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Design and optimisation of an innovative Two-Hub-and-Spoke network for the Mediterranean Short-Sea-Shipping market

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Abstract

Short Sea Shipping (SSS) is generally considered as a privileged transport mode in terms of reducing road congestion and related external costs. In the last two decades, SSS has attracted a lot of attention in the European Union, where it is also regarded as a key factor for economic and social cohesion between countries. In this regard, the present study proposes a new network design that aims at improving and increasing freight traffic between the north-western and the south-eastern shores of the Mediterranean Basin. The proposed model, designed for Ro-Ro (Roll-on Roll-off) freight transport, tries to overcome the limits of the existing multi-port-calling services through an innovative two-hub-based scheme of better scheduled and reliable frequencies and more competitive delivery times. The operating parameters of the new network are determined using a specially designed optimisation approach based on two separate but related mathematical models: a Mixed Integer Linear Programming Model for Service Frequency Selection and a Mixed Integer Linear Programming Model for Service Timetabling. Numerical tests, performed on real demand and supply data covering 23 ports in 8 Mediterranean countries, show the validity of the proposed approach to determine an optimal network configuration for the organisation of transport services in the area.

Keywords*:* Network Design Optimisation; Mediterranean Corridors; Short Sea Shipping; Service Frequency Selection; Ro-Ro Market; Motorways of the Sea.

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1. Introduction

Short Sea Shipping (SSS) is one of the main options that EU transport policy is focusing upon for developing sustainable and cohesive transport among EU member states. Although a definition of SSS is not easy (Paixão and Marlow, 2002), the market is traditionally decomposed into three different sub-sectors: the pure intra-European market; the feeder market; and the cabotage market (Casaca and Marlow, 2007). The latter typically includes pure domestic trade, while the first two constitute the international side of the SSS market. Within the Mediterranean area, these three sub-markets could be conceptually integrated to create one large market embracing ports located along the coastal areas of both EU and non-EU countries. Such a wide area would offer a huge potential market for the further development of SSS services. The Mediterranean not only plays a key role in international East-West trade but, following the development of MENA (Middle-East and North-Africa) countries, it is also gaining increasing importance as a trade area for intra-regional Mediterranean traffic. Note that MENA countries have seen their GDP increase by 4.4% per annum in the period 1995-2016, while in the same period the average increase in the EU28 was 1.9%. Traffic data for the period 2001-2014 further confirm this growth trend, showing an increase of about 160% in north-south maritime freight flows from the Mediterranean to the Middle- and the Far East- Gulf, and a 92% increase in the opposite direction (EUROSTAT, 2017).

Despite the above growth trends, closer economic integration among the countries on the northern and southern shores still appears inadequate in terms of stable and sustainable commercial relationships and of maritime connections able to support such a development. It should also be noted that although until a few years ago the renewed centrality of the Mediterranean in commercial strategies was to be almost exclusively attributed to container traffic, now the Ro-Ro sector also plays an important role. The Ro-Ro sector concerns the transport of rolling cargo, i.e., cargo which is on wheels, such as trucks or trailers (but also containers if they are handled as swap bodies), and which can be rolled on and off the decks of a ship which has roll-on roll-off facilities. A ship designed to handle cargo in this way is known as a Ro-Ro ship. Ro-Ro ships have enjoyed great commercial success over the last years in the Mediterranean. According to recent estimates, since 2012, the number of Ro-Ro ships in the Mediterranean has increased by 7.4% (SRM, 2018). This growth can be easily attributed to the well-recognised economic and operational advantages Ro-Ro ships offer over traditional vessels. Particularly, with the advent of the latest generation ships that can carry a combination of different types of freight with the greatest flexibility, shipping companies can rapidly make

the operational and organisational adjustments needed to optimise vessel load factors, so as to cope, for instance, with possible crises or demand shocks in a given market. On the whole, Ro-Ro shipping seems to have very favourable prospects in the years to come. Notwithstanding this, the development of Ro-Ro networks in the Mediterranean still needs to improve to ensure more efficient and sustainable trade relations within the basin.

