An approach to port network capacity

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***Abstract*— Port capacity from a traffic perspective has yet to be defined, but its measurement should allow the assessment of port infrastructures and the identification of their main constraints or bottlenecks.**

In this paper, we will present a review of link and network capacity definitions for different domains and new definitions for ports are formulated. A brief review of capacity calculation methods is presented.

A computational approach for capacity calculation is presented. The process of a vessel in a port is described in order to identify the model scope, the required parameters and the assumptions for building the simulation tool. With this model different scenarios are generated in order to identify the influence and relevance of different parameters for the port network capacity.

I. INTRODUCTION

Globalization trends have led to a large increase in maritime transport that entails a growth in the traffic demand in ports. Furthermore, vessels have evolved to enlarged dimensions and higher speeds. These facts trigger more difficult maneuverability and hazardous situations.

A port represents a complex system in terms of infrastructure design and traffic flow, because of this, an exhaustive analysis of an actual infrastructure or future design can help to reduce or avoid dangerous situations. Capacity is a relevant indicator that helps to identify the main constraints of any network and allows the evaluation of the performance of a system (port) in economical or safety terms.

The aim of this paper is the formulation of new definitions for link capacity and network capacity for port traffic and their calculation through a computational approach. In section II, a review of existing capacity definitions for several transportation domains is presented and new definitions for port capacity are formulated. In addition, this section includes a review of different network calculation methods. In section III, the real-life process of vessels in a port is described and the description of the simulation model is presented. Moreover, the assumptions included in the model are presented. In section IV, the algorithm for the new simulation tool is described as well as the evaluation of several simplified port networks with different layouts. The final chapter exposes the conclusions of this research.

II. LITERATURE REVIEW AND CAPACITY DEFINITIONS

Current port capacity definitions refer to terminal capacity not infrastructure capacity as a transport system. To develop a proper definition and calculation method for port network capacity from a traffic perspective, there are several issues that have to be resolved and reviewed as how capacity has been defined in other studies, not only in ports or waterways, also for other transport modes. Furthermore, capacity calculation methods and traffic rules are also introduced.

Two types of capacities can be distinguished for a transportation network, being link and network capacity. Link capacity is used to define the capacity of an isolated stretch, while network capacity is defined for the whole combination of several links or nodes, also considering the interaction between them.

A. Link capacity

When referring to capacity, researchers commonly refer to link capacity. However, for different modes a broader perspective of capacity definitions is needed.

Table I presents an overview of different capacity definitions formulated for different fields. The general dictionary definition is related to the possibility of absorb or contain, which in traffic would be traverse a point or section. As it can be seen for road traffic, its definition considers that the ability of absorb is equivalent to the maximum hourly rate of vehicles expected to traverse a point, including a time period and roadway boundary conditions. Moreover, the word 'reasonably' gives to the definition a wider scope and freedom to fix a maximum rate depending on other aspects, like cultural or behavioral issues. In this field it also exists the *Fundamental Diagram* (FD) that shows the graphical relation between the flow rate (hourly capacity) and the density (storage capacity), and the capacity point can be determined (Daganzo, 1997).

Transit capacity is defined with two concepts with a similar definition, considering also the maximum amount of units through a location , only considering two different units. The first one considers the number of people in the vehicles as indicator, but this indicator does not provide proper information about the number of vehicles that are in the system. The second one considers the number of vehicles, as it was defined also for roads.

TABLE I. LINK CAPACITY DEFINITIONS

Field	Definition
General	"The ability or power to contain, absorb or hold". (HarperCollins Publishers, 2014)
Road	"The capacity of a facility is the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions". (National Research Council & Transportation Research Board 2010)
Transpor--tation in general (Transit capacity)	As a definition for *person capacity*: "The maximum number of people that can be carried past a given location during a given time period under specified operating conditions; without unreasonable delay, hazard, or restriction; and with reasonable certainty". And as a definition for *vehicle capacity*: "The maximum number of transit vehicles (buses, trains, vessels, etc.) that can pass a given location during a given time period at a specified level of reliability". (Kittelson & Associates et al., 2013)
Airport	"A maximum average flow that a facility can accommodate over a time period long enough to include a large count and which could be sustained for an infinitely long time". (Newell, 1979)
Ports and waterways	"Traffic capacity is the capability of a waterway to deal with the traffic and when the traffic volume exceeds this limit traffic flow stops, as is often experienced on congested roads". (Fujii and Tanaka, 1971)
	"The maximum traffic volume to be handled by the approach system satisfying the required service level and safety level". (PIANC, 2014)

Airport capacity definition does not consider the maximum peak as the rest. Its capacity is defined as the maximum average flow which means that the system can accommodate, in many situations, more flow. This represents a conservative definition that not considers the absolute maximum.

In reference to definitions directly related to the research field, the first one was developed based on road capacity definition but it represents a simplified definition, following the assumption that over a certain traffic threshold, flow stops completely, which it has been proved to be not certain.

The second definition considers capacity as the maximum traffic volume satisfying specific service and safety conditions. The main drawback is that considers the traffic volume in terms of amount of vessels. In order to get a good indicator, it has to be comparable with other, but in this case, this definition misses a time reference. Also the level of service is not a relevant issue for capacity definition, since it is qualitative measure used to relate the quality of traffic service.

