1000	2000
2	2500	1000	1500	2000	2000

Table 3 summarizes the data used for each of the 6 scenarios created, including the interval of demand, the terminal service times, types of vessels considered, the layout, and the number of berths per terminal.

The vessel flow demands were set between a range of values (see Table 3), and the range was divided into 20 different demands between the boundaries. Due to the stochastic results for each demand, 10 runs for each demand were performed, which resulted in a total of 200 values per scenario. Maneuvering times in the turning basins were fixed (10 minutes) in this research.

Table 3. Data scenarios (II)

Scenario	Expected Demand [vessels/day]		ST [h]		Vessel fleet	Layout	Berth term.
	Min.	Max.	µ	σ			
S1	50	80	10	1	1	1	10
S2	85	125	10	1	1	2	10
S3	50	80	5	0.5	1	1	10
S4	25	60	10	1	1	1	5
S5	50	80	10	1	2	1	10

The simulation time considered was 3 days, because the maximum ST considered is 10 hours, which allows the simulation to have around 6 cycles of vessels in each berth at a minimum. These several cycles reduce the stochastic effects in the final results.

The results section that follows summarizes the possible effects for a port network with specified interactions between indicators, infrastructure layout and scenarios type.

Results

First, scenario S1 was analyzed in detail to identify possible patterns.

In Figure 3, the relationship between the WT / ST ratio and berth occupancy shows that with increasing demand, the WT / ST ratio increases exponentially with berth occupancy. Research based on queuing theory shows a similar trend, so we trust the model output (Groenveld, 2001). Like the previous results, this comparison proves that, above a certain BO value, any increase in D will only produce an increase in waiting times, while the service time cannot be improved.

Figure 4 is a scatter plot of the paired outflow and demand data points. These are the average values obtained from 10 runs, with 20 different demands, producing 200 results for each scenario. For S1, the relation between outflow and demand (vessel arrival) increases linearly until a certain point, at which the increase in demand produces a lower increase in outflow from the port. This pattern is the first indication that the capacity of the port network might be approaching for this scenario. However, the same comparison for S3 shows a relation which seems to be linear. This situation can be explained by examining berth occupancy (see Figure 5), which shows a linear relationship between outflow and berth occupancy, implying that outflow increases along with berth occupancy.

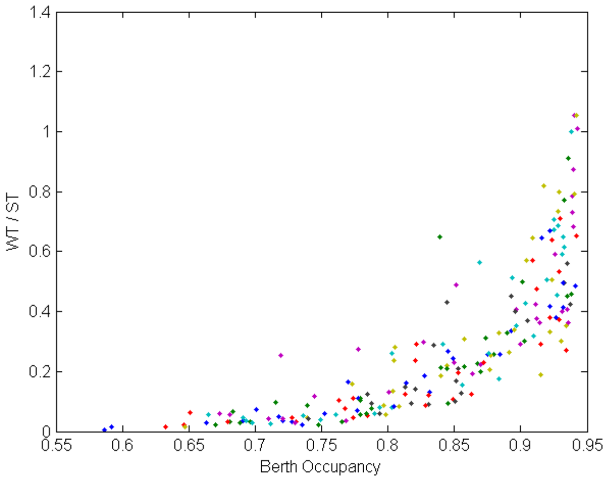

Figure 3. WT / ST ratio vs berth occupancy (Scenario 1) (each color is one of the 20 different demands for each simulation)