In recent years, an increasing number of projects promoted by several Euro-Mediterranean programmes have been focusing on the design of solutions to promote stable and sustainable commercial relationships between the two Mediterranean shores, with special regard to interventions aimed at improving the maritime connections that can favour such a process. In particular, the focus of this paper is on the outcomes of a project funded under the last 2007/2013 ENPI CBC MED - European multilateral Cross-Border Cooperation Programme, the so-called OPTIMED project, whose primary aim was to optimise the Ro-Ro trade between the north-western and south-eastern shores of the Mediterranean (Fadda et al., 2017; CIREM, 2014). The objectives to be achieved with the OPTIMED project focused both on improving the efficiency of the Mediterranean shipping supply system in terms of reducing journey times, of regularity and frequency of connection services as well as rendering it more sustainable from an environmental perspective, and more effective concerning its ability to attract new demand and improve commercial relations between the countries on the two shores. In so doing, the project designed a new topological structure of the shipping network connecting the two Mediterranean shores and proposed an integrated organization of its transport services. The approach adopted was based on a change of perspective in the organization of the transport service in the area: from unintegrated and fragmented connections to a coordinated two-hub-based Ro-Ro network option characterised by scheduled services and more competitive delivery times.

This paper analytically describes the newly proposed network structure and the optimisation approach that was used to determine the organization of the transport services along its arcs and nodes. Particularly, the proposed application intends to demonstrate that denying transhipment for Ro-Ro freight traffic cannot be axiomatic, as it is commonly believed, but needs to be proven. This study demonstrates the inexistence of such axioma for an inefficient multi-port-calling system by proposing and implementing an alternative hub-and-spoke network for international SSS in the Mediterranean basin.

The structure of the paper is as follows. Section 2 introduces the application area and describes the considered transport network as it stands now. Section 3 illustrates the topological structure of the proposed network and describes

the main features of the problem addressed in view of its mathematical formalization. Section 4 presents a brief literature review of methods and models for the Maritime Network Design problem. Section 5 models the problem studied by a two-step approach based on two tailored Mixed Integer Programming Models. Section 6 illustrates the main results of the performed application while Section 7 discusses the main key success factors of the proposed network and some policy implications. Finally, Section 8 concludes.

2. The application area

The application area coincides with the project area. It includes the eight partner countries of the project consortium interested in investigating a new integrated solution for improving the east-west Ro-Ro maritime connections among their shores. Countries involved include:

- France, Italy, and Spain in the north-western part;
- Cyprus, Egypt, Lebanon, Syria, and Turkey in the south-eastern one.

Within these countries, the identification of the Mediterranean ports of interest was carried out according to the following criteria:

- nature of the traffic served - since the research focuses on the Ro-Ro sector, only the ports serving a consistent share of Ro-Ro traffic were included in the analysis. Therefore, other ports, despite their importance, were excluded;
- commercial requirements – only the ports that have stable east-west trade relationships with the countries involved were included.

The following ports were thus selected:

- Valencia, Sagunto, Castellon, Barcelona, Tarragona, Marseille, Sète, Toulon, Savona, Genoa, Spezia, Livorno, Civitavecchia, Naples, and Salerno on the EU side;
- Mersin, Latakia, Tartous, Beirut, Tripoli, Alexandria, Damietta, Port Said, and Limassol on the MENA side.

To better outline the study area, a simplified network graph was built by identifying a single centroid node (node of generation and attraction of demand) for each area of origin and destination of the goods. Each of these areas can comprise more than one port in that part of the coastal shore in which maritime services of the corridor of interest are available (Table 1). The final structure of the considered graph consists of seven port centroids for the European

coasts, and seven for the MENA region, for a total of 98 potential origin/destination (O/D) connections: 49 from West to East and 49 from East to West (Figure 1). Each centroid node can be intended as connected through a fictitious arc (times and costs are zero) to each node belonging to it.

Table 1. Network centroids.

	Country	Centroid	Ports belonging to the centroid
EU area	Spain	Valencia	Valencia, Sagunto, Castellon
		Barcelona	Barcelona, Tarragona
	France	Marseille	Marseille
		Sète	Sète, Toulon
	Italy	Genoa	Genoa, Savona
		Spezia	Spezia, Livorno
		Naples	Naples, Salerno
MENA area	Turkey	Mersin	Mersin
	Syria	Latakia	Latakia, Tartous
	Lebanon	Beirut	Beirut, Tripoli
	Egypt	Alexandria	Alexandria
		Port Said	Port Said
		Damietta	Damietta
	Cyprus	Limassol	Limassol