From the overview of link capacity definitions, it can be derived that existent definitions determine the capacity of a link as the maximum traffic or throughput during a certain time period (flow) through a specific cross-section for most of the different modes of transport, given certain infrastructure and safety conditions.

It has to be considered that port infrastructure is set up from different parts. There are basins or approach channels, where the flow can be measured through a section in a time period, but there are also crossings, turning basins or berthing locations, where maneuverability is limited and dangerous and its capacity is limited by the amount of vessels in the zone.

Based on PIANC (2014) definition, an appropriate general definition for link capacity for ports and waterways would be: *"the maximum flow to be handled by a given cross section or location satisfying the requirements on navigation and safety level"*.

Equation (1) shows the mathematical expression to determine port link capacity (C_{link}) through the maximum flow (q), and (2) shows flow dependence on link layout(α), fleet composition (β) allowed to sail in that link, safety level (γ), traffic rules (ε) and demand (δ).

$$C_{link} = \max(q) \tag{1}$$

$$q = f(\alpha, \beta, \gamma, \varepsilon, \delta) \tag{2}$$

Parameters γ and ε are related and dependent between them, since a port design to satisfy a certain safety level would need specific traffic rules and a change in traffic rules to increase capacity would lead to a variation of the safety level. Moreover, traffic rules include navigation requirements. The demand (δ) considers the total amount of vessels distributed over time, including their origin-destination (O-D) distribution.

B. *Network capacity*

Since a port is a junction of different links, for maritime transportation management and planning, network capacity becomes an important indicator for the system from a macroscopic traffic level.

Usually there is confusion with the term *port capacity* when the definition of *terminal capacity* is used. For terminals the *maximum annual capacity* is defined as *"the capacity that can theoretically be attained if the berths have a 100% occupation, and provided that there are no constraints on the land-side of the terminal. But, since ship arrivals and ship loading and unloading are time-wise stochastic processes, a 100% occupation leads to tremendous congestion on the sea-side of the terminal and to excessive ship waiting times"* (Ligteringen and Velsink, 2012). It does not consider vessel interaction during the sailing process from the entrance towards the berths until they leave again.

In order to reach a suitable definition for port network capacity, several issues have to be taken into account. Traditional maximal flow problem for communication networks, water distribution or electric power systems (Yang et al., 2000) do not consider:

- Travel delay increases with increasing flow as a result of congestion.
- Consider O-D travel time to get the maximum throughput.
- Route choice behavior is considered in most of the transportation analysis as a way to optimize the throughput.

Previous issues applied to port network fulfil that travel delay increases in any link of a port when there is congestion, but port network can have one link congested because its lower capacity but the complete network could be not congested. Considering the O-D travel time or demand can help to analyze and optimize flows in a network by rescheduling some of the trips. Ports have fixed routes for each vessel to their berth regulated by port authorities, then route choice behavior should be considered.

For network capacity in transportation at a macroscopic level, Lave and De Salvo (1968) come up with the following definition of physical capacity of a waterway: *"The physical capacity of a waterway might be measured in terms of the number of barges that could be locked through in the course of a year. More precisely, a waterway might be described as a serial processing system since a tow must traverse the waterway in prescribed order to move from origin to destination. Under these conditions, the capacity of a system is determined by the capacity of the slowest serving facility (the narrowest bottleneck). For a waterway, it is the lock which determines capacity"*. This definition considers a waterway as linear links junction with different elements, but does not consider possible interactions or dependences between some of the parts of the system or bottlenecks. In accordance to the link capacity, the throughput of the system is determined by the most restrictive bottleneck, but this is only valid for special networks which have a linear design. In order to evaluate the influence of each element over the network an assessment of relevant parameters and their interactions are necessary.

For road network capacity there are several concepts proposed in previous studies. The concept of *reserve capacity* assumes that the maximum capacity of a network is defined by a multiplier that maximizes the existent O-D demand matrix without violating link capacities or not exceeding a defined level of service (Wong & Yang 1997).

Practical capacity concept is defined as the summation of all the O-D demands plus an additional demand that the network can accommodate below its level of service (Yang et al. 2000), and it allows to choose both route and destination based on travel costs, while the current demand is preserved.

A comparison and application between the previous concepts (Kasikitwiwat & Chen 2005) shows that the first concept is based on an existing O-D pattern and the capacity is determined by scaling all O-D pairs with a common multiplier, while the second allows a non-uniform O-D growth in the distribution. It is concluded that *reserve capacity* is useful when there is lack of zonal growth information and the *practical capacity* is useful to estimate the network capacity of an existing city.

A more recent formulation for road network capacity has been developed. The idea of Macroscopic Fundamental Diagram (MFD) or Network Fundamental Diagram is that at the level of an area it exists a relationship between the number of travelers on the road and the average speed of these travelers. Geroliminis and Daganzo (2008) showed the relationship between the number of completed trips and the production function which is defined as a weighted average of the flow on all links. The definition finally gives a relation between the traffic flow and density. However, it has one limitation, it requires an homogeneity in traffic conditions in the network.

From these road network concepts it can be extracted that in order to be able to make a proper definition of the port network capacity, a function of the O-D demand have to be considered.

