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ARTICLE

Transportation system models to analyse ports competition and cooperation

Francesco Russo[1] · **Giuseppe Musolino**[1]

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Abstract

Some global drivers of the shipping market, such as the carriers' alliance consolidation process and the growing ship sizes have determined critical conditions in standalone ports in the XXI century. The traditional attitude of each port during the XX century was to consider other ports, even if they belong to the same territorial system, as competitors following the postulate of the natural monopoly of access to a territory. However, the necessity to respond to the binding requests of port users and of the ship gigantism brought to different experiences between ports belonging to the same territorial system. New forms of cooperation and competition took place at different levels. The paper presents a theoretical equilibrium model to analyse the competition and/or cooperation scenarios of two, or more, ports belonging to a territorial system. The model is based on the consolidated topological-behavioural paradigm of Transportation System Models (TSMs). The proposed equilibrium model allows to simulate the condition inside a port system, which moves from a competition attitude between ports to a cooperation one, within the same modelling framework. The model could provide to the port authorities, managers, planners and researchers a quantitative tool to understand the competition-cooperation scenarios and to define alternative strategies in relation to the decisions taken by other actors of the market.

Keywords Maritime system · Competition · Cooperation · Ports, territorial system · Transport System Models (TSMs) · User equilibrium · System optimum

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✉ Giuseppe Musolino
giuseppe.musolino@unirc.it

Francesco Russo
francesco.russo@unirc.it

[1] Dipartimento di Ingegneria dell'Informazione, delle Infrastrutture e dell'Energia Sostenibile, Università degli Studi Mediterranea di Reggio Calabria, 89100 Reggio, Calabria, Italy

1 Introduction

In the last decades of the XX century the globalization has shifted the national economies from import-substitution (or investment-led) to export-oriented policies. Therefore, a great increase was registered in external trade volumes generated in all regions of the world. In broad terms, some of them became production regions (e.g. the Far-East), while some others became regions where intermediate and final consumptions are concentrated. Maritime transport became one of the pillars of the globalization of trade generated by the above process. Today, more than 80% of world merchandise trade by volume is carried by sea (UNCTAD 2022).

In this context, ports gained strategic importance as they became crucial nodes in the global supply chain. A new port strategy started at the beginning of the XXI century, which contradicts what had been the historical postulate of ports: natural monopoly of access to a territory. In order to cope with the growth of sea transport, mentioned above, three different processes were activated that have changed the global game of sea transport: the consolidation of carriers (UNCTAD 2022) and the increase in the size of ships (Tchang 2020; Rodrigue 2020), on the sea side; the improvement of access to the hinterland on the land side (Dong et al. 2018).

As these processes consolidated, the position of individual port became increasingly complex, and can present problems of vulnerability dependent on the direct links with other ports (García et al. 2021). In several cases, ports have been reduced their volumes, or have reached zero. The port of Taranto in Italy is a textbook example. The traditional paradigm of "competition" between ports had not held up in the face of the alliance between carriers, increasingly with integration also on the land side, and naval gigantism. The new paradigm of "cooperation" has been proposed and implemented in many port systems (Song 2003).

The cooperation paradigm is evolving in two different forms: merger of two ports into a single new authority; alliances that are made at different levels: from strategic choices to the sharing of individual infrastructure projects.

The problem of cooperation and competition strategies for ports in the international container transport was defined in the first of XXI century by Heaver et al. (2001). The problem of competition and cooperation between ports was introduced in Song (2003), and later developed in further studies, as briefly described in the next section.

The general theoretical framework of Transportation System Models (TSMs) has never been used to explain the process of competition-cooperation between ports. The basic theory of TSM is the topological-behavioural paradigm. The authors extended the TSMs from the consolidated field of passenger mobility and the distribution of goods on land transport networks to a different field: that of ports. The novelty of this study, which is a distinctive feature compared to the published studies, is the use of the theoretical model of transport equilibrium in the context of TSM to study a port system.

The proposed theoretical model can support the analysis of the different scenarios for a port system, offering the possibility of using transport science with its fundamental equations formalized in the TSM.

According to the context introduced above, the paper is articulated into five steps depicted in the flow-chart of Fig. 1.

The first step, contained in this introduction, reports the two research questions of the paper:

- Research Question 1 (RQ1), "*How big players (ports) are responding to: carrier alliances, increasing ships' dimension and territorial accessibility processes? And which model has mainly been used?*".
- Research Question 2 (RQ2), "*Is it possible to build a theoretical model that allows to study the competition-cooperation process between ports, in the framework defined by TSM?*".

The second step (Sect. 2) synthetizes the evolution of ports and the existing models to study their evolution during the XXI century, in the attempt to respond to the RQ1. The third step (Sect. 3) presents a theoretical equilibrium model of competition-cooperation of ports belonging to a territorial system, based on the Transportation System Models (TSMs). The proposed equilibrium allows to simulate the condition inside a port system, which passes from a competition attitude between ports to a cooperation one, using the same modelling framework. The fourth step (Sect. 4) presents a prototypal application of the proposed theoretical model with a numerical example. The model is proposed in the attempt to respond to the RQ2. The last section reports the conclusions in terms of importance of the problem and theoretical solution proposed; novelties and peculiarities introduced for studying the evolution of port systems with TSM framework, limitations of the proposed approach and future work.