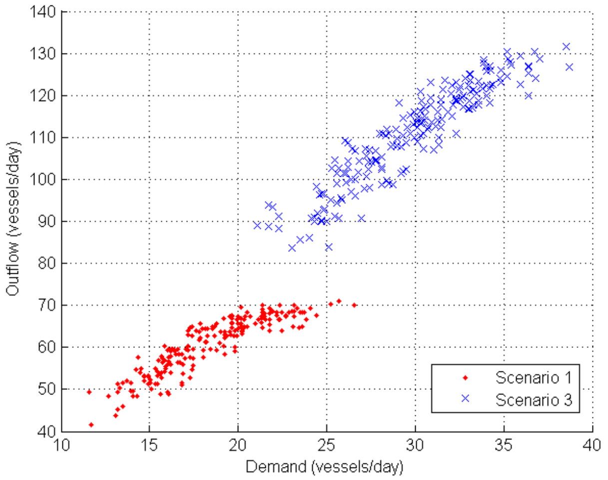

Figure 4. Outflow vs demand flows

For S1, although the demand was divided into 20 different values between the fixed boundaries, for each simulation, there is an increasing point density in the upper part of the figure. This suggests that demand can increase berth occupancy only so much, and that outflow cannot be increased once berth occupancy has reached its limit. In this scenario, berths become the limiting factor. However, looking at the same results from S3, there is an

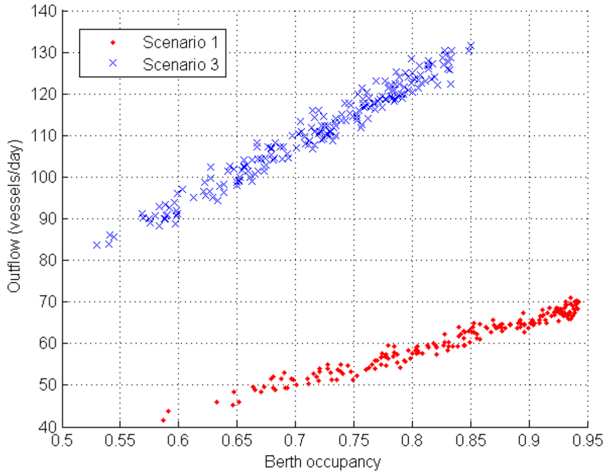

Figure 5. Outflow vs berth occupancy

average density of points for all the different values of berth occupancy. This pattern suggests that, if there is congestion, the limiting factor is the infrastructure and not the terminals. These competing explanations cannot be resolved by examining Figure 4. Even though, these relations give an insight into network performance, the relationship with capacity is not clear.

Another relation between indicators is O and WT / ST, shown in Figures 6 and 7 for scenarios 1 and 3, respectively. These Figures both show a similar trend. In both cases, for their specific demands with different outflows, the outflow stops increasing linearly after a certain waiting time.

Two other types of representation (boxplot and error bars) are used with the same indicators, outflow, and WT / ST ratio, to show relationships with extra information. The boxplots group the results and provides a clearer view of the density in each group and their deviations. The error bars, on the other hand, show the average value and a line below and above, the length of which represents a standard deviation.

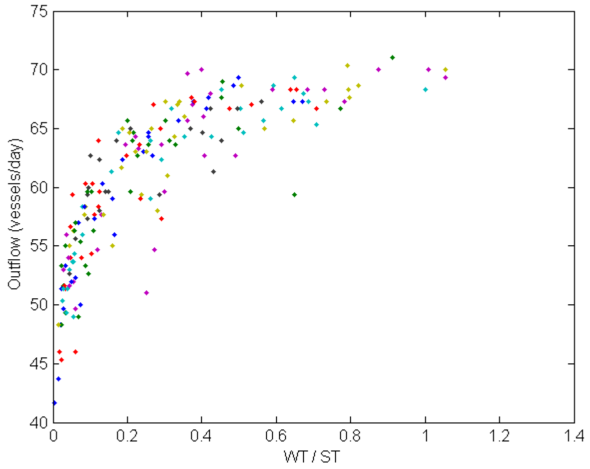

Figure 6. Outflow vs WT / ST (Scenario 1)

