Spatial-Temporal Simulation of Routes Connecting Containers Ports

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Abstract. Ports are crucial in global trade, and shipping trade is relevant for all industries. Even more so now that we are experiencing political and social stresses, a situation which means that maritime routes are increasingly less safe and economically more expensive. Inefficiency emerged as a fundamental factor in the competitiveness of a maritime terminal, and research on container ships plays a relevant role in understanding and assessing the competitiveness of the infrastructure. Consequently, the time elapsed between entering and leaving the port can express the capacity of the infrastructure to handle loading and unloading operations, thus representing a measure of receptiveness. Obtaining detailed data for different ports requires a deep understanding of ship turnaround time, workloads at the yard, and company priorities, thus relying on direct interviews with port workers. Due to the exploratory nature of the study and to overcome the costly and time-consuming on-field surveys, this paper analyzed the performance through a simulation process. As input, typical waiting and handling time probability curves for major container ports are derived from a large dataset of Automatics Information Systems, and some of the most crowded and longest commercial routes are analyzed to evaluate route performances in terms of exchanged numbers of containers, waiting time at the anchoring, and berth operations. The proposed framework involves multiple steps concerning (i) possible route stops, (ii) berth occupation, and (iii) route speed variation with the final goal of reducing the loss of time and increasing the exchanged number of containers for the terminal.

Keywords: maritime logistics · AIS · container ports · mesoscopic simulation

1 Introduction

The quantity of freight moved by maritime transport in 2023 was more than 12,000 million tons (with an increase of approximately 2.4% compared to the previous year) and the trade by containers was close to 160 million exchanged TEUs (but with a decrease of 0.14% with respect to 2022) [1]. With reference to the main maritime routes, the East–West routes (Trans-Pacific, Asia-Europe, Transatlantic) in 2023 handled more than 36% of global containerized trade volumes. In the coming years, growth is expected both in the total quantity transported and in the number of containers moved [2, 3]. Therefore, the development of ports [4–6] and the efficient movement of containers across ports are

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a cornerstone of global logistics. This aspect is treated in the literature from many points of view: technological [7, 8], economic [9, 10], and environmental [11, 12]. One of the approaches used to analyze the container market is the representation of the shipping network as a multi-layer graph, where (in general) each layer corresponds to a set of specific routes. Such a type of representation allows us to analyze the shipping network in order to individuate weak points and evaluate indicators on the performance of the network. Defining the structure of the network, many authors refer to centrality measures (derived from graph theory) to analyze them [13, 14], as an example of measuring the importance of a port in the related geographic area [15] while others focused on the uncertainty of the travel time [16, 17].

In this work, attention is focused on the trip of the single container from the origin to the destination, taking into account key operational events such as ship arrivals, loading and unloading operations, and port transitions. To achieve this goal, after representing the network with graph theory, a mesoscopic simulation approach is implemented. Key aspects include ship-port interactions, container tracking, and statistical analysis. Efficient routing and scheduling are essential to minimize costs and environmental impact. Public transport simulation techniques, commonly used in urban transit systems, provide a promising framework for modeling maritime shipping networks. The model considers container shipping lines (e.g., RTW, pendulum, feeder) as collective transport routes. A frequency is associated with each line, and distances between ports on the same line are calculated. Using graph theory, optimal routes are determined between origin-destination port pairs, treating the problem as a hyper-path computation. The proposed approach facilitates network optimization, efficiency analysis, and dynamic simulations. The approach allows the following:

- defining a transport network composed of ports and shipping lines;
- calculating distances between ports and travel times;
- constructing a graph representation of the shipping network;
- computing optimal routes between all port pairs.

Referring to supply chain resilience, this approach can be useful to assess failure scenarios, that is, when a service fails (partially or completely) and it is required to define a new route to reach the destination.

The paper is structured as follows. In Sect. 2 the literature review, Sect. 3 contains the description of the proposed methodology, while Sect. 4 reports the results of a test application. Finally, the conclusions in Sect. 5.

2 Literature Review

The transport revolution based on the use of containers [18] drastically reduced the cost of maritime freight transport and has caused the birth of a global liner shipping network that allows even small importers/exporters to exchange goods internationally [19]. In this context, the connectivity between different ports plays a crucial role in international container trade, affecting the value of export and the volume of transshipment [19].