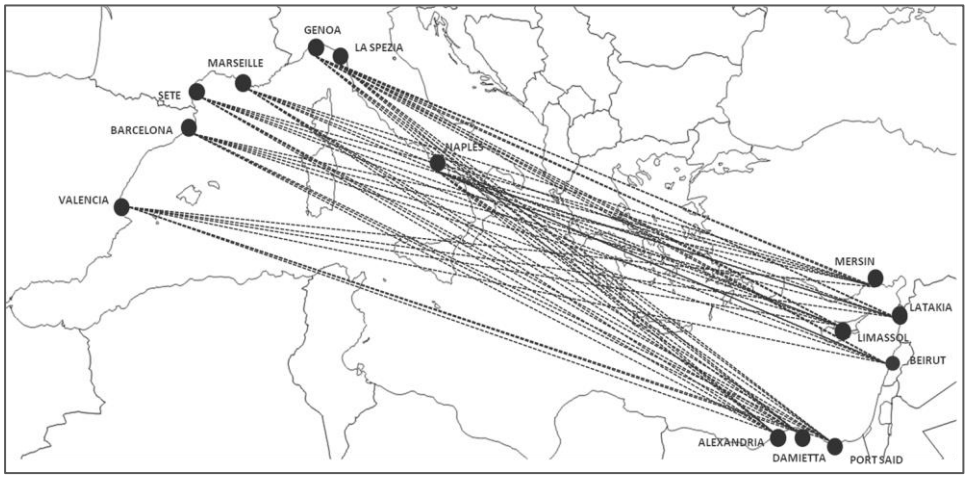

Figure 1. Simplified representation of the 98 O/D connections between the identified port centroids in the study area.

2.1 Characterisation of the existing scenario

A survey of the Ro-Ro liner services available between the identified ports was carried out in order to outline the general characteristics of the existing transport supply in the area. The following activities were performed to reconstruct the existing system of Ro-Ro connections among the 14 port centroids:

- acquisition of the list of Ro-Ro companies, regularly calling at the selected ports;
- description of the services offered in terms of routes, sequence of ports of call, frequency, ships' features and service timetables (using the information contained in the official websites of the shipping companies).

This process identified 16 Mediterranean Ro-Ro and Con-Ro[†‡] liner services, providing at least one service per month and connecting at least two ports on opposite shores. In most cases, the services identified appear fragmented and unintegrated, a 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.

In a second stage, starting from the 16 identified services and the collected information, each of the 98 shore-to-shore connections was characterised in terms of distance, travel times, sequence of ports of call, number of intermediate stops and frequency. The following criteria were used:

- each O/D pair was characterised through the shortest route, selected among those available, based on the length of the itinerary;
- the possibility of interchange between lines was considered only when no single line offered a direct connection between two port centroids, thus necessitating the combination of at least two lines;
- when more than one line operated along the same O/D route, the frequency was calculated as the sum of the frequencies characterising the various services provided by each company.

Some general operating parameters of the existing network are summarised in Table 2. These data will be resumed and discussed later in the paper to assess and benchmark the performance of the current network option with respect to the optimised one that we propose.

Table 2. General features of the existing transport supply among the identified port centroids.

†

‡ Con-Ro: hybrid of a Ro-Ro and a container ship.

Description	Unit of measure	Mean
Weekly Frequency	times/week	1.3
Number of Intermediate port calls	stops/travel	3.6
Sailing Distance	nm/travel	2016.4
Sailing Time	h/travel	106.1
Port Time	h/travel	65.3
Total Journey Time	h/travel	338.9

Within this framework, the main scope of the research was to study an alternative Ro-Ro network option potentially able to better serve the existing and future transport demand in the area by means of scheduled, regular and reliable frequencies and more competitive delivery times.

3. Problem Description

Compared to other transportation systems, such as railway or trucks, the design of an efficient maritime network can be much more complex (Ducruet and Notteboom, 2012). Over the past decades, one of the main debates about maritime network design has concerned the opportunity to adopt hub-and-spoke schemes rather than the more traditional multi-port-calling ones, compared to which they are generally more convenient and cost-efficient (Imai et al., 2009). Although several features of hub-and-spoke schemes can easily apply to a variety of networks (Zheng and Yang, 2016), their adoption has so far been investigated mainly with reference to the container industry, where they are most widespread (Mingjun et al., 2015; Meng and Wang, 2011; Gelareh et al., 2010).