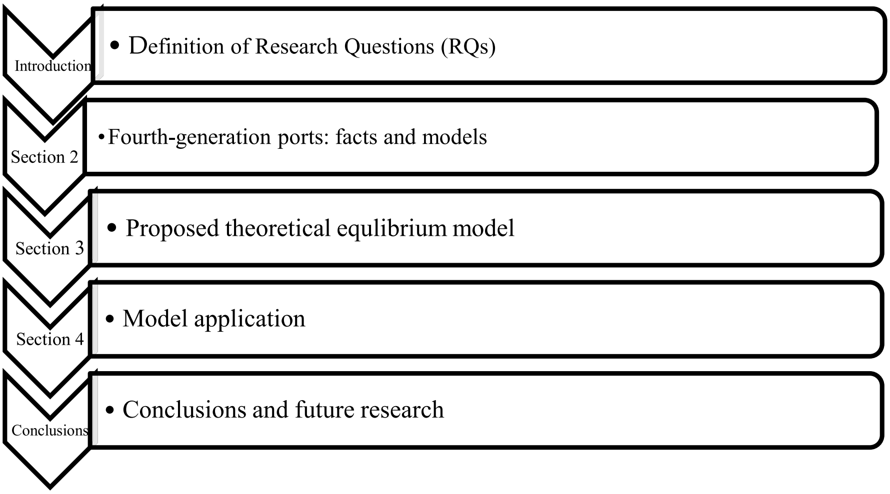

Fig. 1 Flow Chart of the research methodology

2 Fourth-generation ports: facts and models

The section is subdivided into two parts. The first part (par. 2.1) synthetizes the evolution of ports and the second one reports a selection of models existing in literature to study the coopetition process, in the attempt to respond to the RQ1.

2.1 Port systems

Ports are the gate for the exchange of freight and people since ancient times. As previously introduced, ports may be classified according to the concept of generation (UNCTAD 1994; Russo and Musolino 2020). The first-generation ports were built close to the cities. The *City Port* model was dominant for centuries. The second-generation ports are the *Industrial Ports*. They are built close to industrial areas to support the supply of raw materials and final products of industrial plants during the XX century. The third-generation ports emerged after 1980s. The *Container Port* was born due to the worldwide diffusion of container and to the growing requirements of the international trade. Ports were fully embedded in the international supply chain, becoming generators of added value (Musolino et al. 2022a, b; Russo et al. 2022, and references included).

At the end of the XX century the dichotomy between the international (global) nature of port customers (shipping lines, terminal operating companies, forwarding companies, …) and the territorial (local) constrains of ports, became more evident. The presence of municipal or regional administrations inside ports governance, has traditionally prevented investments outside their territory and has induced to consider other ports as competitors (de Langen and Nijdam 2009). Ports shifted from their traditional competitive attitude towards a cooperative attitude with closer ports, generating the born of fourth-generation ports, the *Cooperative Port* (Russo and Musolino 2021a; Roumboutsos et al. 2022). UNCTAD (1999) introduced a definition of fourth-generation ports, "which are physically separated but linked through common operators or through a common administration…", which followed the previously three (UNCTAD 1994).

In the following years a number of papers emendated and elaborated the port generation approach defined by UNCTAD, and they introduced further elements in order to capture the new trajectory that was delineating for ports. Paixao and Marlow (2003) argued that the uncertainty that affect world economic growth pattern was not consistent with the idea of a third generation and they proposed a new logistics approach based on agility. According to Flynn et al. (2011), the fourth-generation ports definition of UNCTAD focused on internal efficiency, neglecting to requirements of stakeholders and customers. They proposed a conceptual framework of fifth generation ports with world-class customer-centric and community ports representing the next evolutionary step on the port ladder. Lee and Lam (2016) proposed to revise the concept of fifth generation port, previously introduced by Flynn et al. (2011) and they empirically applied it to compare four Asian ports: Shanghai, Singapore, Hong Kong and Busan. Their analysis, even if the description of the factors is less vague than the one of Flynn et al. (2011), have still a qualitative nature. The technical debate on this class is still ongoing; focusing on the fundamental technological integrators of port actors and functions (see Russo and Musolino 2021b; Musolino et al. 2022b, and references included).

In order to address an answer to RQ1 proposed in the introduction, it can be noted that the last two decades were characterized by an observed evolution of closer ports to cooperate, other than the tradition behaviour to compete (Martín-Alcalde et al. 2016). In some cases, ports were forced due some external treats; in other cases, ports were driven by common needs (Inoue 2018). There is a factual evidence of the new process that involves the ports.

The treats, or needs, belong to the following, above introduced, three categories.

(1) *Carrier's alliance consolidation* reduced the bargaining power of port authorities and made ports vulnerable in relation to the requests of deeper channels and berths, and of higher capacity of container terminals (Yoshitani 2018).
(2) *Growing ships' dimension* together with hub and spoke shipping system determined pressure on ports to invest in the development of sea-side material facilities. But not all the ports can sustain this competitive game, which requires relevant amount of funds and which risks to replicate similar investments in ports located in proximity (Inoue 2018).
(3) *Enhancing hinterland access* allows to some ports in proximity to find more convenient to develop shared port centric logistics systems, rather than acting in an autonomous way.

The forms of cooperation revealed between ports may be schematized in two typologies: the merger and the alliance.

(i) *Mergers* are those that pass from two or more port authorities to one, with a single decision-making structure. The merger conveys the decisions of the individual partners (e.g. authorities) into a new institutional subject (e.g. one new authority), that defines and pursues new and coherent goals. One example of merging is Italy, that is the only country which proposed the "port system" concept at national scale in 2015 (MIT 2015). Before the reform, Italy had twenty-four Port Authorities, after had 15 Authorities. In the field of mergers, it is possible to report the case of Antwerp and Zeebrugge, currently under construction. Cooperation started both with top-down processes, as in Italy, and with bottom-up processes as in Belgium.
(ii) *Alliances* have different characteristics and can range from the closest, which involve the sharing of an economic sector of the two companies with shared governance, to those aimed at a single objective, such as the creation of an infrastructure of common interest. The alliance allows the individual partners (e.g. authorities) to keep their own independency in order to pursue common objectives. The alliance has a limited period before becoming extinct. The alliance field can be considered as a continuum from a maximum level, that is sharing of an economic sector, to a minimum one, that is the alliance on specific projects (see Slack et al.