International maritime trade requires that the global shipping network allows effective port access in any country [20], therefore, it is necessary to analyze the network

and define some indicators to assess its performance. Bartholdi et al. [21] proposed an index to measure the connectivity of a port considering both the topology of the shipping network and the movements of containers between ports in the network. Wang et al. [22] implemented an approach to extract the global shipping network from historical data collected with the automatic identification system (AIS) of the ships; the aim is to analyze the freight flows at different geographical levels. Tsiotas and Ducruet [23] provided a methodological framework able to analyze the global container shipping network in relation to distance and identified three different geographical levels in its structure: local connectivity, international connectivity and intercontinental connectivity. Pan et al. [24] used a graph-based approach to quantify container shipping network connectivity and improve it by adding new links between ports (a gravity model is applied for this scope) if necessary. Jiang et al. [25] proposed a learning method to analyze the container shipping network and provided the results of a cluster analysis. Representing the global container shipping network as a multilayer network (where each layer represents the route of a shipping company), Xu et al. [26] used an AIS data set to identify the global container shipping network and introduced some indices to compare ports within the network. Focusing on European ports, Liu et al. [27] calculated three service-based centrality indices (degree, closeness and betweenness centrality) to compare the centrality of each port with respect to liner services with China. Wang and Cullinane [28] proposed a framework to calculate the centrality measures of a container port, taking into account the characteristics of the port and its role in the entire network (for example, market coverage). The aim is to identify the importance of a port in the network (at regional and/or global level) in relation to the centrality measures.

A study on the container network robustenss is report in Want et al. [29], which developed an analysis based on network evolution over the time. Chen et al. [30] proposed a definition of resilience (calculated from the perspective of shippers) for a local container shipping network and provided a measurement model to assess it. Viljoen and Joubert [31] discussed the vulnerability of the shipping container network when some links are removed to simulate a disruption; the results demonstrated that the container shipping network remains functional, although it is disrupted, even a change in the service configuration is required. Starting from the consideration that there are shipping routes that cross the main channels of the world (e.g., Panama, Suez), Wu et al. [32] analyzed the vulnerability of the entire shipping network by removing the routes that require the use of one of the channels. Some network metrics are used to quantify vulnerability. Huang et al. [33] proposed a shipping hub-and-spoke network design problem to optimize the position of the hub and spoke ports considering the risk of failure (complete or partial) of the port and the port congestion. Calatayud et al. [34] noted that the vulnerability of the shipping flows depends on the position occupied by the countries in the network. In particular, they explored the case of containerships and liner shipping services to highlight the dependence and vulnerability of international trade emerging from the network structure.

3 Methodology

The goal of the proposed is to model the movements of the containers across different ports: given a container, the procedure finds the best route to get it from the port of origin to the port of destination using the available shipping lines. To do this, in addition to having information on ports and lines, it is necessary to simulate the supply system and the operations that take place in the port. Figure 1 shows schematically the proposed approach. The procedure consists of three blocks: the identification of the *shipping network*, voted to calculate the *shortest paths*; a *mesoscopic approach* that takes as input the shortest paths, and the result of a *discrete event simulation* aimed at simulating the events that occur from the ship's arrival in port until its departure. The first operation is data collection, aimed at obtaining information on *ports* (e.g., position) and *shipping lines* (e.g., frequency). The next step is the characterization of the supply: the *graph construction* takes as input the port positions (that represent the nodes of the graph) putted in the set V, and the shipping lines (that represent the arcs of the graph), putted in the set E. After the graph $\boldsymbol{G}(E, V)$[1] is obtained, the shipping network $\boldsymbol{T}(V, E, \boldsymbol{c})$ is identified by associating a cost at each arc, considering the characteristics of the shipping lines. To evaluate the arc costs (vector **c**), the arcs are divided into three sets (disjoint), with the same approach used for public transport lines ([35]):

1. *on-board* arcs (set E_1), that link two ports, the associated cost is the travel time $c_1 = d/v$, where d is the distance between two ports and v is the average ship speed;
2. *loading arcs* (set E_2), which simulate the load of the container on the ship, the associated cost (under the assumption that the shipping line is perfectly regular) is the waiting time $c_2 = 1/2 \cdot \phi$, where ϕ is the shipping line frequency;
3. *unloading arcs*, whit cost c_3 linked with the handling/transshipment operations.

