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A NETWORK DESIGN OPTIMIZATION PROBLEM FOR RO-RO FREIGHT TRANSPORT IN THE TYRRHENIAN AREA

Summary. Roll-on Roll-of (Ro-Ro) transport is one of the primary options EU policy is focusing on for developing intermodal transport and MOS initiatives, aimed at reducing road transport (especially trucks). In line with EU guidelines, this study proposes an integrated and optimized network scheme for the maritime Ro-Ro freight services currently operating in the Italian Tyrrhenian area to improve the overall supply of shipping services. The methodological approach used is based on the integration of the timetables and frequencies of existing freight shipping services using an original mathematical model that assigns demand flows to the network while trying to minimize a multi-objective function composed of a weighted sum of travel times and tariffs. Quantitative results show the positive impact generated by rescheduling and coordinating liner shipping and demonstrate how a 'Tyrrhenian network system' considered as a whole would be more attractive than the single services taken collectively.

1. INTRODUCTION

Short sea shipping (SSS) represents one of the main pillars of EU transport policies, as it aims to reduce road congestion, shift freight transport from road to short sea shipping, and enhance economic and social cohesion between countries. The core of the EU strategy for the promotion of SSS lies in the Motorways of the Sea (MOS) initiative, which aims, in a direct way, to switch a significant proportion of freight traffic from the road to seaborne transport in order to achieve a greater balance between the various modes of transport. Roll-on Roll-of (Ro-Ro) transport is one of the main options European policy is focusing on for developing intermodal transport and MOS policies. Ro-Ro transport offers two main advantages over road transport: more competitive overall costs, especially for unaccompanied freight transport over medium distances and a significant reduction of environmental and social costs as a result of easing congestion and increasing road safety.

The Tyrrhenian area with its numerous commercial ports and the short sailing distances between them represents the perfect ground for developing MOS and SSS initiatives. However, looking at the existing situation, the framework of maritime freight transport in the area consists of a multitude of shipping companies, which mainly operate in the absence of synergies and coordinated market strategies. Although the number of existing liner services may seem considerable, a more in-depth analysis reveals that these services have no distinctive feature for which they can be considered a 'Tyrrhenian system'. In most cases, the services are fragmented and not integrated, a significant number of routes overlap as they have been conceived singularly and sized only on the basis of shipping companies' fleet availability rather than to meet actual demand. Often, notwithstanding

various maritime services arrive at and depart from the same port, timetables are not coordinated, and there is no physical integration between quays. Moreover, many ports with high potential demand for maritime transport are not interconnected with regular services, so one cannot talk about a 'maritime network' but only about a set of single services. The result is an inefficient connection system that unavoidably favors the use of road transport, attributable mainly to the lack of synergy and integrated policies implemented by the Mediterranean countries [1]. In particular, the intra-company competition regime appears not appropriate for tapping the potential of the Tyrrhenian area, and new management policies need to be put in place in an attempt to develop a more effective and competitive 'Tyrrhenian system'. Although it is now widely recognized that integrated management policies can yield to significant benefits for achieving higher global efficiency and competitiveness [2], the adoption of coordinated market strategies is far from being realized as it can collide with the traditional reluctance of maritime operators to undertake new collaborative initiatives and with the marked centralized management style of the sector [3]. Needless to say that in a free market context, such kind of collaborative initiatives can take off only if the benefits they can yield to maritime operators, especially in terms of opportunity to maintain and increase their existing market share, are clearly perceived and recognized by the operators themselves.

The development of MOS has been strongly supported by EU policies [4]. However, if we look at the past supporting EU programs for maritime transport, they seem to have concerned almost exclusively the provision of subsidies to operate existing or new maritime links. The not always satisfactory results of such initiatives seem to suggest the need for a change in the perspective that has been so far adopted by EU programs: from a single-service perspective to an integrated perspective [1]. In this regard, this study aims to propose an integrated and optimized network scheme for the maritime Ro-Ro freight services currently operating in the Italian Tyrrhenian area, which can be useful to decision-makers interested in investigating alternative integrated strategies to improve the overall maritime transport supply in the area. The operating parameters of the new integrated network are determined through a specially designed optimization approach based on the integration of timetables (less total travel time, including waiting time at the port), and of the frequencies of the liner services of interest. In the proposed application, shipping companies maintain their proper Ro-Ro networks and market shares but operate according to mutually coordinated service timetables. The aim of the proposed network is to improve the accessibility of island regions while providing an essential contribution to how shipping services can be streamlined to render them more competitive than road transport. The paper is organized as follows. Following this brief section providing an introduction to the problem and the reasons for the research work presented, Section 2 presents a brief literature review on maritime network design and discusses the peculiarities of the problem addressed. Section 3 describes the main features of the problem under study. The analyzed problem is modeled in Section 4 through an original optimization model based on a multi-objective function. Section 5 is devoted to the discussion of the main data and numerical results of the application. Finally, Section 6 concludes.