> 2009; Yoshitani 2018; Lee and Cullinane 2016; Inoue 2018). In the field of alliances, it is possible to recall a wide range that goes from the ports of the River Delta and the Yang Tse Delta in China, to the northern ports of the West Coast USA, to those of Japan, to various other European examples, from those of Malmoe and Copenhagen to the French ones to the German ones on the North Sea and the Baltic Sea. At the extreme, the weaker alliance is that aimed at the realization of specific infrastructural projects, such as the alliance between Long Beach and Los Angeles (Heaver et al. 2001), in the 90 s of the twentieth century, for the development of a port intermodal rail and a rail project known as the Alameda Corridor Project.

According to this approach, the definition of fourth generation of port (UNCTAD 1999), that considers common operators and administrations, may be actualized by considering two main categories of cooperation (Heaver et al. 2001; Dong et al. 2018).

(i) The *vertical cooperation of ports* (with upstream and downstream actors of the supply chain) generally concerns ports that do not have overlapping productive activities. If they have overlapping activities these are minimal, while they have many complementary productive activities. This is often the case with ports located along a river and in the estuary.
(ii) The *horizontal cooperation among the ports*, on the other hand, is the most complex one in which between the two (or more) ports there are multiple overlapping productive activities. This is the case that requires adequate modelling tools to study the two situations of competition between the two ports or of cooperation.

The above categories represent a basis of multi-port gateway regions and of multi-port hub regions (Notteboom 2009), when the same port system has been individuated even if without a common governance.

2.2 Cooperation/competition modelling

The general competition between ports was analysed by several profiles, using models belonging to the class of multi-criteria evaluation: the analytical hierarchy process (AHP), has been developed in a hierarchical fuzzy process (FHP), which overcomes the limits of non-additivity of the AHP (Yeo and Song 2006). The approach to compare efficiency of ports, often used (Niavis and Tsekeris 2012), is that which considers production functions. Parametric analyses (Deterministic Frontier Analysis—DFA; Stochastic Frontier Analysis—SFA) require a priori explication of a production function, while non-parametric ones (Data Envelopment Analysis—DEA; Free Disposal Hull—FDH) do not they require it.

The name coopetition was used for describe a cooperative-competitive behaviour among ports. The strategic option is introduced in concept and in practice in Song (2003), who proposed the paradigm of coopetition from the economics and strategic management perspectives by describing the case study of Hong Kong ports and South-China ports. Sahoo and Song (2022) analyse the degree of competition and co-operation for three major ports in Asia: Shanghai, Singapore and Busan. These ports generate the greater throughputs and subsequently create economic values in the region. The study proposes an inter-dependency ratio of container ports to estimate the degree of co-opetition among the ports based on the trading patterns of container line services operating in the ports.

Some of the works that have investigated the theoretical problem and/or have recalled the most important experimental situations that have occurred worldwide, are recalled below. Xian-jing (2009) uses the game theory to study the relationship of coopetition between ports. The paper analyzes the ports of Shanghai and Ningbo firstly presenting the model based on the Prisoner's Dilemma under the single-stage strategy, then analyzes the conditions under cooperation and give advices. Shao (2012) studied the two most important ports in the Yangtze River Delta, Shanghai port and Ningbo-Zhoushan port, considering that Ningbo-Zhousan derive from a completed merging process. The author makes an analysis of their co-opetition strategies by employing the methods based on the game theory. Ishii et al. (2013) analysed the competition between the two ports of Busan and Kobe by means of Nash equilibrium approach. Asadabadi and Miller-Hooks (2018) formalize the co-opetition problems among ports, as a bi-level multiplayer game theoretic approach, wherein each individual port takes protective investment decisions while anticipating the response of the common market-clearing shipping assignment problem in the impacted network. This lower-level assignment is modelled as a cost minimization problem. Linear properties of the lower-level formulation permit reformulation of the individual port bi-level optimization problems as single-level problems. The same authors (Asadabadi and Miller-Hooks 2020) evolve the proposed bi-level approach using game theoretic optimization models for assessing and improving the resiliency and reliability of the global port network. In the field of analysis of competition and competitiveness Lee et al. (2018) proposed a hybrid method of consistent fuzzy preference relation (CFPR), with an advanced multi-criteria analysis method. Weichen (2023) states that port managers and governments have promoted the process of port integration in multi-port regions, but a lack of coordination between ports frequently arised. The work analyses the interactions between relevant stakeholders, including governments and port operators, by means of dynamic simulation methods. The methods proposed are based on game theory, where players have a rational behaviour and have a common knowledge. Yuan et al. (2024) analyse the process of port cooperation and the elements that allow its stability through evolutionary game theory approach. The authors find that incremental benefits, costs other elements affect the stability of port cooperation. Wu et al. (2024) focus on the co-opetition between dry port and seaports in reducing vulnerability to climate change-related disasters. The co-opetition process is simulated by means of a two-stage game-theoretical economic model. A model application on the development of China Railway Express indicates that cooperation leads to more seaport adaptation investment, while competition results in reduced investment.

At the end, it is possible to conclude that many big players (ports) are deepening and pursuing the cooperative strategy and that the main theoretical model used is the game theory.