Then, starting from $\boldsymbol{T}(V, E, \boldsymbol{c})$, the *shortest paths* are calculated using a procedure for the search for the shortest path (in our case, the Dijkstra's algorithm). In shortest path calculation, the cost considered is the sum of the previously defined costs, as follows:

$$c = c_1 + c_2 + c_3 \tag{1}$$

The procedure described up to this point therefore allows us to obtain the shortest paths that the ships will follow during the simulation; note that these paths remain fixed for the entire simulation.

The shortest paths, the container *demand*, and the results of a discrete *event simulation* are the input for the *mesoscopic simulation* of the system. Focusing on the discrete event simulation approach, it is applied to simulate the events related to the status of the ship; then four different of them can be considered:

- ship arrival, the ship arrives at the port and prepares for the anchoring phase,
- ship at anchor, the ship waits at anchor until it is time to enter port,

[1] A graph is defined by a set of elements called nodes and by a set of pairs of nodes belonging to the nodes. The links in a graph modeling a transportation system represent phases and/or activities of possible trips [35].

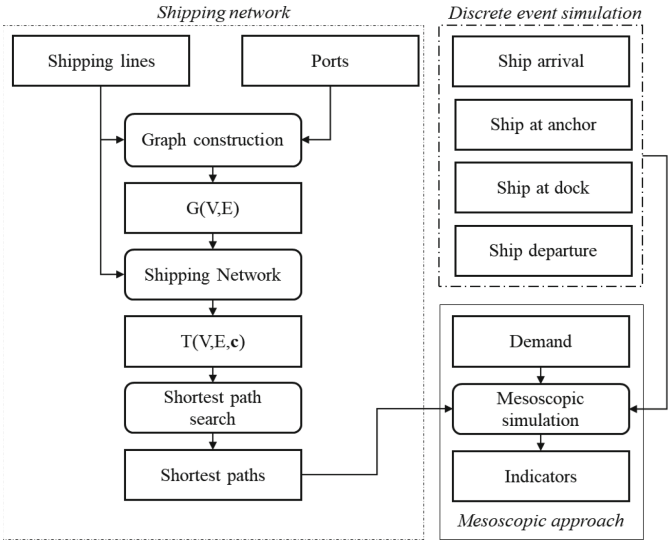

Fig. 1. The proposed approach

- ship at dock, the ship is stationary at the dock during loading/unloading operations,
- ship departure, the ship has finished loading/unloading operations and, respecting the scheduled departure time, is leaving for the next port.

In general, the mesoscopic approach works by grouping elements in packets elements with homogeneous characteristics and simulating the movements of such packets. The approach proposed in this paper considers as a packet a single container that travels from the origin to the destination following the shortest path. Since the simulation is dynamic, the demand values also have a time coordinate, this means that for each container, it is considered the instant t_0 of arrival at port and the instant t_1 of departure from port. Between these two time instants, the instant t_3 in which the container is loaded on the ship must be considered. The *indicators* obtained as output of the simulation are the following:

- the waiting time of the container, intended as the difference between the instant of arrival at port ant the instant when the container is embarked;
- the travel time;
- the transshipment time, to be considered only in the case when to move from one port to another one it is necessary to use at least two different shipping lines.

The proposed approach is scalable to take into account other specific situations: in fact, the graph approach described below allows each situation to be represented both in terms of topology (shipping arcs) and costs (in general, at each arc the cost of a maritime operation can be associated).

4 Test Application

The test application reported in the next paragraph aims to illustrate the applicability of the proposed method, without claiming to build the global container shipping network. In fact, only a subset of shipping lines is considered (Sect. 4.1), at the international and local levels.

4.1 Supply Network

The supply network consists of some lines selected on the web from the data made available by shipping companies. In this particular case, 2 shipping lines have been considered, and they were identified among those offered by the CMA CGM company. The lines considered are as follows:

- Amerigo (*AMERIGO,* Fig. 2), a line operating from Mediterranean Sea and North America (East Coast) and vice versa;
- SSLMED Cross Med Service (*CROSSMED,* Fig. 3), Intra Mediterranean (Spain, Morocco, Italy, Turkey, Egypt, Lebanon, Syria).