2. THE MARITIME NETWORK DESIGN PROBLEM

Maritime network design is widely addressed in the literature [5]. Compared to other transportation systems, such as rail or road, designing an efficient maritime network is much more complicated, because several port-related issues need to be taken into account, such as, among others, port accessibility, port reputation, and loading/unloading operations efficiency [6]. This problem has been thoroughly investigated by Ameln and Fuglum [7] who developed three mathematical models for the liner shipping network design problem (LS-NDP). Many papers in the literature deal with the design of hub and spoke networks. Some consider fixed hubs [8, 1], whereas in others, the choice of the hub is part of the decision-making process [9, 10]. The aforementioned works deal with contemporary network design and fleet deployment, but in some instances, the goal is to optimize fleet deployment given a fixed service network. This problem is relevant in real-world applications where it frequently occurs that two different decision makers have to address the network design and the fleet deployment problem in two different moments [11, 12]. Recently, a new cargo network has been designed by

Ningwen et al [13] by integrating a gravity-type model for origin-destination demand with a supply model to generate a new hub-and-spoke network calibrated for rapid growth in demand. For shipping problems, once the service network is designed and the fleet is assigned, the main cost component, from a company perspective, is known. The last phase of the planning, services scheduling, plays an essential role in ensuring feasibility of the plan and in improving customer service quality. An extensive and established scientific literature exists on ship scheduling [14, 15]. From a methodological and algorithmic point of view, maritime network design has been broadly addressed in the literature. A rich integer programming model for liner shipping network has been presented in Brouer et al [16]. In the study by Agarwal and Ergun [17], a combined liner shipping network design and cargo routing optimization problem is addressed with additional constraints such as weekly frequency. In the study by Zheng et al [18], an hub-and-spoke shipping network design problem is studies, whereas in Meng and Wang [8], a mixed multi-port calling and hub and spoke network is faced, and the benefits with respect to a pure multi-calling and a pure hub-and-spoke networks are investigated. The proposed mixed integer programming formulation has been tested on realistic shipping operations among Europe, Asia, and Oceania. A branch and cut algorithm for the container shipping network design problem, able to solve to optimality instance up to 15 nodes, is proposed in Reinhardt and Pisinger D [19]. Gelareh et al [20] introduces the liner shipping hub network design in a competitive environment, in which the competition between a new-comer liner company and the existing dominating operators is addressed. The problem goal is to locate the hubs and propose a shipping network for the new operator in order to maximize its market share. The problem is solved by a Lagrangian method combined with a primal heuristic. Collaboration among liner shipping companies for the total revenue maximization is instead studied in Agarwal and Ergun [21], merging mathematical programming approaches with game theory. Asgari et al [22] considers the possibility of both cooperation and competition among shipping companies and compares results obtained with a pure competition and a pure cooperation strategy, modelling the problem with a game-theoretic approach. Wang and Meng [23] model a problem of liner shipping network design with deadlines using a mixed-integer nonlinear nonconvex problem that is solved by a column generation-based heuristic.

In this study, we consider the problem of scheduling shipping services for Ro-Ro transportation starting from a given network. This problem is frequently addressed in real-world situations, especially when working on existing maritime networks. In fact, in these cases, shipping companies already own their vessels and are usually unwilling to reorganize their fleet and change the services they operate. However, sometimes they may be prepared to reschedule them to increase overall supply. Different aspects may affect customer choice, such as total travel time, the number of transshipments, tariffs, frequency of service, the value of time, etc. An extensive description of the main determinants of maritime transport costs and of the generalized cost components that are typically taken into account by customers in their modal choice can be found in Wilmsmeier and Martinez-Zarzoso [24]. In this application, we consider only two cost components: total travel time (considered as waiting time in port, load/unload time and journey time) and total tariffs from origin to destination. The choice of these two variables is not random, as travel times and monetary costs are recognized as the two most important components considered by users in the modal and route choice [25, 26, 27].

With respect to the existing literature, the main innovation introduced by this paper concerns the adoption of a bi-objective function to optimize a hierarchical function in which both time spent on the network and cost are considered. We study and compare the case in which the primary objective is the cost associated with the transport with the case in which the primary objective is the time spent on the network. We propose a Mixed-Integer Programming model, which is flexible and could be easily extended to investigate alternative network settings.

3. PROBLEM DESCRIPTION

For some years now, the EU Commission in its review process of the Trans-European Transport Network (TEN-T) policy has been working to promote intermodal and sustainable transportation

systems and to eliminate the bottlenecks that traditionally characterize its transport infrastructures. Mainly, EU policies concerning the development of MOS as pillars of the TEN-T network are increasingly focused on the importance of strengthening the connections between core and comprehensive nodes. This necessarily also requires greater integration between peripheral and insular regions and continental ones. The present work fits into this context, with the primary goal being to respond to the need to improve essential transport services for the development of island and peripheral regions by rescheduling existing connections so as to enhance the performance of the entire maritime network in the Tyrrhenian area. Typically, different shipping companies operate within a network providing services that are not mutually coordinated and consequently contribute to the global inefficiency of the transport network. For this reason, even for a given set of services, it is often possible to improve transport supply through a smart and coordinated scheduling plan and a system of connections better suited to Origin-Destination (O/D) flows. The various liner services operating in a short-sea network can typically be grouped into two categories: direct services or in connection. Direct services connect directly one origin to one destination, whereas services in connection involve transshipment to one or more intermediate destinations. As the different service frequencies and capacities are known, in that we are dealing with the optimization of existing connections, the primary goal of the optimization process consists of organizing such services within a feasible schedule able to minimize average travel time within the network, while containing average shipping tariffs. Total travel time includes both the time a ship spends at sea and the waiting time at ports. As for the latter, from an organizational point of view, there are two main ways in which it can be reduced:

–   by better distributing the various departures of the same service throughout the week, to reduce the average time a customer has to wait for the service of interest. This waiting time accounts for the availability or not of the service in relation to its frequency. Freight waiting times are expressed in hours (h). For the purpose of this application, it is calculated as a function of frequency, as the time between successive sailings divided by two as shown by equation (1):

$$\text{Waiting Time} = 168/(\text{frequency} / 2) \qquad (1)$$

where: 168 are the hours in a week;

–   by better coordinating arrivals and departures of services in connection, to minimize waiting times between connections while ensuring the necessary time for loading/unloading operations. In this regard, it is worth noting that a service arriving at a port can have a connection with a service departing from the same port only if there is sufficient time to complete loading/unloading operations before the second service departs. To this end, good port performance always needs to be guaranteed to comply with service requirements.

Total shipping tariff includes both the sea freight rate and handling tariff at the port node. As is well-known, in the transportation sector, times and tariffs both have a decisive influence on the attractiveness of the various transport alternatives and as such they necessarily drive any optimization process that involves transportation systems [26]. A useful optimization tool has to be able not only to consider both aspects but also to simulate the different weight they can assume in decision-making processes depending on the specific customers' preferences.

4. METHODOLOGY

In this section, we present an original mathematical model for assigning demand flows to a maritime network that attempts to minimize a generalized cost function, in which both shipping tariffs and total travel times are considered. The total travel time includes the time at sea, the waiting time at intermediate ports for services in connection, and the port turnaround time. The total tariff includes both sea freight rate and port handling tariff. We consider an objective function composed of a weighted sum of two single objectives, i.e., the minimization of travel times and of shipping tariff, which allows to hierarchically consider the two different objectives. Before describing the mathematical model, we need to introduce the notation used and the following sets:

–   *S*: set of direct services;

- K: set of combinations of one or two services connecting one origin to one destination;
- L: set of O/D pairs;
- D: set of days in the planning horizon (weekly);

the following constants:

- *compatibility (l,k):* equal to 1 if O/D pair l can be served by combination k (i.e., if origin and destination of k correspond to origin and destination of l), 0 otherwise;
- t_s: travel time of service s;
- c_s: shipping tariff of service s;
- ρ_s: loading/unloading time associated with arrival port of service s;
- $s1_k$: first service of combination k;
- $s2_k$: second service of combination k (if k is composed of a single service, the second service is taken as a dummy service with t, c and ρ equal to 0);
- Q_{ld}: demand for O/D pair l on day d;
- $Cmax_l$: maximum allowable tariff for OD pair l;
- τmax_l : maximum allowable elapsed time for O/D pair l;
- ε: a very small constant;
- M: a very large constant;

the following variables:

- X_{kld}: binary variables taking 1 if O/D pair l is served by combination l on day d, 0 otherwise;
- T_s: departure time of service s;
- τ_{ld}: elapsed time from arrival at origin port to arrival at destination port for O/D pair l on day d;
- c_{ld}: shipping tariff for O/D pair l on day d;

and finally, the model equations:

$$min \; \alpha \sum_{l \; in \; L} \sum_{d \; in \; D} \tau_{ld} \, Q_{ld} + \; \beta \sum_{l \; in \; L} \sum_{d \; in \; D} C_{ld} \, Q_{ld} \tag{2}$$

$$\sum_{\substack{k \; in \; k| \\ compatibility(l,k)=1}} X_{kld} = 1 \quad \forall l \in L \quad \forall d \in D \tag{3}$$

$$X_{kld} \le 1 - \varepsilon \left(T_{s1(k)} + t_{s1(k)} + \rho_{s1(k)} - T_{s2(k)} \right) \quad \forall k \in K \quad \forall d \in D \tag{4}$$

$$T_{s1(k)} \ge 24(d-1) + 8 - M(1 - X_{kld}) \quad \forall k \in K \; \forall l \in L \quad \forall d \in D \tag{5}$$

$$\tau_{ld} \ge -24(d-1) - 8 + T_{s2(k)} + t_{s2(k)} + \rho_{s2(k)} - M(1 - X_{kld}) \quad \forall k \in K | s2(k) \ne 0 \quad \forall l \in L \; \forall d \in D \tag{6}$$