3 Proposed theoretical equilibrium model: from competition to cooperation

The section proposes an equilibrium model to simulate the competition-cooperation behaviour of ports that are in horizontal economic relationships.

The proposed model is based on the theory of Transport System Models (TSM) (Cascetta 2009; Cantarella et al. 2019).

TSMs simulate a transport system by means of a process, where travel demand and transport supply interact, providing costs (or disutilities) and flows. The three modelling components of the TSMs are the transport supply model, the travel demand model and the demand–supply interaction model.

The *equilibrium model* relies on the User Equilibrium (UE) approach or on the System Optimum (SO) one (Cascetta 2009; Cantarella et al. 2019). According to UE approach, users' choices aim to minimizing their individual costs (First Wardrop principle); while according to SO approach, users' choices aim to achieve the minimum total cost for all users, although some of them choose non-minimum cost alternatives (Second Wardrop principle) (Wardrop 1952).

The UE and SO models are based on rather different behavioural assumptions. It can be assumed that the UE model simulates a competitive behaviour of users, who make choices aimed at minimizing their individual cost; while the SO model simulates a cooperative behaviour of users, who make choices aimed to minimize the total cost (of all users). The SO costs and flows correspond to objectives that a transport system manager generally pursues.

3.1 Ports system specification

The port system of fourth generation is generally composed by some ports, each one generally having one or or more terminals. The proposed model can be used for any number of fungible ports and terminals.

The transport system is specified as follows:

(i) the supply is represented by a port system, composed by ports with one or more terminal for each;
(ii) the demand is represented by the behaviour of an alliance, who chooses the port for a ship arriving in proximity of the port system (with the same transport cost from the origin).

Consequently, the TSM is composed by:

(i) a supply model, which is given by the port system with (dis)utility functions, usually defined as cost functions depending on ship flows;
(ii) a demand model, which is given by a port choice model driven by (dis)utility, which includes (congested) transport costs;
(iii) a demand–supply interaction model, based on the equilibrium approach (UE and SO) to estimate transport costs (or disutilities) and flows.

In order to study the port system, two scenarios are considered: competition between the two ports and cooperation between the two ports. The theoretical model must allow to highlight the differences in the two scenarios.

Once the scenarios have been defined, it is necessary to know whether the ports are in congested or non-congested conditions.

In the case of non-congested ports, the costs do not depend on the flows and therefore carriers can choose the port by optimizing their utility, regardless of the number of ships. In this case the demand model with a network loading model allows to obtain the flows in the ports.

The problem to be studied is the congestion condition, that is, when flows determine a modification of costs, and the costs determine the modification of flows, determining a circular dependency between costs and flows.

It is therefore necessary to have a theoretical model that allows to compare the two scenarios, competition and cooperation, in the case of congestion of one or more ports of the system, that is of circular dependency between costs and flows.

3.2 Theoretical model formulation

According to above theoretical elements of the TSMs, the two equilibrium assignment models, UE and SO, are used as follows.

It is useful to make some assumptions that are used in the two formulations of the equilibrium assignment model. The general assumption is to use a supply model expressed through a network of representative links of administrative functions and physical movements that take place in each port.

Specifically, links representing the cost of using the port and links representing the loading and unloading times in which the cost depends on the flow.

The single ship is the reference unit of flow; therefore, the port time (cost) depends on the number of arriving ships at port. As in the road case, where cars and trucks are present, the presence of ships of different sizes may be treated with equivalent coefficients.

3.2.1 Competition between two congested ports: UE model

UE equilibrium model may be considered if the following assumptions hold.

(i) The port transit operation time depends on ship arriving flow (congested ports) and ports have a competition attitude. No merger, or alliance, policy is defined.
(ii) The (ocean) carrier, assumed as decision-making unit, chooses the port to dock its ship, that allows minimizing the port transit time (cost) of its individual ship (First Wardrop principle).
(iii) The port choice model is deterministic, according to the First Wardrop Principle. In this case, the UE equilibrium model is called Deterministic, (D)UE. The (D)UE formulation is adopted in this paper as first step of analysis. The competition could be also simulated by means of a Stochastic User Equilibrium, or (S)UE, formulation (see Cascetta 2009).

The (D)UE equilibrium is formulated as follows

$$\mathbf{f}^{\mathbf{opt,UE}} = \min\phi(\mathbf{f}) \tag{1}$$

with$\mathbf{f} = [.., \mathbf{f_p}, \ldots]^T$, vector of ship flows, with f_p ship flow arriving at port p;

$\phi(\mathbf{f}) = \Sigma_p \int_0^{fp} c_p(x_p) dx_p$, objective function to minimize, defined as *integral cost,* obtained as the sum on all ports of the integral of marginal costs of each ship arriving at port p;

$c_p(x_p)$, marginal cost function of the individual ship at port p;

$\mathbf{f}^{opt,UE}$, optimum vector of ship flows, or (D)UE equilibrium flow vector, for which costs associated to the choice of alternative ports are equal, that determine the minimum value of objective function $\phi(\mathbf{f})$.

3.2.2 Cooperation between two congested ports: SO model

SO equilibrium model may be considered if the following assumptions hold.

- The port operation time depends on ship arriving flow (congested ports) and port are in a cooperation attitude. A merger policy is defined.
- The ocean carrier, assumed as decision-making unit, chooses the port to dock his ship, that allows minimizing the total port transit time (cost) of all arriving ships (Second Wardrop principle). The ocean carrier receives the indication about the port of destination for his individual ship from a port authority.
- The port choice model is deterministic, in order to reproduce the condition of the Second Principle (Wardrop 1952).