Recent research developed in rail network traffic defines *absolute capacity* as *"the maximum number of trains that can traverse the entire railway or certain critical (bottleneck) section(s) in a given duration of time"* (Burdett & Kozan 2006), called also *theoretical capacity* with a similar definition by other researchers (Abril et al. 2008). Since these definitions consider the ideal maximum throughput of a network, they introduce the concept of *actual (sustainable) capacity*, which is defined as *"the amount that occurs when interference delays are incorporated on the critical section(s)"* (Burdett & Kozan 2006). Capacity is estimated from the called bottleneck approach, as the definition presented for waterways, meaning that a single bottleneck limits the total flow throughput in the entire corridor and finally the total capacity of the network would be the total throughput between all locations. The main drawback of this definition is that it assumes again a linear network, whereas in a port network with several bottlenecks, some of them even having a lower capacity may not represent a bottleneck. For example, a turning basin could allow only 1 vessel inside, but if there were not any berth available, no vessel would go inside the basin.

This review of network capacity definitions from different fields reveals that the identification of bottlenecks, O-D demand as well as specific idiosyncrasies of the processes of a specific infrastructure design may affect any system capacity and they have to be taken into account in order to evaluate a system as a whole. It has to be considered that the same elements in a system with different locations can change completely the result, that is why a specific evaluation should be done for each desired port or network in general.

One suitable definition for port network capacity would be: *"the maximum amount of vessels that can be handled by a port, with its specific configuration, satisfying the maximum throughput feasible for the system"*.

Equation (3) expresses the network capacity (C_{net}) for a port as the maximum outflow (q_{out}), which results as the maximum amount of vessels leaving the network during an specific time interval. These flows (4) are dependent on port layout (α), fleet composition (β) allowed to sail inside the network, safety level (γ), traffic rules (ε) and demand (δ) of the network. Parameters have the same characteristics as in (2).

$$C_{net} = \max (q_{out}) \tag{3}$$

$$q_{out} = f(\alpha, \beta, \gamma, \varepsilon, \delta) \tag{4}$$

Network capacity definition is dependent on its *configuration*, which includes the combination of α, β and δ, present in the mathematical expression.

A constraint for (3) is that the resulting capacity value has to satisfy the *maximum throughput feasible* of the system. This means that the resultant maximum outflow is obtained in which waiting times due to traffic events are not considered in relation to α, β, γ and ε.

C. *Capacity calculation*

In the previous sections, several theoretical capacity definitions were reviewed and new link capacity and port network capacity definitions have been formulated. In order to be able to apply these definitions in a quantitative way, there are several network capacity calculation methods that have been already developed in different fields.

As it has been introduced before, for road traffic there are the *reserve capacity* and *practical capacity* concepts that have been implemented as a method for calculate a value for network capacity (Kasikitwiwat and Chen, 2005).

Other road capacity calculation method are the application of FD or MFD from empirical data, for link or network capacity respectively. MFD was evaluated as a network indicator to evaluate accessibility in a neighborhood (Geroliminis and Daganzo, 2008).

Queueing theory has been often used to estimate capacity. In order to apply this theory a schematized port system is required, with simplification of the facilities and with the no inclusion of complex variables like weather or tidal windows.

Due to the limitations of queueing theory, in order to estimate capacity in ports and waterways, the simulation model *Harboursim* (Groenveld 1983) was developed based on this theory as an event-driven model. This model is a tool for port authorities to deal with port extensions or new satellite ports. Results obtained from this model shows if there are problems in the system, in terms of waiting times, but it does not allow to identify problems between processes. For instance, when dealing with variety of circumstances as crossings, different types of vessels, traffic regulations or weather conditions this model would not reflect the interaction with vessels, only their delays in terms of waiting times. In such complex cases, traffic flow simulation models should be used in for a detailed stage (PIANC 2014).

A computer simulation model is required to be able to simulate more detailed and complicated situations, representing the real-life processes. This tool helps to clearly identify different aspects that should be considered for representing the whole port process, as realistic as it is possible, and the interaction between different processes.

Recently, a simulation model for the assessment of approach channels has been developed (Rayo, 2013). It allows the identification of the main influential parameters in the waiting time for the arriving vessels. In addition some measures to reduce the delay of ships were implemented.

With the same purpose, a simulation model to estimate the port network capacity is introduced in section III.

D. *Vessel traffic rules*

All the navigation processes include traffic restrictions and rules to be followed in order to guarantee a certain level of safety without assuming high risks. For maritime traffic there are international rules that were formulated in the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) in 1972. These rules are applicable on waters outside of established navigational lines of demarcation.

In the specific case of ports, they have specific rules fixed in each case depending on their idiosyncrasies. When there are undefined situations, COLREGS are considered.

In this research certain traffic rules for vessels are specified within the assumptions in the next section.

III. VERBAL MODEL

This section describes the real-life processes in a port, the model created to describe part of the network and the assumptions necessaries for the application of a computational tool describing these processes, which is applied to compare different values of port capacity within a specific layout. This is the so-called verbal model.

The main goal of this simulation model is helping in the identification of the main constraints or bottlenecks in port traffic and assess their effects on the throughput of the system in order to calculate its capacity in further research. The development of a time-step simulation model allows the representation of many different scenarios and the comparison between them.

A. *Port process description*

The aim to build a tool recreating the most relevant processes from port capacity perspective, requires a clear description of all the steps from the entrance of a vessel in a port until its exit.