$$\tau_{ld} \ge -24(d-1) - 8 + T_{s2(k)} + t_{s2(k)} + + \rho_{s2(k)} - M(1 - X_{kld}) \quad \forall k \in K | s2(k) = 0 \; \forall l \in L \; \forall d \in D \tag{7}$$

$$C_{ld} \ge (c_{s1(k)} + c_{s2(k)} \, X_{kld}) \quad \forall k \in K \quad \forall l \in L \; \forall d \in D \tag{8}$$

$$X_{kld} \in \{0,1\} \quad \forall k \in K \quad \forall l \in L \quad \forall d \in D \tag{9}$$

$$C_{ld} \le Cmax_l \quad \forall l \in L \quad \forall d \in D \tag{10}$$

$$\tau_{ld} \le \tau max_l \quad \forall l \in L \; \forall d \in D \tag{11}$$

The objective function shown in (2) is given as a linear combination of travel times and tariffs weighted by the demand quantity of each O/D pair. By appropriately fixing the coefficients α and β, it is possible to transform the objective function into a hierarchical function in which, when comparing two solutions, the secondary objective counts only if the value of the primary objective takes the same value. In other words, if a solution Z has a better value than the primary objective with respect to

solution *Z'*, *Z* will be globally better than *Z'*, whatever the values of the secondary objective. Constraints (3) impose that, on each day, each O/D pair must be assigned to a compatible combination. Constraints (4) imply that an O/D pair can be assigned to a combination if and only if the related goods are available at origin port before the first service of the combinations departs. The total elapsed time between arrival at origin port and arrival at the destination port is computed using constraints (6) for combinations composed of two services, and through constraints (7) for combinations composed of a single service. The total shipping tariff for each O/D pair on each day is computed in (8), whereas the domain of the variables is specified in (9). Finally, constraints (10) and (11) are not explicitly mandatory but allow to exclude extreme solutions in which the travel time is very low but the tariff is exceptionally high, and vice versa. Note that we assume that goods to be shipped on day *d* become available at the origin port before 8 a.m. If we change this assumption, we must substitute, in the model equations (5, 6, 7), the number 8 with the specific time of the day in which the goods become available.

5. APPLICATION DATA AND RESULTS

5.1. Application Data

The geographical context of the study concerns the Tyrrhenian area and specifically the Italian maritime connections between Sardinia, Sicily, Liguria, and Tuscany. Following EU policies, the application focuses on the optimization of the maritime connections among the four core port nodes of the four regions, i.e., Cagliari, Genoa, Leghorn, and Palermo. An extensive data collection was performed to obtain the data and information required for defining the existing demand and supply scenarios, based on which we calibrated the operating parameters of the new coordinated network.

Table 1

Weekly O/D matrix (No. of Ro-Ro units) – year 2016

O/D	Genoa	Cagliari	Leghorn	Palermo
Genoa	-	357	0	867
Cagliari	426	-	849	150
Leghorn	0	843	-	643
Palermo	791	246	676	-

Collected data include features of both demand and supply.

Demand characteristics are the traffic volumes exchanged among the four ports in the study area during the four-year period 2013-2016. Traffic volumes concern the number of Ro-Ro units exchanged on a monthly basis. Traffic data were obtained by means of a detailed collection form submitted to the four port authorities of interest from May to September 2017. In this application, to illustrate O/D demand, we refer to Tab. 1, which gives the weekly O/D matrix for the year 2016 in terms of the number of Ro-Ro units transported for the different O/D pairs.

As for the supply data of interest, they include the following:

–   port features - handling time and handling tariff information for each port of interest. Both items of information were directly provided by the ports of interest by filling in a collection form. Such information was collected considering the single Ro-Ro terminals instead of whole ports as important differences may occur even among the terminals within the same port [28]. For the purpose of the present application, the handling time of a port (h/Ro-Ro ship) is calculated as the average of the times indicated by the single Ro-Ro terminals of the port as usually necessary to perform a complete loading-unloading cycle on a Ro-Ro ship. Similarly, the handling tariff of a port is here calculated as the average of the tariffs for loading/unloading a semi-trailer onto/from a Ro-Ro ship (€/Ro-Ro unit) applied by the single Ro-RO terminals of the port;

- ship features - capacity of the ship(s) currently operating the Ro-Ro freight services between the ports of interest;
- service features - services times, frequencies, and shipping tariffs (€/Ro-Ro unit) of the existing liner shipping services connecting the ports of interest.

Ship and service information were collected with the preliminary support of the port authorities of interest, which provided us with the list of the ro-ro shipping companies regularly calling at their ports and connecting at least two of the four ports of interest. Four shipping companies meeting these requirements were identified. In the first phase, the information contained in the official websites of these companies was used to characterize the services of interest in terms of schedules, timetables, frequencies, and features of the ships operating the various services. Afterward, the local offices of the four companies were approached by telephone in order to validate the information collected and to overcome the problems related to missing and inconsistent data. Tab. 2 and Tab. 3 show the data used in the proposed application. In particular, Tab. 3 describes the various liner services currently operating among the four ports analyzed, namely, the port of origin, port of destination, weekly frequency, ship capacity, and shipping tariffs. The first column lists the ID codes of the considered O/D pairs. As in some cases different companies operate on the same route, the same O/D pair can appear more than once in Tab. 3, depending on the number of operators providing the service on a given route.