The SO equilibrium is formulated as follows:

$$\mathbf{f}^{\mathbf{opt,SO}} = min\chi(\mathbf{f}) \tag{2}$$

$\chi(\mathbf{f}) = c(\mathbf{f})^T\mathbf{f}$, objective function to minimize, defined as *total cost,* which depends on vector, $\mathbf{f}$, defined above; $\boldsymbol{c}(\mathbf{f})$, cost vector; $\mathbf{f}^{\mathbf{opt,SO}}$, optimum vector of ship flow, or SO equilibrium flow vector, for which the total port transit time (cost) of all arriving ships is minimum (minimum value of objective function $\chi(\mathbf{f})$).

4 Model application: test case

The section reports a test application in a typical port system, composed by two ports: Red port, R, and Blue port, B.

The treatment is identical for the case of several ports and for the even more general case of several terminals in several ports. For each of the two ports, again for simplicity of analytical treatment and graphic representation, one single link is considered to represent the whole port operations.

4.1 4.1 Supply, demand and assignment models

The supply model presented in this work derives from a specific corpus of literature concerning the supply models for maritime freight transport and commercial ports (see Russo 2005; Midoro et al. 2005; Assumma and Vitetta 2009; Russo et al. 2014).

The (dis)utility function is specified as the total port time, which depends on ship flows arriving at the port:

$$t_p\left(\mathrm{f_p}\right) = \mathrm{t_{0,p}}\left(1 + \mathrm{a}\left(\mathrm{f_p}/\mathrm{Cap_p}\right)^{\mathrm{b}}\right) \tag{3}$$

with:

$t_p(\mathrm{f_p})$ [h], total time in port p, which depends on the arrival flow $\mathrm{f_p}$ in port p, defined as the total time that the ship spends in the port p from its arrival in the harbour bay to its departure after the conclusion of port operations (the cost function is assumed separable, see Cascetta 2009);

$\mathrm{f_p}$ [ships/month], arrival flow of ships at port p;

$\mathrm{t_{0,p}}$ [h], total time in port p without congestion (it provides an average time for the execution of the sequence of port operations in absence of congestion);

$\mathrm{Cap_p}$ [ships/month], capacity of port p, defined as the maximum number of ships that may be handled at the port p in a reference time period;

a, b, parameters.

The function of Eq. (3) is called separable, as expresses the dependency of total time in port p from the arrival flow in port p. In general, the function cannot be separable, expressing the dependency of total port time in port p from the arrival flow vector, **f**: $t_p(\mathbf{f})$, in other words, the total time in port p could depend from flows in other ports.

Table 1 reports the parameters, used in the test case presented, of the port time function. The capacity of the two ports is the same (Cap = 500 [ships/month]); and this holds also for the parameters, a and b, that shape the port time function.

Table 1 Parameters of the supply model

Port	Cap	$\mathrm{t_0}$	a	b
	[ships/month]	[h]		
Red (R)	500	30	2	4
Blue (B)	500	350	2	4

The ratio between the performances of the two ports without congestion is assumed to be: $t_{0,B}/ t_{0,R} > 10$. It is worth noting that it was deliberately assigned a high value to the parameter $t_{0,B}$ (respect to the parameter $t_{0,R}$), to emphasize the differences between the two ports.

The equation that synthetize the supply model of the port system is the difference between total port time of port Red and of port Blue, $\Delta t_{R,B}()$:

$$\Delta t_{R,B}\left(f_R\right) = t_R\left(f_R\right) - t_B\left(f_B = d - f_R\right)[h] \tag{4}$$

with d, total demand, or total number of arriving ships at the port system.

The equation of the deterministic demand model of the port system is:

$$f_R\left(\Delta t_{R,B}\right) = \begin{bmatrix} 0 & if \Delta t_{R,B>0} \\ \in [0, d] & if \Delta t_{R,B=0} \\ d & if \Delta t_{R,b<0} \end{bmatrix} \tag{5a}$$

$$f_B = d - f_R \tag{5b}$$

The total demand is assumed to be:

$$d = f_R + f_B = 1000\left[ships/month\right] \tag{6}$$

4.1.1 Competition between two congested ports: UE model

The carrier behaviour, in the case of competition between two congested ports, is described by means of the (D)UE equilibrium model (Eq. 1).

The integral cost function, $\phi()$, specified for the two ports:

$$\phi(f_R f_B) = \int_0^{fR} c_R\left(x_R\right)\, dx_R + \int_0^{fB} c_B\left(x_B\right)\, dx_B \tag{7}$$

is graphically illustrated in Fig. 2.

The minimum value of the function $\phi()$ corresponds to the vector of optimal flows (or UE equilibrium flows):

$$\mathbf{f}^{\mathbf{opt,UE}} = \left[f^{opt,UE_R}, f^{opt,UE_B}\right] \tag{8}$$

that determines equal values of port times (see Eq. 3)

$$t_R\left(f^{opt,UE_R}\right) = t_B(f^{opt,UE_B}), \text{ or } \Delta t_{R,B}(f^{opt,UE_R},\ f^{opt,UE_B}) = 0 \tag{9}$$

The condition of Eq. (9) is depicted in Fig. 3, which reports the plots of the port times function for each of the two ports: the Red port and the Blue port. The two curves intersect at the point where the ports times are equal, representing the (D)UE equilibrium flows.