The port process starts when a vessel requires to access a port. The Vessel Traffic Service (VTS) provides information about the berth availability among other conditions (weather, tidal window, etc.), and if it is feasible to enter the port, then the traffic situation is checked. Vessels with permission of the quay master can enter the port and sail towards their destination, if not, they wait outside the port in the anchorage.

In case that a vessel is allowed to enter the port, it will sail to a specific berth through the approach channel or entrance waterway. Until its arrival to the berthing area, each vessel will sail through different parts depending on the size and complexity of the port, which are turning basins, crossings and inner basins. Each of these parts will have specific requirements in sailing and maneuvering.

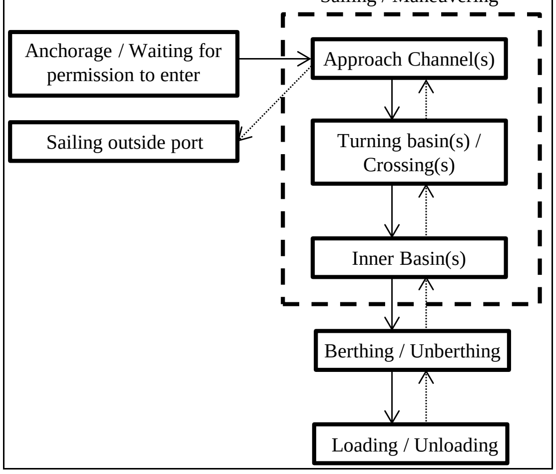

Figure 1. Vessel port processes

Once a vessel has passed all these processes, it will be able to berth and cranes will start the unloading and loading processes. At the time that a vessel is already ready to depart, new permission is required to leave the port. After permission is given, the reverse process occurs.

Fig.1 shows a simplified scheme of the different processes previously introduced. From all the processes involved in the arrival and departure process for vessels in a port, this research focuses on the sailing and maneuvering processes through the approach channels or waterways, inner basins and their connections with turning basins or crossings, included in the discontinuous box in Fig. 1.

These processes are considered as relevant for a port network, which in our expectation have significant effect on the capacity. Waiting for berth availability in the anchorage, maneuvering time, loading/unloading process as well as the anchoring process will be taken into account in future research.

In port traffic is important also to consider the possibility that there are specific rules and restriction for some vessels or some scenarios, like vessels who can only sail alone because of their limited maneuverability, hazardous cargo, among others.

B. *Model description*

The model developed needs of three main input information.

The layout of the simplified port has to be described, including the specific length for basins or approach channels and the location and number of crossings or turning basins. It is defined by a junction of 6 stretches with the same length. Fig. 2 shows an example of the distribution of Origin-Destination (O-D) locations and the order number which defines its layout, where 0 is no constraint, 1 is a turning basin and 2 is a crossing to another berth. In this case the layout is '12001'. The different configurations of port layouts will follow this example.

Other information required for navigation is vessel characteristics, their maximum and minimum speeds, length and maneuvering times. Finally, several traffic rules are required, which are a limitation in number of vessels in turning basins or crossings, the time required for maneuvering in them and the safety distance with the predecessor vessel or before entering the maneuvering areas.

All these parameters define the input for each simulation in order to run the model and create different scenarios, as it will be shown in the next section chapter.

C. *Assumptions*

In the model development, some assumptions have been made in order to represent the complex real-life world in a simplified model. Firstly, some assumptions related to the model are presented:

- Vessel movements are one-dimensional. For the head-on situation between vessels, in opposite directions, it is considered that they do not have any influence between them and their speeds are not modified.
- Maneuvering interaction in turnings or crossings is not considered, only the time spend in that area.

There are other assumptions that are considered just for this research that can be considered or modified in future research, which are:

- The system considers the navigation part from one origin towards a defined destination. The end of their trip is before a location for a berth or maneuvering before berthing or sailing out of the port.
- Vessels are generated in Origin 1 (Fig.2) towards the rest of Destinations, randomly assigned, or from the other Origins towards Destination 1. Vessels with Destination 1 always sail direct from their Origin to that Destination, without intermediate stops inside the port.
- Berthing and maneuvering are not considered and all generated vessels start sailing with unconstrained speed until they find some constraints.
- Vessel generation is independent and the number of vessels with a determined O-D does not influence the rest of O-D.
- There is not any night effect in the model.
- Although weather and tidal conditions are influent parameters for port navigation, they are assumed as stable in order to compare the influence of different rules or layouts under the same conditions.
- Vessel's lengths are the same for all but the speed is random in a range depending on the expertise of the bridge team.

IV. Simulation Model

In this section the algorithm developed for the simulation and different simulated scenarios are presented.

A. *Algorithm*

The main algorithm used for the simulation model is a time-step approach. This approach is selected because of the need of updating the current situation every step, which will allow to determine if following vessels are allowed to enter into the system or into the restricted areas as crossings or turning basins.

A scheme of the main algorithm is shown in Fig. 3.

The main parts of the algorithm for each time step are:

- *Vessel generation*: new vessels entering the system (port) are generated.
- *Infrastructure availability*: it is checked if the traffic situation along the different parts of the port is correct to allow the entrance of vessels.
- *Navigation:* in accordance to the current positions, the following position is determined.