Table 2

Port handling times (h/Ro-Ro ship) and tariffs (€/Ro-Ro unit)

	Port handling time (h)	*Port handling tariff (€/Ro-Ro unit)*
Genoa	5	65
Cagliari	4.2	84
Leghorn	4.5	65
Palermo	5	27

5.2. Application results

In this section, we describe the main results obtained for testing the proposed mathematical model on the demand and supply instance presented in Section 5.1. The model has been solved by the commercial solver for Mixed Integer Programming Xpress 7.9, running on a PC with an i7-5500U processor at 2.4 GHz with 16 GB of memory. It is important to note that even though this application refers to a specific case study, both the model proposed and approach adopted can be easily applied to many demand and supply configurations. The tests were conducted to compare the average travel times and tariffs characterizing the existing non-optimized maritime network (Scenario 1) with those of the optimized hypothesis (Scenario 2). The planning horizon of reference is weekly. To analyze a multi-objective version of the problem in which the two different objectives concerning the minimization of travel times or travel tariffs are considered one at a time, the numerical tests were performed hierarchically using the two objectives. More specifically, for both scenarios considered, the demand flows were assigned to the network as follows:

- once, giving priority to the minimization of total travel times and using the tariff element as a secondary preference factor;
- once, giving priority to the minimization of total shipping tariffs and using the time element as a secondary preference factor.

Results for Scenario 1 - Existing maritime network

Scenario 1 refers to the application of the proposed model to the existing liner shipping network: service frequencies and timetables are both taken from the existing situation. To study this scenario, we add to the model presented in Section 4 the following set of constraints: $T_s = T_{FIXs}$ ($\forall s \in S$), where T_{FIXs} is the departure time in the actual schedule provided by the companies. In this way, we fix the scheduling part, and we optimize flow assignment for each O/D pair l on each day d. Tab. 4 shows the

numerical results for demand assignment to the existing network assuming to privilege once the minimum time criterion (right column), and once the minimum tariff (left column). Each service is characterized by its ID, departure day, total travel time, and tariff. The bottom line shows the resulting average travel time (h) and tariff (€/Ro-Ro unit). Looking at these data, it emerges,

 – when the minimum tariff criterion is preferred, the resulting assignment of demand flows across the network produces an average total travel time of 44 h and an average tariff of 597 € per Ro-Ro unit;
 – when the minimum time criterion is preferred, the resulting assignment of demand flows across the network produces an average total travel time of 41 h (-3 h compared to the previous case), and an average tariff of 606 € (+9 € compared to the previous case) per Ro-Ro unit.

Table 3

Features of the analyzed services

O/D ID	Origin Port	Destination Port	Weekly Frequency	Ship Capacity (No. of Ro-Ro units)	Shipping tariff (€/Ro-Ro unit)
1	Cagliari	Genoa	3	120	520
1	Cagliari	Genoa	5	178	410
2	Cagliari	Leghorn	3	178	430
2	Cagliari	Leghorn	5	120	510
3	Cagliari	Palermo (via Salerno)	3	160	420
3	Cagliari	Palermo	1	110	560
4	Genoa	Cagliari	5	178	410
4	Genoa	Cagliari	3	120	520
5	Genoa	Palermo	6	160	780
5	Genoa (via Salerno)	Palermo	5	250	1100
6	Leghorn	Cagliari	3	178	430
6	Leghorn	Cagliari	5	120	510
7	Leghorn	Palermo	3	145	900
8	Palermo	Cagliari (via Salerno)	3	160	420
8	Palermo	Cagliari	1	110	560
9	Palermo	Genoa	6	160	780
9	Palermo	Genoa (via Salerno)	5	250	1100
10	Palermo	Livorno	3	145	900

The numerical results for the two scenarios are presented and discussed below.

Results for Scenario 2 - Optimized maritime network

Scenario 2 refers to the application of the proposed model to the optimized maritime network in which the service frequencies are known and taken from the existing situation, whereas the services timetable is determined through the optimization model to minimize total travel times and tariffs. Tab. 5 shows the results for demand assignment to the optimized network assuming to privilege once the min time criterion (right column) and once the min tariff (left column). As for Scenario 1, each service is characterized by its ID, departure day, total travel time, and tariff. Looking at the average travel times and tariffs shown in the bottom line it emerges,

 – when the min tariff criterion is preferred, the resulting assignment of demand flows across the optimized network produces an average total travel time of 27 h and an average tariff of 588 € per Ro-Ro unit;
 – when the min time criterion is preferred, the resulting assignment of demand flows across the network produces an average total travel time of 24 h (-3 h compared with the previous case), and an average tariff of 606 € (+18 € compared to the previous case) per Ro-Ro unit.