This study intends to investigate the applicability of hub-and-spoke schemes to Ro-Ro networks. To this end, a new network option connecting the two Mediterranean shores is thus designed by transferring the hub-and-spoke paradigm, which is typical of the container market, to the Ro-Ro sector. From a topological point of view, the newly proposed network has a two-hub based structure (Figure 2). Two hub ports are identified, Porto Torres (Sardinia, Italy) serving the western coastal shore and Beirut (Lebanon) serving the eastern one.

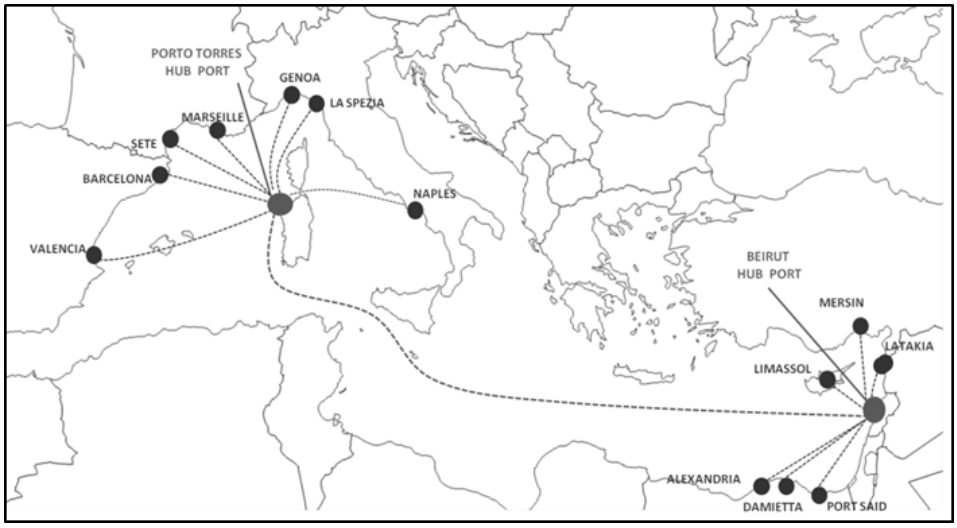

Figure 2. The basic topological structure of the new network.

Both ports have been chosen for their barycentric position within the Mediterranean basin (to minimise the average distances in the connections with the origin/destination ports) and considering the availability of appropriate port and dry-port areas to be used for cargo handling operations. Each hub serves the set of origin/destination ports of reference according to the hub-and-spoke distribution scheme in which all traffic volumes move along spokes linked to the hub in a system of connections arranged like a wire wheel.

In view of its mathematical modelling, the problem can be summarised as follows.

Connections among ports are ensured by two types of maritime services:

- origin and destination ports are linked to the hub of reference by frequent and regular feeder services;
- the two hubs are connected through regular mother services. Mother services cover larger distances compared to feeder ones.

Feeder services are performed by the so-called feeder ships. In export flows, feeder ships collect Ro-Ro units from different origin ports and transport them to the Ro-Ro hub port of reference where they are loaded onto mother ships. In import flows, feeder ships load Ro-Ro units unloaded from mother ships and distribute them to the various ports of destination.

From an operating perspective, the main problem is to determine the optimal frequencies, capacities and timetables of the maritime services, both mother and feeder, while ensuring freight transport demand is satisfied and total delivery

times minimised. The freight transport demand refers to the amount of goods to be transported between each pair of origin/destination ports in a given period, typically a week.

The optimisation process of the transport service within the proposed network has to reconcile two conflicting goals:

- maximisation of service quality for shippers, which means maximising service frequency in order to guarantee the high availability of the transport service for users;
- minimisation of unused capacity for each service, which means ensuring the economic convenience of the system for companies operating the various services.

For each pair of O/D ports, the total capacity of the service connecting them can be computed as the service frequency multiplied by the capacity of the vessel operating the service. Note that a minimum load factor has to be imposed to ensure the economic feasibility of the transport service.