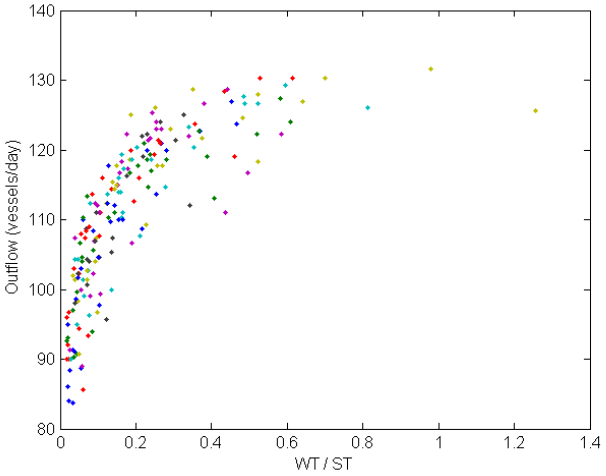

Figure 7. Outflow vs WT / ST (Scenario 3)

The boxplots for scenarios 1 and 3 (Figures 8 and 10) show that the outflow has a higher increase respect WT / ST up to a certain point where it decreases and becomes relatively stable. Moreover, the error bar plots (Figures 9 and 11) show the same trend. These plots represent a clear trend and appear to provide the basis for estimating a capacity

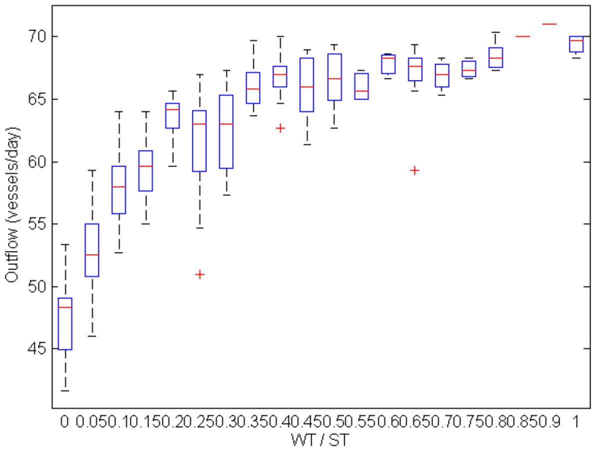

Figure 8. Boxplot outflow vs WT / ST (Scenario 1)

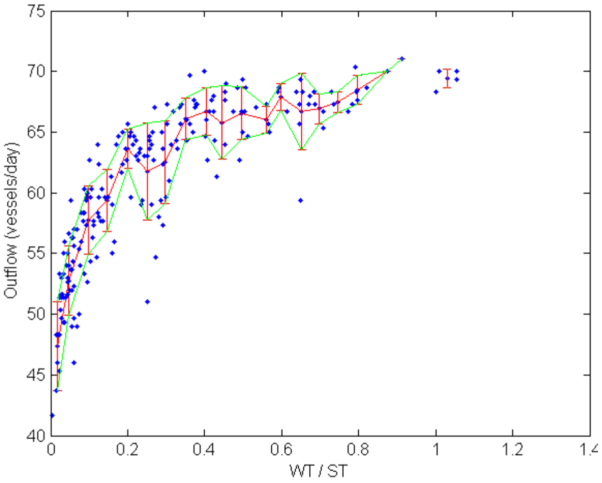

Figure 9. Error bars Outflow vs WT / ST (Scenario 1)

point. Some of the analysis from the other scenarios provided a basis for testing this assumption.

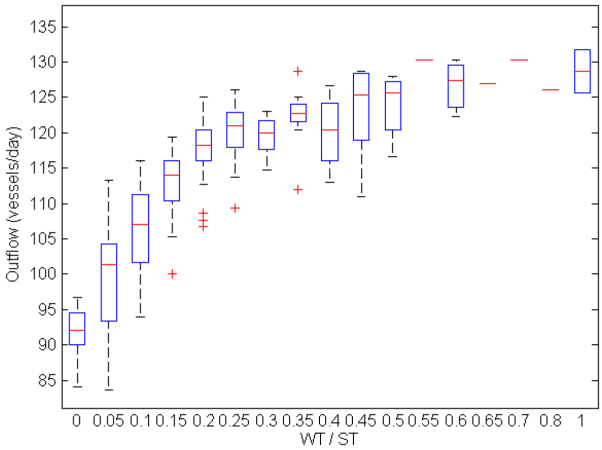

Figure 10. Boxplot outflow vs WT / ST (Scenario 3)