Table 4

Numerical results of the application. Scenario 1 – EXISTING NETWORK

	Min tariff criterion				Min time criterion		
O/D	Day	Time (h)	Tariff (€)	O/D	Day	Time (h)	Tariff (€)
1	1	32	410	1	1	32	410
1	2	32	410	1	2	32	410
1	3	32	410	1	3	32	410
1	4	32	410	1	4	32	410
1	5	39	520	1	5	39	520
2	1	60.5	430	2	1	36.5	510
2	2	36.5	430	2	2	36.5	430
2	3	60.5	430	2	3	36.5	510
2	4	36.5	430	2	4	36.5	430
2	5	36.5	510	2	5	36.5	510
3	1	29	420	3	1	29	420
3	2	53	420	3	2	53	420
3	3	29	420	3	3	29	420
3	4	36	420	3	4	36	420
3	5	24	560	3	5	24	560
4	1	38.2	410	4	1	38.2	410
4	2	38.2	410	4	2	38.2	410
4	3	38.2	410	4	3	38.2	410
4	4	86.2	410	4	4	38.2	520
4	5	62.2	410	4	5	62.2	410
5	1	41	780	5	1	41	780
5	2	41	780	5	2	41	780
5	3	41	780	5	3	41	780
5	4	41	780	5	4	41	780
5	5	41	780	5	5	41	780
6	1	60.2	430	6	1	36.2	510
6	2	36.2	430	6	2	36.2	430
6	3	60.2	430	6	3	36.2	510
6	4	36.2	430	6	4	36.2	430
6	5	36.2	430	6	5	36.2	430
7	1	38	900	7	1	38	900
7	2	62	900	7	2	62	900
7	3	38	900	7	3	38	900
7	4	62	900	7	4	62	900
7	5	38	900	7	5	38	900
8	1	59.2	420	8	1	59.2	420
8	2	35.2	420	8	2	35.2	420
8	3	59.2	420	8	3	59.2	420
8	4	35.2	420	8	4	35.2	420
8	5	47.2	560	8	5	47.2	560
9	1	40	780	9	1	40	780
9	2	40	780	9	2	40	780
9	3	40	780	9	3	40	780
9	4	40	780	9	4	40	780
9	5	40	780	9	5	40	780
10	1	61.5	900	10	1	61.5	900
10	2	37.5	900	10	2	37.5	900
10	3	62.5	900	10	3	62.5	900
10	4	38.5	900	10	4	38.5	900
10	5	62.5	900	10	5	62.5	900
Mean value		44 h	597	Mean value		41 h	606

Table 5

Numerical results of the application. Scenario 2 – OPTIMIZED MARITIME NETWORK

	Min tariff criterion				*Min time criterion*		
O/D	*Day*	*Time (h)*	*Tariff (€)*	*O/D*	*Day*	*Time (h)*	*Tariff (€)*
1	1	23	410	1	1	23	410
1	2	23	410	1	2	23	410
1	3	23	410	1	3	23	410
1	4	23	410	1	4	23	410
1	5	23	410	1	5	23	520
2	1	44.5	430	2	1	20.5	510
2	2	20.5	430	2	2	20.5	430
2	3	20.5	430	2	3	20.5	430
2	4	44.5	430	2	4	20.5	510
2	5	20.5	430	2	5	20.5	430
3	1	20	420	3	1	20	420
3	2	44	420	3	2	20	420
3	3	20	420	3	3	20	420
3	4	44	420	3	4	37	560
3	5	20	420	3	5	13	560
4	1	22.2	410	4	1	22.2	410
4	2	22.2	410	4	2	22.2	410
4	3	22.2	410	4	3	22.2	410
4	4	22.2	410	4	4	22.2	410
4	5	22.2	410	4	5	22.2	410
5	1	25	780	5	1	25	780
5	2	25	780	5	2	25	780
5	3	25	780	5	3	25	780
5	4	25	780	5	4	25	780
5	5	25	780	5	5	25	780
6	1	44.2	430	6	1	20.2	430
6	2	20.2	430	6	2	20.2	430
6	3	20.2	430	6	3	20.2	430
6	4	20.2	430	6	4	20.2	430
6	5	20.2	430	6	5	20.2	510
7	1	47	900	7	1	23	900
7	2	23	900	7	2	47	900
7	3	23	900	7	3	23	900
7	4	47	900	7	4	47	900
7	5	23	900	7	5	23	900
8	1	43.2	420	8	1	19.2	420
8	2	19.2	420	8	2	19.2	420
8	3	43.2	420	8	3	36.2	560
8	4	19.2	420	8	4	12.2	560
8	5	19.2	420	8	5	19.2	420
9	1	25	780	9	1	25	780
9	2	25	780	9	2	25	780
9	3	25	780	9	3	25	780
9	4	25	780	9	4	25	780
9	5	25	780	9	5	25	780
10	1	46.5	900	10	1	46.5	900
10	2	22.5	900	10	2	22.5	900
10	3	22.5	900	10	3	22.5	900
10	4	46.5	900	10	4	46.5	900
10	5	22.5	900	10	5	22.5	900
Mean value		27 h	588	*Mean value*		24 h	606

By analyzing and comparing the results for the two scenarios, it is possible to draw some considerations. The use of the proposed optimization model to reschedule and coordinate existing services allows to determine an optimized network option characterized by average travel times that are significantly lower than those of the non-optimized network: -38% (-17 h) using the min tariff criterion and -41% (-17 h) using the min time criterion. In the application, the time element seems to provide more room for improvement than the tariff element. In fact, the use of the min time criterion yields the same average tariff in the two scenarios. On the contrary, the average travel time appears very different (-17 h in Scenario 2), confirming the benefits of a smart and coordinated scheduling plan.