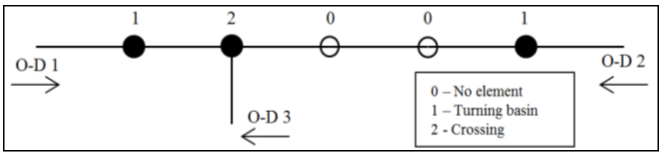

Figure 2. Port layout example

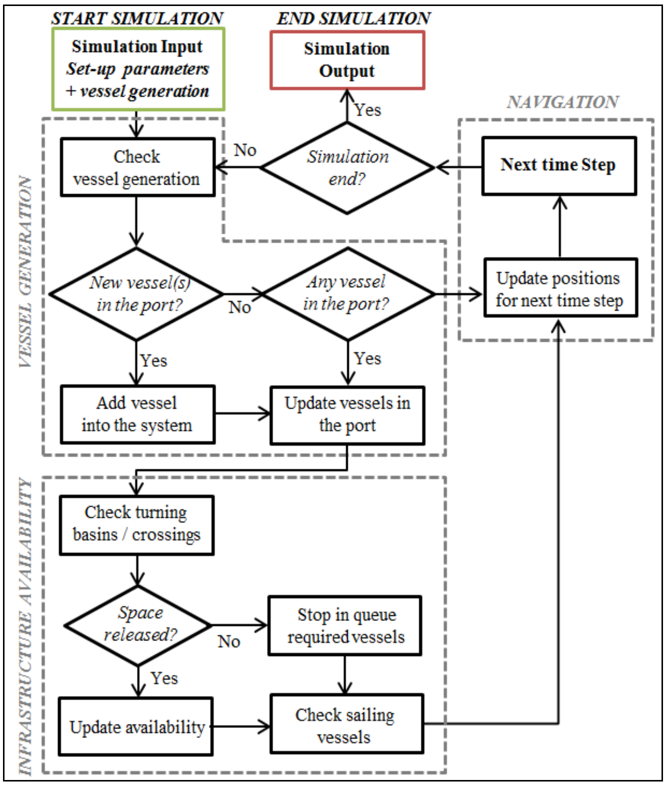

Figure 3. Scheme of model main algorithm

B. Scenarios

The simulation model allows the design of different scenarios with different O-D distribution, geometry of the port and characteristics of the vessels. In order to build different scenarios, the following input is fixed for all the cases:

- Length of vessels of 200 meters and safety distance with the predecessor vessel of 4 times the length (Rayo, 2013).
- Vessel speed is randomly generated between 8 and 15 knots, being typical speeds inside ports (Port of Rotterdam et al., 2014).
- Poisson distributed inter arrival time (90 vessels/day) for Origin 1 and for the total vessel generation from the rest of Origins towards Destination 1.
- Priority in turning basins and crossings is for the arrival vessels.
- Length of each stretch is 2,000 meters.

Comparison between scenarios is divided between link and network capacity calculations.

First, the influence of different port layouts and required maneuvering times for the calculation of link capacity is analyzed. As reference indicators for different scenarios, the maximum number of vessels per hour (MV) passing through a cross section and the average maximum number of vessels per hour (AMV) through the same cross section are considered.

The simulated scenarios have been developed with a simulation time of 10 hours and 200 runs for each simulation, with the aim of getting a capacity quantification.

Table II shows two simulations for the same unconstrained layout with a mean value of AMV close to 7 vessels and MV around 11 vessels. These show that different simulations with the same layout do not have relevant differences and only one simulation for each scenario is analyzed. The standard deviation of MV is around the double of the one for AMV, that is why the following comparison between different scenarios will be carried out based on the AMV results.

The first comparison of different layouts is shown in Table III, where only turning basins or crossings. without their combination are included in different scenarios with different required maneuvering times inside the crossings or turning basins. as well as with a maximum amount of vessels allowed into each of them at the same time. As it can be seen, for both scenario types, mean AMVs are lower than the unconstrained one, but the relevant parameter in its decrease is the maneuvering time. In cases with only one vessel allowed in the maneuvering zone, from 5 to 10 min, it supposes an AMV decrease around 30% and from 10 to 15 min, its decrease is around 20% for both turning basin and crossing. Comparing the decrease for scenarios from 5 to 15 min of maneuvering time, it supposes a decrease of nearly 40% on its AMV.

TABLE II. UNCONSTRAINED SCENARIO

	AMV		MV	
Layout	***μ***	***σ***	***μ***	***σ***
00000	6.91	0.94	11.45	1.80
00000	6.89	0.95	11.12	1.85

TABLE III. AMV FOR DIFFERENT LAYOUT SCENARIOS

Max. vessel allowed inside Turning Basin / Crossing	**1**			**2**		
Turning basin / Crossing time (min)	**5**	**10**	**15**	**5**	**10**	**15**
Layout	***μ***					
00100	6.79	5.41	4.17	6.86	6.02	4.46
01010	6.70	5.17	4.09	6.74	5.66	4.26
11010	6.77	5.03	3.94	6.91	5.30	4.08
	σ					
00100	**0.95**	**0.37**	**0.44**	**0.99**	**0.55**	**0.46**
01010	**0.93**	**0.43**	**0.49**	**0.96**	**0.49**	**0.46**
11010	**0.79**	**0.41**	**0.37**	**1.01**	**0.38**	**0.43**
	μ					
00200	6.74	5.03	4.08	6.69	6.60	6.35
02020	6.58	4.90	3.97	6.88	6.48	6.00
22020	6.34	4.81	3.82	6.67	6.24	5.82
	σ					
00200	0.92	0.36	0.47	0.86	0.92	0.82
02020	0.82	0.37	0.51	0.97	0.93	0.88
22020	0.78	0.39	0.38	0.94	0.83	0.75