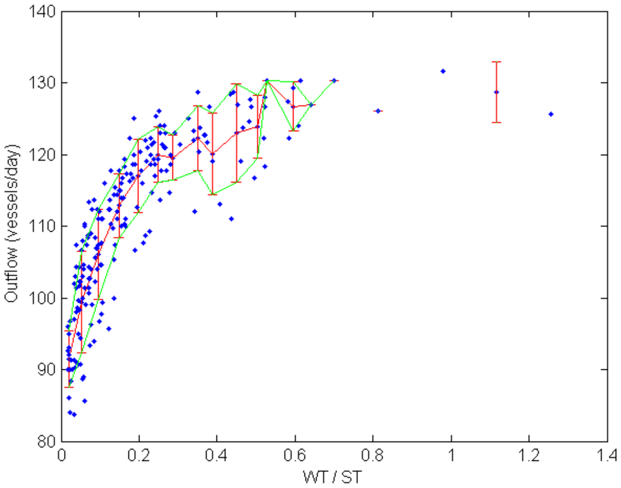

Figure 11. Error bars outflow vs WT / ST (Scenario 3)

The results for scenarios 2, 4 and 5 (see Figures 12–17) show the influence of different values of the configuration on the final result of the indicators.

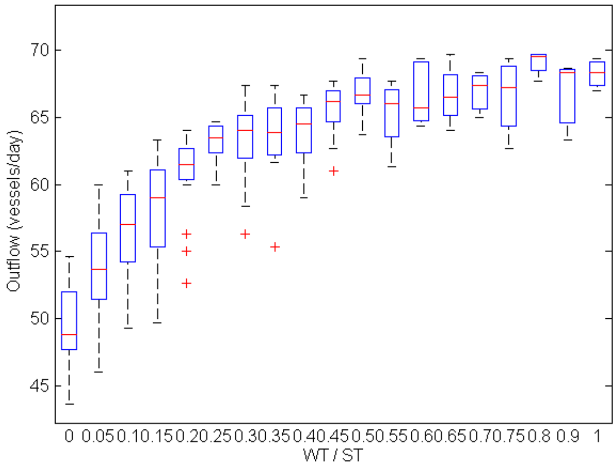

Figure 12. Boxplot outflow vs WT / ST (Scenario 2)

Scenario 2 had the same input as Scenario 1, except for the layout dimensions, which included longer waterway distances. This difference resulted in a faster rate of change of the WT / ST ratio with respect to increasing outflow, and represents a situation where the infrastructure becomes the limiting element in the network. Stochastic variability of the result of the results also appears to be higher, as can be seen by inspecting the error bars in Figure 13. Moreover, appoint of inflection with a clear slope change can also be identified.

Figure 14 shows the outcome for the Scenario 4, which incorporates 5 berths in each terminal, half as many as the other scenarios. The results of this simulation reflect more stochastic variability and a "more fuzzy" trend.

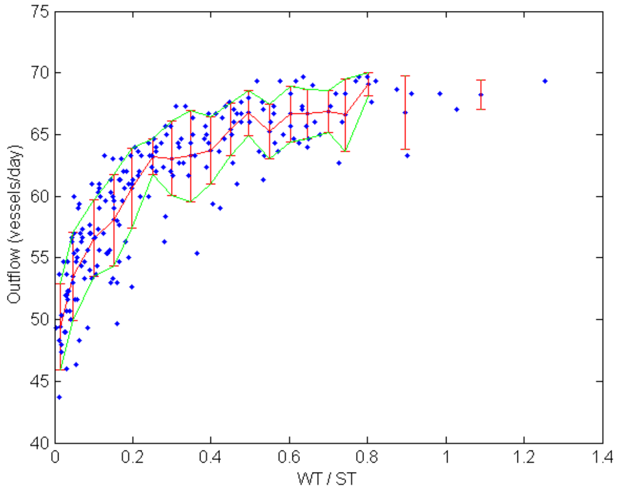

Figure 13. Error bars outflow vs WT / ST (Scenario 2)