5.3. Application limits

This study has proposed a mathematical model to maximize the performance of a maritime network, in terms of both tariffs and travel time minimization. Though computational results prove the ability of the proposed mathematical tool in optimally assigning demand flows on a maritime network while trying to minimize a multi-objective function composed of a weighted sum of travel times and tariffs, it may have some limitations when transferred to the real world. The reason for this has to be found in the fact that, like the vast majority of models, it represents a simplified description of the analyzed phenomenon. To avoid extra complexity, it cannot incorporate all the details and implications of the complex real phenomenon and must necessarily include some approximations as a convenient way to describe the real case. Some limiting factors thus exist owing to a number of necessary approximations made in the application:

- the assignment of demand flows on the analyzed network considers only tariff and time factors. Additional preference elements that can still influence the customer's choice are not considered, among the others, port reliability, consuetude, business strategies, open complaints, payment terms, etc.;
- in assigning demand flows to the network, it is assumed that all ports work 24/7. It should be noted that not all terminals work 24/7; thus, additional waiting times related to effective working hours may arise;
- similarly, in assigning demand flows to the network, it is assumed that ports are always able to perform loading/unloading operations as soon as required. The occurrence of disruptions, equipment unavailability, or other situations that can produce a lengthening of ordinary port handling times is not considered.

Because of these limitations, the results of this study are not intended to be directly transferable to real situations, but they can still provide useful suggestions for more effective planning of maritime services. The proposed model gives network planners a wealth of insights into network structure and properties in a way that is easy to visualize and understand. In this regard, it can offer not only the opportunity to better understand the Tyrrhenian network structure and its global balance but also to make predictions about the global impact of possible network strategies and interventions before their implementation.

6. CONCLUSIONS

In this study, we have addressed the maritime network design problem for Ro-Ro freight transport within the Italian Tyrrhenian area. The proposed methodological approach is based on the integration of service timetables and frequencies of existing liner services using an original mathematical model that assigns demand flows to the network while trying to minimize a multi-objective function composed of a weighted sum of travel times and tariffs. The main contribution of the proposed research work can be to provide a mathematical tool that can maximize the performance of a maritime network, in terms of both tariffs and travel time minimization. The proposed model was tested on a real-world maritime network composed of 4 core ports and 18 existing maritime Ro-Ro liner services. The test was carried out to compare the average travel times and tariffs characterizing the existing

non-optimized maritime network with those of the optimized scheme. Computational results showed the positive impact of services rescheduling and coordination in terms of time and tariff for the network analyzed and demonstrated the greater potential the 'Tyrrhenian network system' considered as a whole could offer compared with the single maritime services collectively. Despite some application limits related to the necessary assumptions made in its formulation, the proposed model offers the important opportunity to provide network planners with a wealth of insights into network structure and properties in a way that is easy to visualize and understand. Furthermore, when used according to a "what if" approach, it can represent a useful decision support tool to evaluate the effectiveness of alternative network interventions, such as the introduction of new services or modifications in frequencies, timetables, and tariffs of the existing ones. It is important to note that, despite the proposed model was specifically designed for the analyzed case study, it is general and can be initialized with all possible demand and supply settings, thus making the approach easily replicable on other network scenarios. In the context of MOS, which represents one of the flagship priorities of EU, the proposed research and its outcomes can thus provide useful insights to EU decision makers to investigate the effectiveness of alternative integrated strategies for improving the overall maritime transport supply within the EU area.