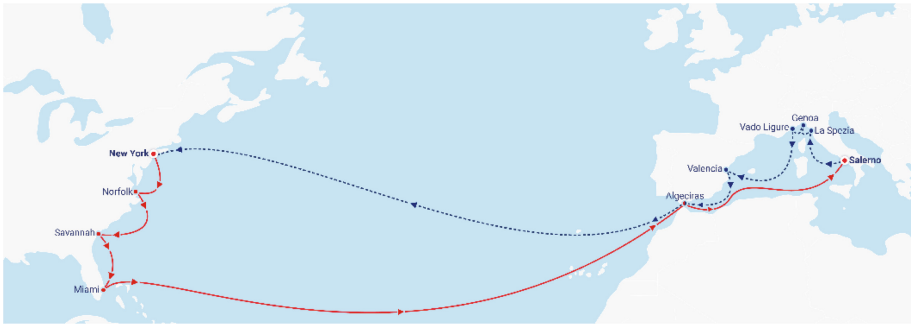

Fig. 2. The Amerigo route

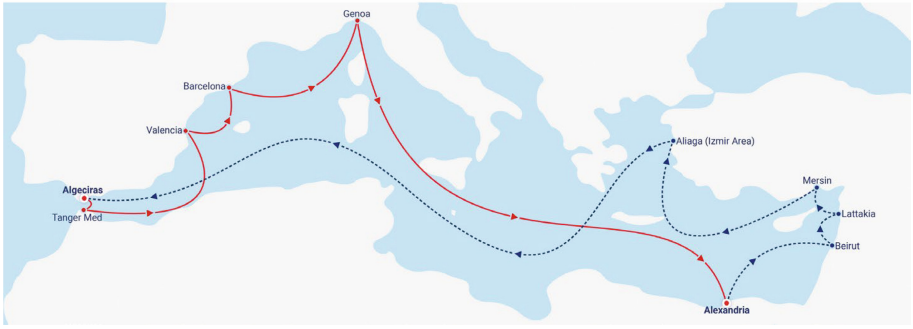

Fig. 3. The Crossmed route

Table 1 reports some characteristics of the shipping routes reported above. In particular, data as frequency, number of ships operating in the route, number of port calls and duration of the navigation are listed.

Table 1. Main characteristics of the considered shipping lines

Name	Frequency [days]	Ship fleet	Ports of call	Duration [days]
AMERIGO	7	7	11	49
CROSSMED	7	4	10	28

4.2 Graph Model

Maritime routes are schematized using a graph-based supply model similar to the one used to represent transit lines, as shown in Fig. 4. With reference to Fig. 4, each port (*P1*,…*P5*) corresponds to a stop that is connected to the corresponding node of the line representing the stationing of the line itself in the port (*L1*, *L2*) by means of a pair of arcs, one representing the loading/embarkation (the purple ones) and the other representing the unloading/disembarkation (the black ones). The different stationing nodes of the lines in the ports are connected to each other by arcs (the blue ones) that represent navigation.

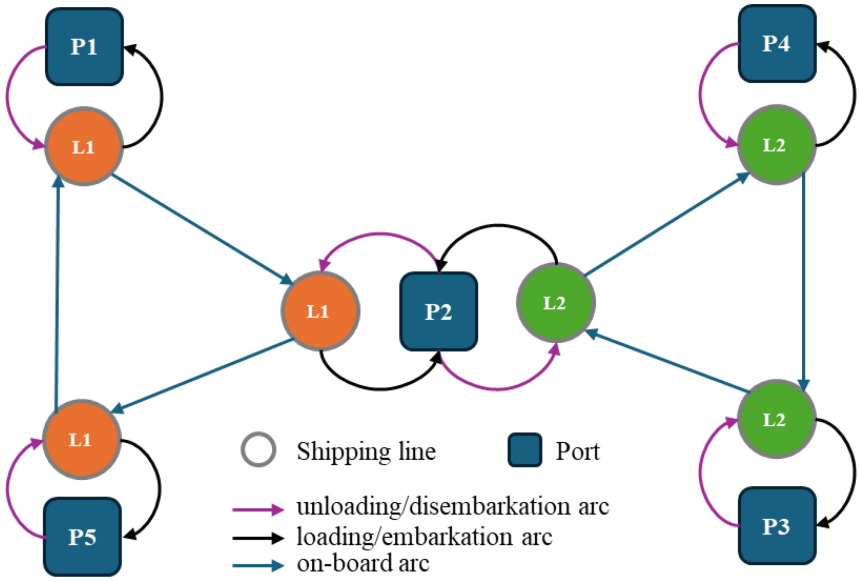

Fig. 4. Representation of the graph

A travel cost is associated with each kind of arc. The navigation time necessary to make the trip from port to port is associated with arcs representing the lines (the blue ones in Fig. 4). Such a time is evaluated considering the day of departure from the port of origin and the day of arrival at the port of destination, as scheduled and without considering the weather conditions.