TABLE IV. AMV FOR DIFFERENT LAYOUT SCENARIOS

Max. vessel allowed inside turning basin / Crossing	**1**	**2**
Turning basin / Crossing time (min)	**10**	
Layout	***μ***	
01020	4.99	5.81
02100	4.96	6.28
10002	4.96	5.87
01201	4.86	5.45
10202	4.83	4.83
20102	4.85	5.98
02212	4.75	6.08
12112	4.76	5.27
21221	4.66	5.83

With respect to the scenarios with two vessels allowed at the same time inside the maneuvering zone. the decrease in AMV between 5-10 minutes and 10-15 minutes is around 20% for turning basins and 10% for crossings. In the case from 5 to 15 minutes, it decreases around 40% for turning basins and around 10% for crossings. This can be explained because in crossings there are vessels that are taking other directions which means that the density after they pass the crossing decreases.

Standard deviations follow a pattern that shows that in less constrained scenarios, standard deviation is higher because vessels have more freedom of speed than in the ones with more maneuvering time. This pattern appears in all cases except for the crossings with two vessels allowed inside the maneuvering zone, because since vessels have higher variation in their destination the generated results have higher deviations.

AMV indicator is directly related to the maximum link capacity, even though it is measured at port entrance and all vessels have to cross that stretch, which highlights one of the busiest links of the system.

In order to calculate network capacity, other indicators are considered to show the effects of different layouts over the port network capacity. As previously defined in (3), network capacity is equivalent to the number of vessels inside the port, as a result from the difference between total inflow and outflow of the system over time. Results help to see which are the effects of different scenarios over ingoing and outgoing vessel traffic and the amount of vessels inside the port.

Fig.4 to Fig.12 show the results for different scenarios and they are discussed below. All scenarios have been built with 10 minutes of turning/crossing time with different layouts and vessels allowed to sail at the same time in restricted areas. Some scenarios with an increased demand are also discussed.

Fig.4 shows the unconstrained scenario where the total inflow and outflow are nearly the same and the number of vessels inside the system is around 4 and 5. Once the port layout is more complex, its influence over the system is shown in the next figures.

Firstly, scenarios with only 1 vessel allowed to sail inside the turning basins and crossings are analyzed. Scenarios ‘11002’ (Fig.5) and ‘12100’ (Fig.7) have around 20% decrease in total inflow and around 35% decrease in total outflow in comparison with the unconstrained one. This is due to longer time for vessels to cross the system. It can be seen that the number of vessels inside the system grows until around 20 vessels at the end of the simulation, which represents 4 times more vessels than the unconstrained scenario. This situation in real ports is not allowed by port authorities, but if a port would have open access for all vessels arriving and departing, its behavior would be like this.

Scenario ‘02122’ (Fig.9) has a decrease in total inflow around 40% and in total outflow around 65%. Even these decreases are higher than the previous scenarios, the amount of vessels inside the port is a slightly lower than in the previous ones. This can be explained because there are more bottlenecks that are causing longer waiting times for the vessels trying to cross the system, but the presence of more crossings allow vessels to exit the network without using the whole network.

Scenario ‘21021’ (Fig.11) has the same number of constraints as the previous one with a different layout that shows a decrease in total inflow around 20% and in total outflow around 40%. This fact can be explained because constraint locations are more spaced between them than in the previous case.

If now the attention is focused on scenarios with 2 vessels allowed to sail inside, scenarios ‘11002’ (Fig. 6) and ‘12100’ (Fig. 8), they have a decrease in total inflow around 15% compared to the unconstrained scenario and a total outflow decrease around 35%. These results are higher than the ones with only 1 vessel allowed to sail. This is a consequence due to the higher availability for vessels to access turning basins and crossings, which leads to a better network performance.

In reference to scenarios ‘02122’ (Fig.10) and ‘21021’ (Fig.12), as in the two previous scenarios, the decreases in flows are between 25% and 50% less than the ones with only 1 vessel allowed to sail inside. This fact is a result of the existence of more crossings in these scenarios, which represent that some of the arrival vessels turn at some of the early crossings and they are not occupying the following parts of the port, which leaves more space for departing vessels to sail out. These scenarios also have a difference with all the previous ones and it is that the number of vessels inside the port remains nearly constant and network performance would not reach as fast a congested state.

Furthermore, another interesting factor to evaluate is the effects of an increase in demand. In this case, two scenarios with an Origin 1 demand increased to 120 vessels/day are simulated. Fig.13 shows the scenario '11002' with an increased demand in comparison to the previous scenario with the same layout and conditions (Fig.5). It can be seen that the total inflow is higher while the total outflow decreases, which leads to a higher increase trend in vessels inside the port. That would create more waiting times along the network.

Fig.14 shows the scenario '21021' also with increased demand. Although results are similar to the previous case, for this layout the effects of the increased demand are lower than in the previous one. It is because in this scenario there is already more vessels inside the vessels and densities are higher, thus the effects are lower.