To design a competitive transport option, it is important to ensure that the various linking services are spread from alternative ports throughout the week to guarantee good daily coverage of the whole area. In so doing, shippers can decide to use the most convenient port of departure for their goods depending on the day they plan to send them. Assuming that the optimal service frequencies and capacities have been defined, the goal of the optimisation process is to organise these services within a feasible schedule able to maximise the weekly coverage of each port while minimising waiting times at the two hubs. The weekly coverage of a port can be defined as the number of days, within a week, in which at least one feeder is leaving from that port or a port nearby. For instance, if a feeder service is leaving from ‘port x’ on Monday and Wednesday, while another feeder is leaving from the nearby ‘port y’ on Tuesday and Thursday, both ports will have a weekly coverage equal to 4, while, if feeders from ‘port y’ leave on Monday and Thursday, both ports will have a weekly coverage equal to 3. In this application, the ports of the same country are considered nearby ports (with the only exception of the port of Naples, which is some distance from the other two Italian ports included in the considered network).

In defining an optimal weekly schedule, it is essential to consider that departures and arrivals of feeder and mother ships must be coordinated in order to minimise waiting times for connection at the hubs while ensuring the necessary time for loading/unloading operations. In fact, a feeder service can be in connection with a mother service only if there is enough time to perform loading/unloading operations before the mother service departs. To this end, good port performances should be guaranteed especially in the two hubs, which are required to ensure high levels of productivity

in order to guarantee minimum port times for the ships, so as to comply with service requirements. The minimum port time represents the total time spent by a ship from the moment it enters the port to the moment it leaves. It consists of the sum of times for berthing, for cargo loading/unloading and for unberthing.

4. Background Literature

Once the topological structure of the network is determined, the main problem is to define its operating parameters in terms of optimal service frequencies, capacities and timetables. The problem faced is a typical problem of maritime network design involving a hub-and-spoke network.

Maritime network design is broadly addressed in the literature (Ameln et al., 2015; Wang and Meng, 2012) and it includes, and often combines, a wide variety of optimisation problems (Huang et al., 2015): among others, network design (Fancello et al., 2019; Mancini and Stecca, 2018), fleet deployment and hub location problems (Farahani et al., 2013). Several studies dealing with the design of hub-and-spoke networks can be found in the literature. Some consider predetermined hubs (Meng and Wang, 2011) while in others the choice of the hub is part of the decision process (Imai et al., 2009; Gelareh and Pisinger, 2011). Particularly, Zheng et al. (2014) propose a two-phase mathematical model to evaluate the impact of introducing hub-and-spoke schemes into maritime cabotage legislation: in the first phase, they deal with the hub location and feeder allocation problem, while in the second phase they address the ship route design and fleet deployment problem. Recently, a new cargo network has been designed by Ningwen et al. (2018) 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.

The above studies deal with contemporary network design and fleet deployment, but several papers aim to optimise fleet deployment for a predetermined service network. This problem is relevant in real-world applications where it frequently occurs that different decision-makers have to address the network design and fleet deployment problem in different moments (Cho and Perakis, 1996; Powell and Perakis, 1997; Fagerholt, 1999; Mourão et al., 2001; Wang et al., 2014). For shipping problems, once the service network is designed and the fleet is determined, the main cost component, from a company perspective, is known. In spite of its marginal role in cost computation, the last planning phase, service 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 (Andersson et al., 2011).

Comprehensive surveys can be found in Ronen (1993) and Christiansen et al. (2004; 2007) while recent trends and future perspectives are described by Christiansen et al. (2013).

As in previous works, the problem addressed in this study concerns the optimisation of the transport service for a predetermined network. Like several studies examined, a two-step approach is proposed to split the maritime network design problem into two easier-to-solve sub-problems. Specifically, the following two problems are dealt with:

- determination of the optimal frequencies and capacities of the services that make up the given network;
- determination of an optimal timetable for the scheduling of the above services.

The two problems are tackled by means of a specially designed optimisation approach based on two separate but related mathematical models that work in a cascade fashion. A detailed description of the two models is reported in the following section, also highlighting their main innovative aspects compared to the existing literature.

5. Methodology

Based on the characteristics of the maritime network concerned and similarities with the literature examined, a two-step approach is proposed to characterise the newly designed transport network in terms of optimal service frequencies, capacities and schedules:

- the first step defines the optimal frequencies and capacities of connection services along the various routes using a specially designed Mixed Integer Linear Programming Model (MILPM) for the service frequency selection;
- the second step defines an optimal timetable for organising the services identified by the previous step, using a Mixed Integer Linear Programming Model (MILPM) for service timetabling.