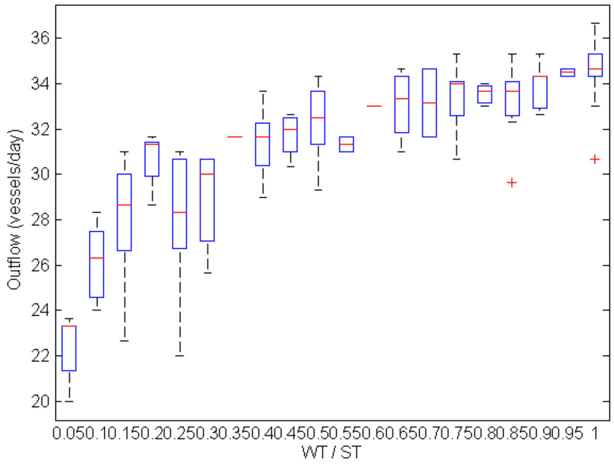

Figure 14. Boxplot outflow vs WT / ST (Scenario 4)

The last scenario analyzed considered a mixed vessel fleet, with two types of vessels with the same share. The results in figures 15 and 16 show the influence of the mix, which included more stochastic variation and a more continuous tendency. In this case, Figure 16 shows that the lower WT /

ST ratios support higher outflow rates up to a value of around 0.2 for the WT / ST ratio. After this point, the number of points decreases and the rate of increase of outflow with WT / ST declines.

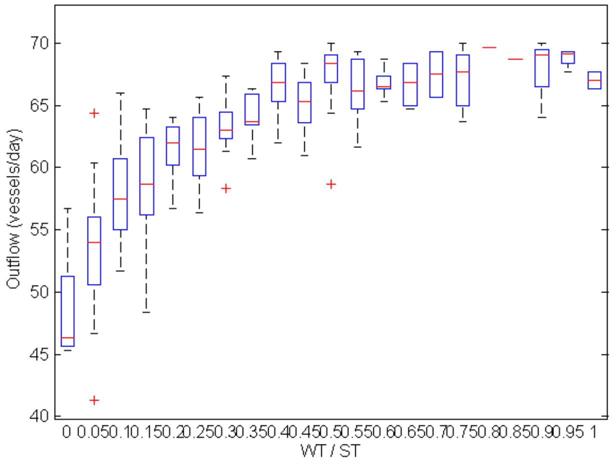

Figure 15. Boxplot outflow vs WT / ST (Scenario 5)

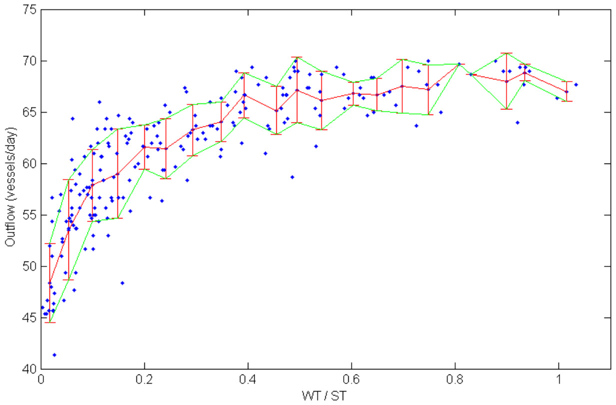

Figure 16. Error bars outflow vs WT / ST (Scenario 5)

This mixed vessel fleet remarks the influence of different fleet and shares inside a port network.

Capacity estimation method

This section introduces a method to estimate PNTC based on simulation. As mentioned, this method depends on the availability of a simulation model to build different scenarios and different demands for the specified configurations.

Traffic flow theory separates traffic in two states with opposite slopes, "free flowing" and "congested," according to flow-density relationships. Since ports always have waiting times and the relation does not have opposite values, as in road traffic, we will call them "normal" and "congested" states. In the figures plotting outflow as a function of the WT / ST ratio, an inflection point can be seen in Figures 17 and 18. The normal flow state, can be identified by a constant and a moderate increase of outflow respect WT / ST, while the congested state can be related to the slow or flat increase of outflow. Although the relations are the same, only with a change of slope, this point can be considered the threshold that satisfies a proper level of service for port traffic.