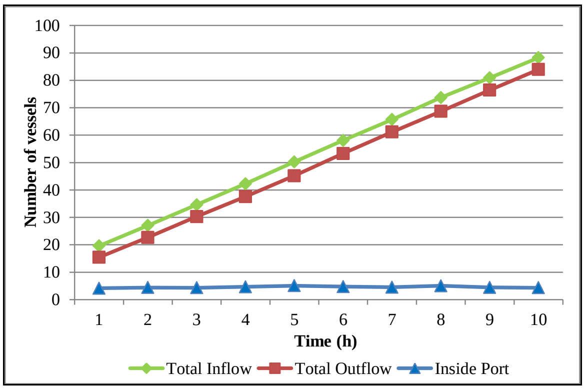

Figure 4. Scenario '00000'

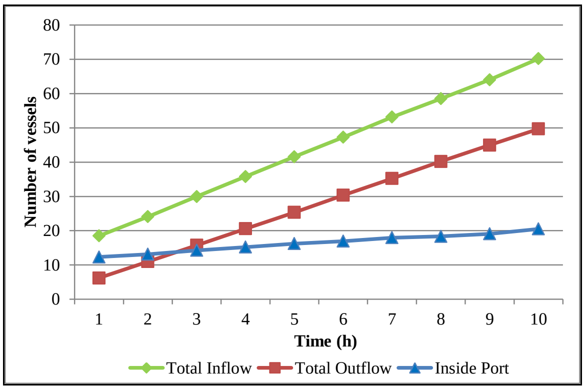

Figure 5. Scenario '11002'(1 vessels in turn/cross)

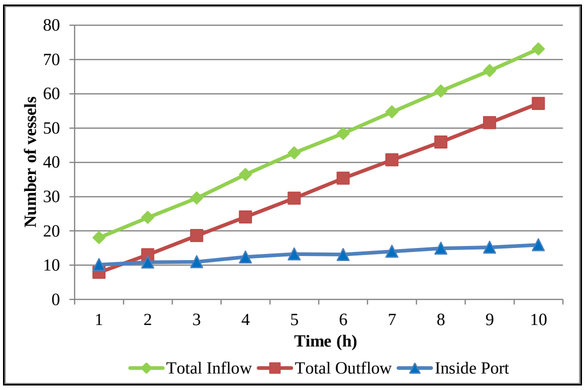

Figure 6. Scenario '11002' (2 vessels in turn/cross)

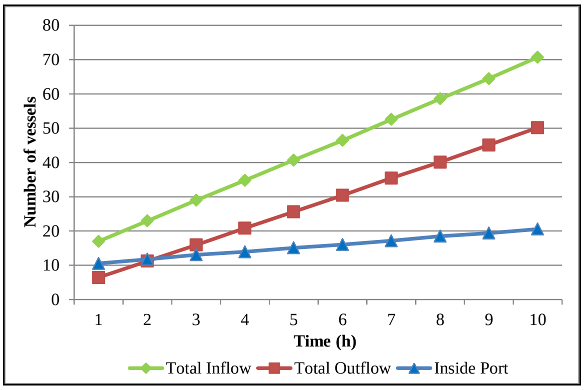

Figure 7. Scenario '12100' (1 vessels in turn/cross)

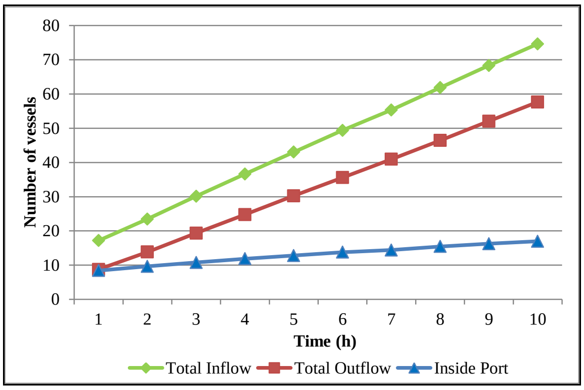

Figure 8. Scenario '12100' (2 vessels in turn/cross)

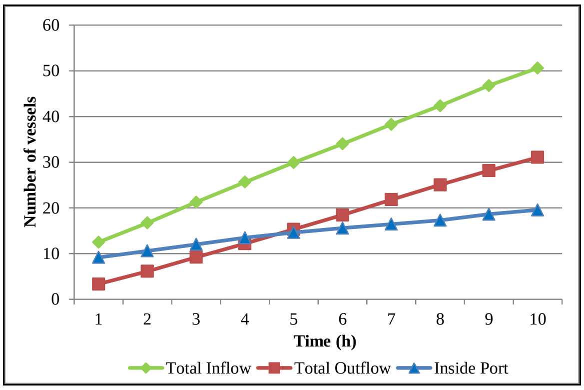

Figure 9. Scenario '02122'(1 vessels in turn/cross)