Acknowledgments

References

1. Fadda, P. & Fancello, G. & Pani, C. & Serra, P. The OPTIMED project: A new Mediterranean hub-based ro-ro network. In: *Transport Infrastructure and Systems: Proceedings of the AIIT International Congress on Transport Infrastructure and Systems*. 2017.
2. Fancello, G. & Pani, C. & Serra, P. & Fadda, P. Port cooperation policies in the Mediterranean Basin: An experimental approach using cluster analysis. *Transportation Research Procedia.* 2014. Vol. 3. P. 700-709.
3. Casaca, A.C.P. & Marlow, P.B. The Impact of the Trans-European transport networks on the development of SSS. *Maritime Economics & Logistics.* 2007. Vol. 9. No. 4. P. 302-323.
4. Paixão, A.C. & Marlow, P.B. Strengths and weaknesses of short sea shipping. *Marine Policy.* 2002. Vol. 26, No. 3, P.167-178.
5. Wang, S., & Meng, Q. Liner ship fleet deployment with container transshipment operations. *Transportation Research Part E: Logistics and Transportation Review*. 2012. Vol. 48. No. 2 , P. 470-484.
6. Ducruet, C. & Notteboom, T. The worldwide maritime network of container shipping: spatial structure and regional dynamics. *Global networks.* 2012. Vol. 12. No.3. P. 395-423.
7. Ameln, M. & Fuglum, J.S. *The Liner Shipping Network Design Problem: Strengthened formulations considering complex route structures, transhipment and transit time*. Master thesis. Norwegian University of Science and Technology (NTNU). 2015.
8. Meng, Q. & Wang, S. Liner shipping service network design with empty container repositioning. *Transportation Research Part E*. 2011. Vol. 47. No. 5. P. 695-708.
9. Imai, A. & Shintani, K. & Papadimitriou, S. Multi-port vs. Hub-and-Spoke port calls by containerships. *Transportation Research Part E*. 2009. Vol. 45. No. 5. P. 740-757.
10. Gelareh, S. & Pisinger, D. Fleet deployment, network design and hub location of liner shipping comp. *Transportation Research Part E*. 2011. Vol. 47. No. 6. P. 947-964.
11. Fagerholt, K. Optimal fleet design in a ship routing problem. *International Transactions in Operational Research*. 1999. Vol. 6. No. 5. P. 453-464.

12. Mourão, M.C. & Pato, M.V. & Paixão, A.C. Ship assignment with hub and spoke constraints. *Maritime Policy and Management.* 2001. Vol. 29. No. 2. P. 135-150.
13. Ningwen, T. & Dimas, A. & Xiaowen, F. & Zhi-Chun, L. Shipping network design in a growth market: The case of Indonesia. *Transportation Research Part E.* 2018. Vol. 117. P. 108-125.
14. Christiansen, M. & Fagerholt, K. & Ronen, D. Ship routing and scheduling: Status and perspectives. *Transportation science.* 2014. Vol. 38. No. 1. P. 1-18.
15. Christiansen, M. & Fagerholt, K. & Nygreen, B. & Ronen, D. Ship routing and scheduling in the new millennium. *European Journal of Operational Research.* 2013. Vol. 228. No. 3. P. 467-483.
16. Brouer, B.D. & Alvarez, J.F. & Plum, C.E.M. & Pisinger, D. & Sigurd M.M. A Base Integer Programming Model and Benchmark Suite for Liner-Shipping Network Design. *Transportation Science.* 2014. Vol. 48, No. 2. P. 281-312.
17. Agarwal, R. & Ergun, O, Ship Scheduling and Network Design for Cargo Routing in Liner Shipping. *Transportation Science.* 2008. Vol. 42. No. 2. P. 175-196.
18. Zheng, J. & Meng, Q. & Sun, Z., Liner hub-and-spoke shipping network design. *Transportation Research Part E: Logistics and Transportation Review.* 2015. Vol. 75. P. 32-48.
19. Reinhardt, B.L. & Pisinger D. A branch and cut algorithm for the container shipping network design problem. *Flexible Services and Manufacturing Journal.* 2012. Vol. 24. No. 3. P. 349-374.
20. Gelareh, S. & Nickel, S. & Pisinger, D. Liner shipping hub network design in a competitive environment. *Transportation Research Part E: Logistics and Transportation Review.* 2010. Vol. 46. No. 6. P. 991-1004.
21. Agarwal, R. & Ergun, O., Network Design and Allocation Mechanisms for Carrier Alliances in Liner Shipping. *Operations Research.* 2010. Vol. 58. No. 6. P. 1726-1742.
22. Asgari, N., Farahani, R.Z., & Goh, M. Network design approach for hub ports-shipping companies competition and cooperation. *Transportation Research Part A: Policy and Practice.* 2013. Vol. 48. P. 1-18.
23. Wang, S. & Meng, Q. Liner shipping network design with deadlines, *Computers & Operations Research.* 2014. Vol. 41. P. 140-149.
24. Wilmsmeier, G. & Martinez-Zarzoso, I. Determinants of maritime transport costs–a panel data analysis for Latin American trade. *Transportation Planning and Technology.* 2010. Vol. 33. No. 1. P.105-121.
25. Button, K. *Transport economics.* Edward Elgar Publishing. 2010.
26. Fancello, G. & Schintu, A. & Serra, P. An experimental analysis of Mediterranean supply chains through the use of cost KPIs. *Transportation Research Procedia.* 2018. Vol. 30. P. 137-146.
27. Lupi, M. & Farina, A. & Orsi, D. & Pratelli, A. The capability of Motorways of the Sea of being competitive against road transport. The case of the Italian mainland and Sicily. *Journal of Transport Geography.* 2017. Vol. 58. P. 9-21.
28. Acciaro, M. & Serra, P. Strategic determinants of terminal operating system choice: an empirical approach using multinomial analysis. *Transportation Research Procedia.* 2014. Vol. 3. P. 592-601.