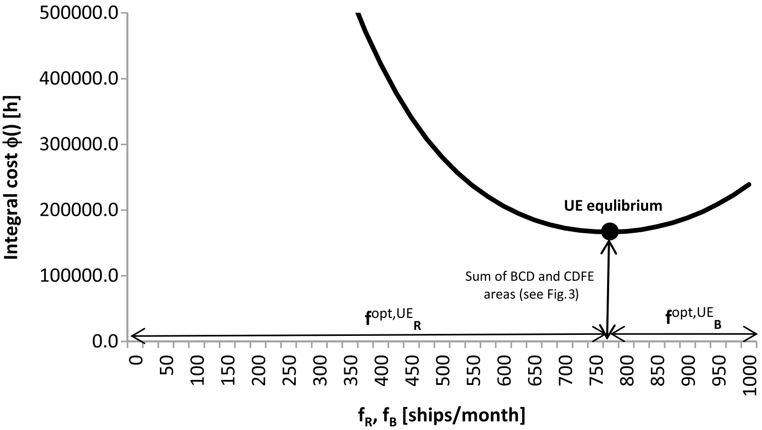

Fig. 2 Plot of integral cost function (ϕ) for the two-ports systems

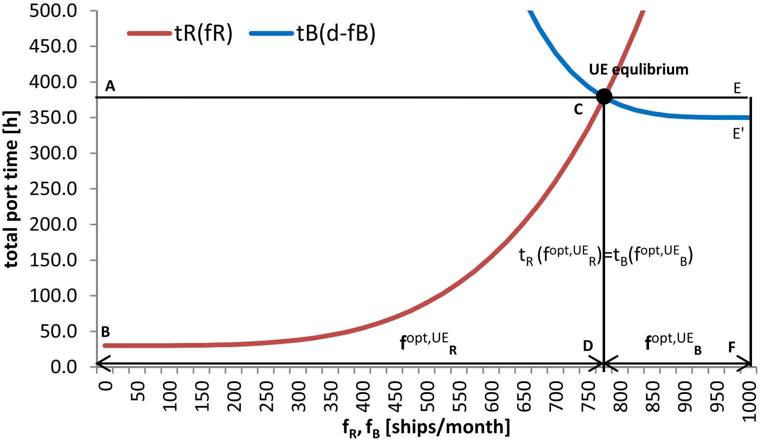

Fig. 3 Port time function for port Red (R) and port Blue (B): UE equilibrium

The sum of the area of the rectangle ABDC and of the rectangle CDFE represents the total port time of all the ships, in correspondence to the DUE equilibrium condition (Eq. 1), calculated for $\mathbf{f} = \mathbf{f}^{\mathrm{opt,UE}} : \phi(\mathrm{f}^{\mathrm{opt,UE}}) = 166{,}528$ [h].

4.1.2 Cooperation between two congested ports: SO model

The carrier behaviour, in the case of cooperation between two congested ports, is described by means of the SO equilibrium model (Eq. 2):

$$\chi\left(\mathrm{f_R f_B}\right) = \mathrm{c}\left(\mathrm{f_R}\right)\ \mathrm{f_R} + \mathrm{c}\left(\mathrm{f_B}\right)\mathrm{f_B} \tag{10}$$

Figure 4 depicts the curve of total cost function, $\chi()$ of the SO equilibrium model (Eq. 10).

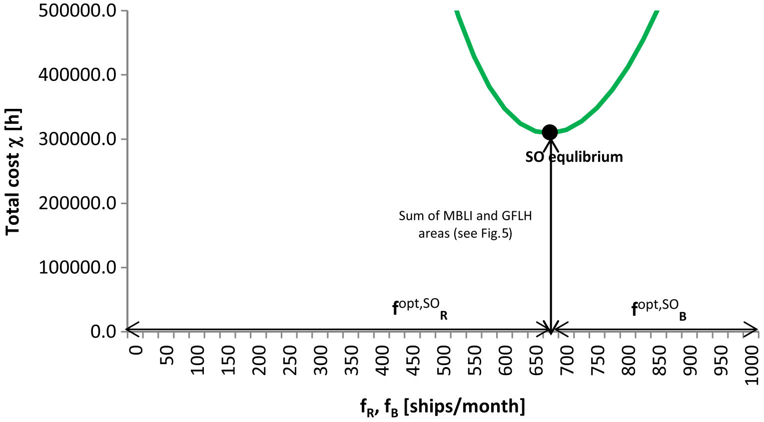

Fig. 4 Plots of total cost function (χ) for the two-ports systems

The SO equilibrium does not coincide with the (D)UE equilibrium. It is evident that, if compared with (D)UE equilibrium flows' vector, the SO equilibrium flows' vector:

$$\mathrm{f}^{\mathrm{opt,SO}} = [\mathrm{f}^{\mathrm{opt,SO_R}},\ \mathrm{f}^{\mathrm{opt,SO_B}}] \tag{11}$$

allocates some ships to a less performing (in terms of port time) port, but less congested.

This configuration of $\mathbf{f}^{\mathrm{opt,SO}}$ determines a reduction of the total cost. The different results between the two models are largely studied and consolidated in literature (see Cascetta 2009; Cantarella et al. 2019) and are due to the different theoretical assumptions about choice behaviour of the carrier, as the two Wardrop's principles show.

Figure 5 reports the difference, in terms of port times, in the SO equilibrium one, where the ports times for the two ports are not equal. The sum of the area of the rectangle MBLI and of the rectangle GLFH represents the total cost in correspondence of the SO equilibrium condition (Eq. 2): $\chi(\mathbf{f}^{\mathrm{opt,SO}}) = 309{,}131[h]$.

It is worth noting that the total cost in correspondence of the SO equilibrium condition (Eq. 2), calculated for $f = f^{opt,UE}$, is: $\chi(\mathbf{f}^{\mathrm{opt,UE}}) = 376{,}856[h]$, which is higher than the previous one. These comparisons are discussed in the next paragraph.