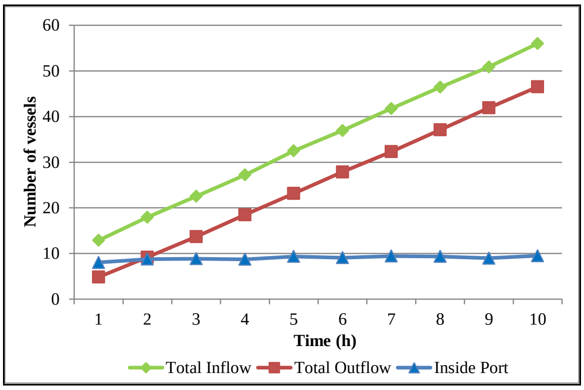

Figure 10. Scenario '02122'(2 vessels in turn/cross)

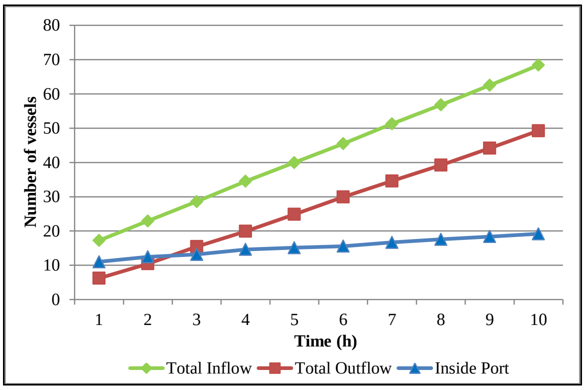

Figure 11. Scenario ‘21021’(1 vessels in turn/cross)

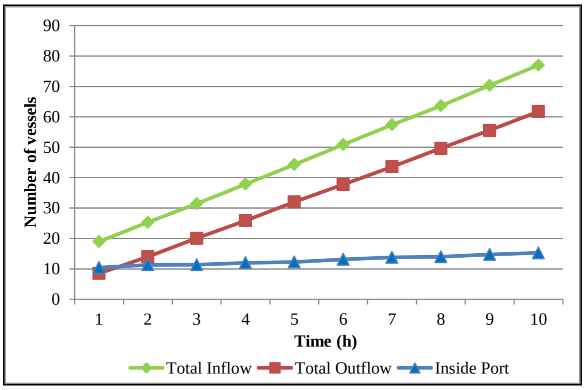

Figure 12. Scenario ‘21021’(2 vessels in turn/cross)

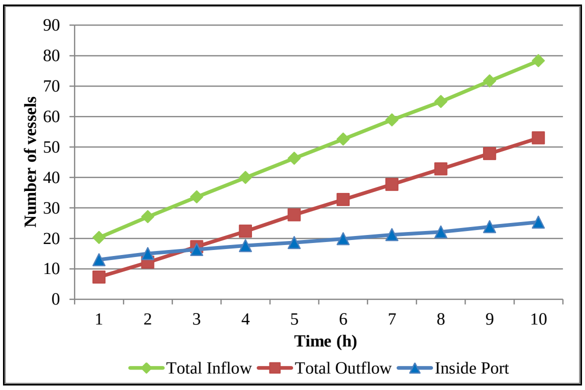

Figure 13. Scenario ‘11002’ (1 vessels in turn/cross and 120 arrival vess/day)

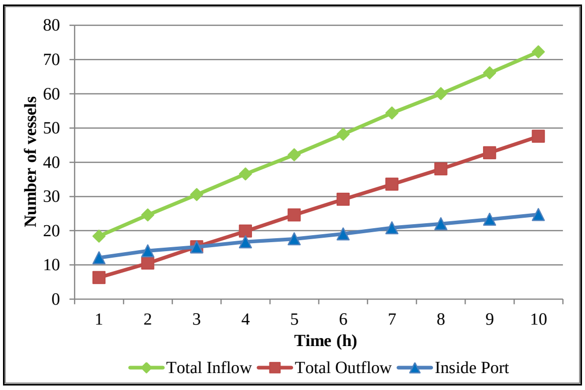

Figure 14. Scenario ‘21021’ (1 vessels in turn/cross and 120 arrival vess/day)

V. Conclusion

In this paper, link and network capacity definitions are reviewed in order to get a clear view of how capacity should be estimated. These definitions are the base for choosing the parameters to include into the model.

The port navigation process is described and its network elements are identified in order to simulate vessels behavior on a macroscopic level. The model is based on a simplified system in order to quantify the influence between different layouts and conditions.

Results analyzed in the previous chapter show that the differences in capacity when measuring AMV are influenced by different layout and the more complex it is the port network, the lower the AMV value is. However, it has been founded that the most influent parameter is the time restriction in maneuvering zones where vessels are not allowed to sail together.

Combined scenarios show how the number and location of crossings and turning basins in the layout of a port can affect to the performance of the traffic inside its network. The presence of crossings instead of just turnings is favorable for the network performance because the vessels are not using all the port infrastructure as a linear bottleneck system. Another relevant issue to be taken into account is the number of vessels allowed to sail into specific areas of a port, hence it can imply substantial differences in the final performance of the system. In addition, it has been shown that the effects of different demands are crucial for any port network capacity estimation or approach.

Although in this paper a deep analysis of relevant parameters has been carried out, further research will analyze the influence or optimization of these parameters and it will be developed with higher detail, including the effects of different ranges of speeds and overtaking situations, among others. Furthermore, a more realistic approach should be developed considering dependent O-D demands, which means departure demand from the port dependent on the arrival one, as well as, the possibility to allow some vessels to do intermediate trips inside the port.

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