The average waiting time (generally ½ of the intertime between two successive passages of the same line at the port) is associated with the loading arcs (the purple ones); a fictitious time, representing the handling time, is associated with the unloading arcs (the black ones).

The routes on which the containers are routed to reach the port of destination from the port of origin are computed as the minimum cost paths connecting origin to destination in the graph considering the costs above defined for each arc.

With reference to Fig. 4, the route that containers follow to reach port *P3* starting from port *P5* corresponds to boarding on line *L1*, up to port *P2* where they are unloaded and the transshipment takes place boarding successively on line *L2* to reach the port *P3* of destination.

4.3 Results

The simulation covers 60 days and considers as origin-destination the ports belonging to the shipping lines reported in Table 1. The ports considered in this small test are 17 (Fig. 5), and the origin-destination pairs considered are 272, of which 109 involve at least one transfer.

The distance d between them varies from values less than 100 nautical miles to values greater than 4000 miles. In particular (Fig. 6) for 39.71% of the o/d pairs, the travel distance is greater than 4000 nautical miles.

The indicators considered in this test are linked with the time, in particular the travel time, waiting time, and transshipment time are considered. For each indicator, mean and variance are calculated and the coefficient of variation c_v was chosen to summarize the results. Taking into account the distance classes defined above, for each of them c_v is grouped by value as follows:

- $c_v \in [0\%, 5\%)$,
- $c_v \in [5\%, 10\%)$,
- $c_v \in [10\%, 15\%)$,
- $c_v \in [15\%, 20\%)$,
- $c_v \geq 20\%$.

By crossing distance and coefficient of variation classes, it is individuated how much o/d pairs fall in such intervals of distance and coefficient of variation. Tables from Table 2, 3, 4, and 5 report the results of these analyzes.

Table 2 is on the total time, it can be observed that there are 96 *o/d* pairs for which the value of c_v is in the range of [5%, 10%), in particular revealing a low variation for the routes greater than 4000 nautical miles (41 o/d pairs, i.e. the 15% of them, fall in this situation). In addition, there are 88 *o/d* pairs for which the value of c_v is less than 5%, and 53 of them (about 20% of the total pairs) are in the distance range greater than 4000 miles.



Fig. 5. The ports and the routes considered in the test application

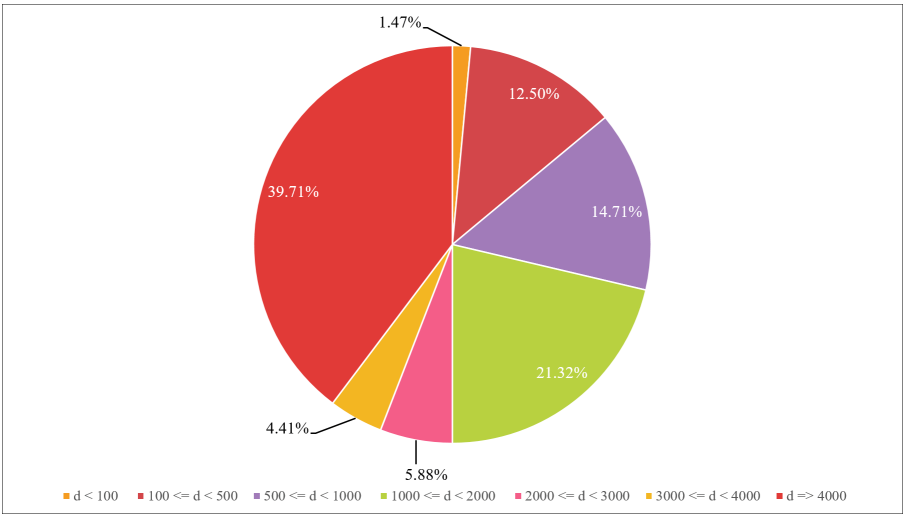

Fig. 6. Travel distance classes (distance d in nautical miles)

Table 3 reports the travel time; in this case for 259 out of 272 pairs, the coefficient cv is less than 5%, the pairs are distributed over different distance classes, with a peak (about 37% of all pairs) for distances greater than 4000 miles.