4.2 Comparison between (D)UE and SO: sensibility analysis

The differences between the parameters of each port have been stressed in the previous paragraph, in order to emphasize the differences, also graphically, between the two equilibrium approaches. This paragraph reports a comparison of the two-ports system scenarios (cooperation SO vs. competition UE) for three different supply configurations (see Table 2):

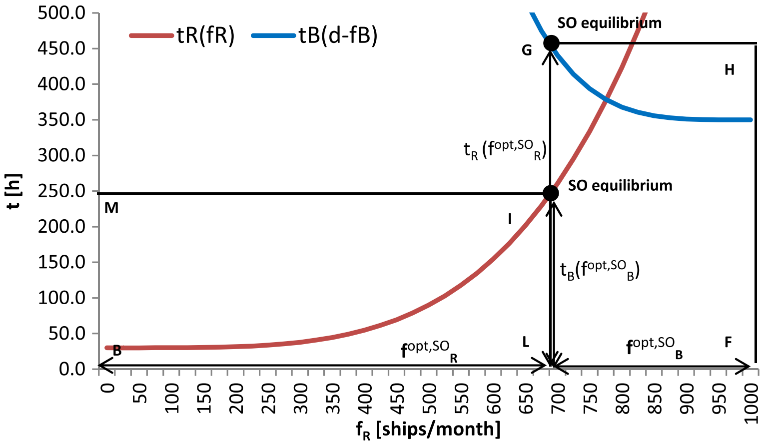

Fig. 5 Port time function for port Red (R) and port Blue (B): SO equilibrium

Table 2 Supply configurations: parameters of the total time function

Supply	Port	Cap	t0	a	b
configuration		[ships/months]	[h]		
1	Red	500	30	2	4
	Blue	500	350	2	4
2	Red	500	30	2	4
	Blue	500	**60**	2	4
3	Red	**250**	30	2	4
	Blue	500	350	2	4
Demand		d [ships/months]			
		1000			

(i) The supply configuration 1 is the one analysed in par. 4.1.

(ii) The supply configuration 2 considers that the two ports have a quite similar value of total port time ($t_{0,B}/ t_{0,R}=2$) in free-flow conditions respect to configuration 1. This means that, in configuration 2, the port time of port Blue strongly decreases (it has a reduction of 480%) due, for example, to investments in dredging the port seabed.

(iii) The supply configuration 3 considers that the port Red has a reduction of capacity of 50% respect to scenario 1. This could be caused, for example, by the temporary closure of a portion of the quay, with the relative cranes.

The proposed supply configurations are representative of the sensitivity of the model to highlight the results of the interventions. The total demand is constant in the three supply configurations and it is equal to d = 1000 [ships/months].

The results of the simulations of the three supply configurations in the two scenarios competition and cooperation, with (D)UE and SO equilibrium models, in terms of optimal flows and objective functions, are reported in Table 3.

The table reports the following values of the objective functions:

(i) $\phi(\mathbf{f}^{\mathrm{opt,UE}})$ of (D)UE model (Eq. 1), or integral cost, calculated for $\mathbf{f} = \mathbf{f}^{\mathrm{opt,UE}}$;
(ii) $\chi(\mathbf{f}^{\mathrm{opt,SO}})$ of SO model (Eq. 2), or total cost, calculated for $\mathbf{f}=\mathbf{f}^{\mathrm{opt,SO}}$;
(iii) $\chi(\mathbf{f}^{\mathrm{opt,UE}})$, or total cost, calculated for $\mathbf{f} = \mathbf{f}^{\mathrm{opt,UE}}$.

By comparing the three supply configurations for the two scenarios, the following elements emerge.

In the supply configuration 2, both the integral cost and the total cost decrease respect to configuration 1, due to the decrement of the whole port time of the two-ports system: $(t_R + t_B)_{\mathrm{conf2}} < (t_R + t_B)_{\mathrm{conf1}}$; while, in the configuration 3 both the integral cost and the total cost increase respect to configuration 1, due to the aggregate decrease of the (whole) capacity the two-ports system: $(\mathrm{Cap}_R + \mathrm{Cap}_B)_{\mathrm{conf3}} < (\mathrm{Cap}_R + \mathrm{Cap}_B)_{\mathrm{conf1}}$.

In the three supply configurations the total cost always reduces passing from a competitive attitude of the two ports, χ $(\mathbf{f}^{\mathrm{opt,UE}})$, towards a cooperative attitude, $\chi(\mathbf{f}^{\mathrm{opt,SO}})$.

The differences of the total cost in the competitive vs. cooperative behaviour of the two ports in each situation are evaluated by means of the following indicators:

(i) absolute variation of the total cost, $\Delta_{\mathrm{abs}}\chi$

$$\Delta_{\mathrm{abs}}\chi = \left|\chi(f^{\mathrm{opt,SO}}) - \chi(f^{\mathrm{opt,UE}})\right| \tag{12}$$

Table 3 Supply configurations: simulation results of DUE and SO equilibrium models (competition and cooperation scenarios)

Supply configuration	Port	Scenario				
		(D)UE (competition)			SO (cooperation)	
		$\mathbf{f}^{\mathrm{opt,UE}}$ [ships/months]	$\phi(\mathbf{f}^{\mathrm{opt,UE}})$ [h]	$\chi(\mathbf{f}^{\mathrm{opt,UE}})$ [h]	$\mathbf{f}^{\mathrm{opt,SO}}$ [ships/months]	$\chi(\mathbf{f}^{\mathrm{opt,SO}})$ [h]
1	Red	775	166,528	376,856	675	309,131
	Blue	225			325	
2	Red	575	63,431	129,713	550	127,244
	Blue	425			450	
3	Red	500	382,191	1,020,000	475	1,016,000
	Blue	500			525	

$\phi()$, integral cost; $\chi()$, total cost.