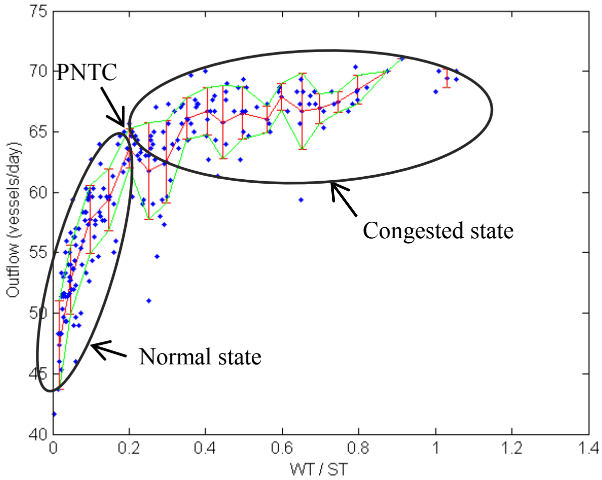

Figure 17. Error bars on plot of outflow as a function of WT / ST (Scenario 1)

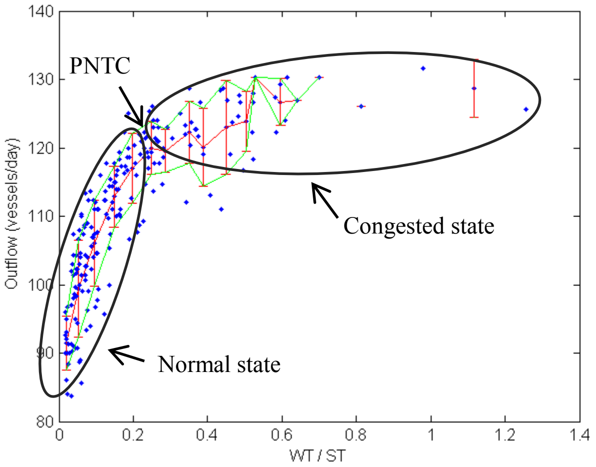

Figure 18. Error bars on a plot of outflow as a function of WT / ST (Scenario 3)

Thus, estimating the PNTC requires the following steps:

- A simulation model must be made producing the following output parameters: the WT / ST ratio, outflow (vessels/day), berth occupancy and demand (vessels/day).
- Values must be set which define the port with desired detail. These parameters must include infrastructure layout, terminals, service times, safety measures and traffic rules.
- With a few runs, a demand interval should be estimated in which different values of WT / ST and berth occupancy are included. The authors suggest values between 0.0 and 0.5 for the first indicator, and values between 0.25 and at least 0.80 for the second.

- A sufficient number of simulations should be run to get a good sense of the stochastic variability of the results.
- The inflection point of a plot of outflow as a function of WT / ST should be taken to represent the PNTC.

Conclusions

This paper presents a method to determine the PNTC, analogous to the MFD in traffic engineering. The method proposed allows the identification of trends in a port network from aggregated data that can be obtained from simulation models. The method has been applied in different scenarios with similar results. The results showed that the relation between outflow and the WT / ST ratio reveals an inflection point where there is a trend change, implying that the capacity of the system has been reached and the system is congested. This congestion can be attributed to either limited berthing facilities or traffic congestion.

This research is based on the traffic assessment of the port network and does not consider costs or restrictions associated with waiting time. Future research should improve the estimation method by incorporating costs. Future models should also parameterize the model with data describing a real port, allowing comparisons between simulated and observed performance. Finally, the incorporation of different port configurations and extra functionalities in future models might reveal other limiting factors, such as pilot/tug availability.

The PNTC estimation method proved to be a useful tool to assess the traffic performance of a port considered as a network during the design phases, and to estimate an acceptable demand for the port that does not entail reaching a congested state.

Acknowledgments

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