Table 2. Analysis of the total time

d^*/c_v	[0%, 5%)	[5%, 10%)	[10%, 15%)	[15%, 20%)	≥20%	***Total***
<100	1			1	2	***4***
[100,500)	10	7	1	2	14	***34***
[500,1000)	11	11	5	4	9	***40***
[1000,2000)	11	29	13	5		***58***
[2000,3000)		4	12			***16***
[3000,4000)	2	4	5	1		***12***
≥4000	53	41	5	6	3	***108***
Total	***88***	***96***	***41***	***19***	***28***	***272***

*Distance in nautical miles

Table 3. Analysis of the travel time

d/c_v	[0%, 5%)	[5%, 10%)	[10%, 15%)	[15%, 20%)	≥20%	***Total***
<100	4					***4***
[100,500)	31	2		1		***34***
[500,1000)	39	1				***40***
[1000,2000)	57	1				***58***
[2000,3000)	16					***16***
[3000,4000)	12					***12***
≥4000	100	3	5			***108***
Total	***259***	***7***	***5***	***1***	***0***	***272***

Table 4. Analysis of the waiting time

d/c_v	[0%, 5%)	[5%, 10%)	[10%, 15%)	[15%, 20%)	≥20%	***Total***
<100					4	***4***
[100,500)	1	3	3	4	23	***34***
[500,1000)	1	8	5	1	25	***40***
[1000,2000)	1	2	13	8	34	***58***
[2000,3000)			2	4	10	***16***
[3000,4000)		2	2		8	***12***
≥4000	11	24	17	10	46	***108***
Total	***14***	***39***	***42***	***27***	***150***	***272***

Table 5. Analysis of the transshipment time

d/c_v	[0%, 5%)	[5%, 10%)	[10%, 15%)	[15%, 20%)	≥20%	***Total***
<100	1					***1***
[100,500)	6	1			4	***11***
[500,1000)	7	3	1		2	***13***
[1000,2000)	20	1	1		4	***26***
[2000,3000)						***0***
[3000,4000)	3				1	***4***
≥4000	31	2			21	***54***
Total	***68***	***7***	***2***		***32***	***109***

Table 4 relies with the waiting time, for this component of time most *o/d* pairs fall in the range with a coefficient c_v greater than 20%, the range distance between 1000 and 2000 miles, and the range greater than 4000 miles are worth highlighting.

Finally, Table 5 reports the values of the transshipment time (note that the values in this table are limited to the 109 o/d pairs for which the transshipment is possible). In this case, 68 od/pairs (about 62% of the total) have a c_v less than 5% (about 28% are in the distance range greater than 4000 miles, about 18% in the range between 1000 and 2000 miles). There are also 32 cases (29%) for which the coefficient of variation assumes values greater than 20%.

5 Conclusions

This study presents a simulation framework for modeling container movements across ports based on a novel application of public transport simulation techniques transferred to container shipping. In fact, shipping routes are represented as public transport, considering specific arcs for loading/unloading and handling operations. A procedure based on three blocks has been developed: (1) the shipping network identification (considering both routes and frequencies); (2) a discrete event simulator, to simulate the procedures that are activated when the ship arrives at the port; (3) a mesoscopic simulation procedure to simulate dynamically the travel of a container (it is assumed that the packet to move in the simulation is the container) assessing the performances of the shipping services.

The proposed approach is applied to a test case, considering some existing shipping routes with related frequencies, and, for each simulated container belonging to an o/d pair, its travel is followed during simulation. Such travel can be direct or not, in this last case, the container is transferred from one ship to another (also belonging to different companies) to reach the destination. In particular, the simulation has been performed for a time horizon of 60 days (i.e., the demand is spread over 60 days and the simulation continues until the last container has arrived at its destination), for 17 ports and 272 o/d pairs (109 of them involve the transshipment). The coefficient of variation of the time has been chosen as an indicator to assess the procedure.

The model offers valuable insight into logistics operations and forms the basis for further research in this domain.

The limitations of this work are the size of the database and the fact that the data comes from only one shipping company. Both aspects can be easily overcome in future research developments.

Future work will focus on integrating real-time data, visualizations, and economic factors to further optimize global supply chain efficiency also considering the analysis of a case study. In addition, the procedure could be improved by introducing a procedure that allows the paths to be modified during the travel (re-routing).

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