Table 4 Supply configurations: comparison of total cost indicators

	$\Delta_{abs}\chi$ [h]	$\Delta_{\%}\chi$ [%]
1	67,725	18.0
2	2469	1.9
3	4000	0.4

(ii) percentage variation of the total cost, $\Delta_{\%\chi}$

$$\Delta_{\%}\chi = \left|\left(\chi\left(f^{\text{opt,SO}}\right) - \chi\left(f^{\text{opt,UE}}\right)\right)/\chi\left(f^{\text{opt,UE}}\right)\right| \tag{13}$$

The entity of the total cost reduction from a competitive attitude of the two ports towards a cooperative one is higher in the situation 1 (see Table 4), where $\Delta_{\%\chi}=18{,}0\%$.

The performances of the two ports are similar and the reductions are less evident in situations 2 and 3: $\Delta_{\%\chi}=1{,}9\%$ in the scenario 2; $\Delta_{\%\chi}=0{,}4\%$ in the scenario 3.

The theoretical model and the test application in a two-ports system allow to formulate an analytical definition of a “fourth generation port” as a port system, which passes from a competition attitude between ports to cooperation one, reducing the total cost by means of horizontal cooperation of ports.

The proposed equilibrium model allows to respond to the research question RQ2 concerning the formalization and implementation of a theoretical model able to quantitatively represent the competition-cooperation process between ports.

The fourth generation port is a “win–win condition” both for the two ports, in terms of unified management, and for the carriers which use the new port system reducing their overall cost. The congested port continues to maintain its traffic level without further infrastructural investments, the other port increases the traffic using the infrastructures at its disposal.

5 Conclusions and future research

The exponential increase of freight traffic at worldwide scale and the consequent increasing role of the port sector, the growth of mega-vessels and the consolidation process (alliances) between carriers, the strengthening of supply chain between sea and land side for the global carriers are all factor that modified the supply, have determined critical conditions for standalone ports.

The necessity of ports to respond to the above main global drivers in the shipping market brought to different cooperation experiences between ports belonging to the same territorial system. The cooperation took place both between operators and administrations in different forms: from full mergers to specific project realization.

In relation to the above elements synthetized by the two research questions specified in the introduction, the research contribution of the paper mainly concerns the three elements reported below.

5.1 Importance of issues addressed and problems solved

The problem of merger and of alliance between the ports is a crucial issue of the current evolution of maritime transport. After the years of carrier alliances and of increasing dimension of ships, some ports operate according to new patters, moving from the historical competition attitude towards cooperation. This process could be observed in some important nodes of transport and logistics of world trade scenario: from Europe, to USA and China. It is worth noting that the different cooperation experiences have been studied manly stand alone, and in few cases without a quantitative approach.

The issue of this change is crucial to understand the future evolution of the international trade and involves the big ports around the world; which handle the 90% of international freight traffic. The problem solved with this work is the development of a theoretical model, founded on the topological-behavioural theory of Transportation System Models (TSMs) to explain how ports could respond to the new requirements imposed by carriers' alliances.

5.2 Novelty and distinctive features of proposed model against published works

The novelty of the study is reported in the following. In the authors' knowledge, the most advanced papers use game theory to explain some forms of ports competition and cooperation, but the general framework of Transportation System Models (TSMs) has never been used. The background theory of the TSMs is the topological-behavioural equilibrium paradigm, which is today commonly shared in the scientific literature. The work extended the TSMs from the consolidated field of passengers' mobility and freight distribution on terrestrial transport networks to a different field: the one of maritime ports. This is a distinctive feature from the existing published studies.

It's hard to discuss the proposed theoretical model against published works because there are no works using a similar approach in the field of maritime ports. The works available in literature deal with the problem of competition mainly with the game theory approach in absence of congestion. In other words, the models do not capture the reduction in port performances (e.g. port times of ships and freight), when there is an incoming flow that is close, or exceeds, port capacity.

The TSM framework allows to simulate the competition-cooperation behaviour between ports in presence of congestion under a unifying theory. The limitation of the work presented mainly lies in the test on a hypothetical scenario. This approach, although useful for a first verification, cannot guarantee that the obtained results take into consideration the complexity of the variables present in real contexts. The next step will therefore be the calibration and validation of the model in a real context.

This phase will allow to adapt the model to a real case study, comparing the results obtained with empirical data.

The work may be considered as a base to further research because it opens several directions to study the maritime system with the core equations given by TSM. Further steps will concern the introduction of SUE (Stochastic User Equilibrium) formulations and of the dynamic formulation to analyse the competition and/or the cooperation between ports and/or terminals.

5.3 Findings and managerial insights drawn from analytical results

The proposed model gives to the ports governance and management a quantitative tool to understand what happen in competition-cooperation process and to define alternative strategies in relation to the decision of other actors, such as carries, operating in the same market.

It is worth noting, as example, the effects of the Ningbo-Zhoushan alliance, that increased more than linearly its traffic against the close port of Shanghai in few years, or the potential effects of the alliance between Shenzhen and Guangzhou, strongly influencing Hong Kong traffic and the other big ports of Far East: from Singapore to Malacca region, and new China corridor to Indian Ocean.

The proposed model may be important to support the analysis and evaluation of port performances, because, gives the possibility to use the transportation science with core equations formalized in TSMs, capturing the congestion effects in the ports. In this way, it's possible also to study what happen inside a multi-terminal port introducing the hypothesis of cooperation, as well as the classical competition.

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Declarations

Competing Interest The authors declare that there are no competing interests.

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