Both models are described in the following paragraphs while the flowchart in Figure 3 illustrates the designed optimisation methodology.

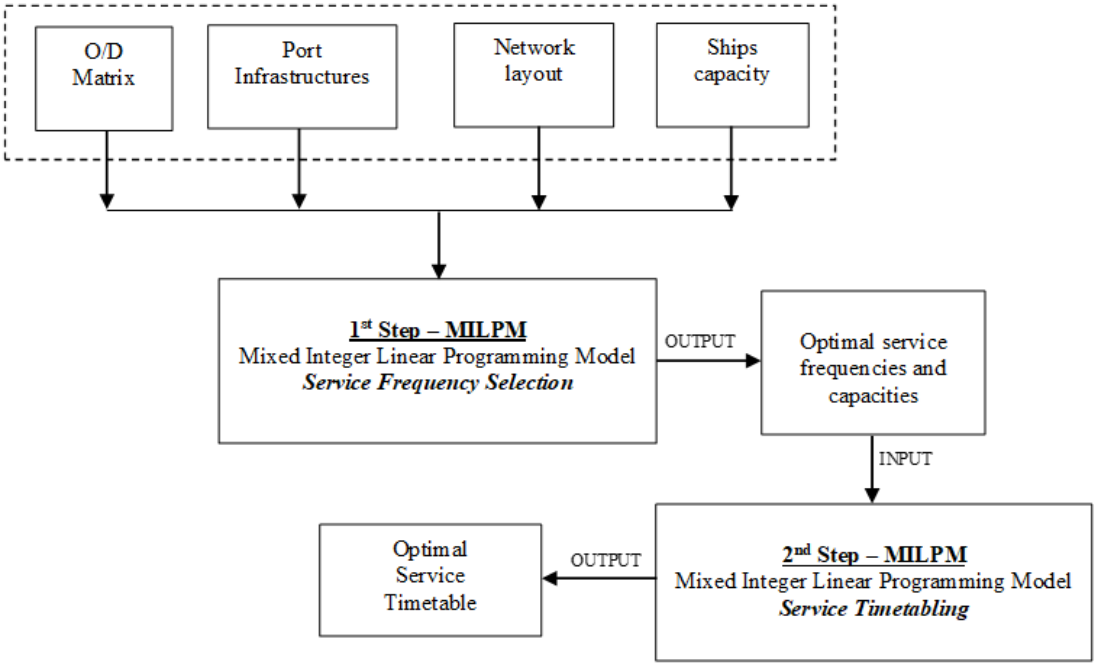

Figure 3. Methodology flowchart.

The two-step approach was chosen as it allows reproducing two planning phases that take place at different times and whose choices are directed to diverse beneficiaries. In defining the optimal frequencies and capacities of connection services, the first model reproduces the first planning choice, which is strategic. This choice belongs to shipowners and/or shipping operators who, typically annually or seasonally, must define the number of ships to be dedicated to the various services. This choice is strategic as it will have medium-term implications on the operator's business. Once the optimal frequencies and capacities of services are defined, the second model identifies an optimal weekly timetable for them. This choice, which is tactical, is addressed to users of maritime services, who require shipping services available throughout the week and with limited waiting times. The two planning moments are strongly related (the strategic choices fall on the tactical choices), as are the two models. From a modelling point of view, the two models work in a cascade fashion in the sense that the second model takes as input the optimal service frequencies and capacities determined by the first model and returns as output an optimal timetable for scheduling these services.

5.1. A Mixed Integer Linear Programming Model (MILPM) for Service Frequency Selection

The goal of the first model is to determine the optimal frequencies and capacities for each mother and feeder service in the network. The proposed objective function is a linear combination of two conflicting objectives. The first one maximises service quality (in terms of frequency) while the second maximises company revenues (in terms of vessels load factor). Differently from most network design problems, which generally focus on minimising costs while ensuring a minimum level of service to customers, this study simultaneously optimises the two objectives. The introduction of the β parameter allows one to weight the relative importance of the two criteria based on the decision perspective considered in the planning process: β=1 assigns the same importance to service quality (user's perspective) and revenues (company's perspective), β>1 gives more importance to companies' revenues while β<1 to service quality. Before presenting the mathematical formulation, it is necessary to introduce the following sets, parameters and decision variables.

Sets:

PortsI: set of origin ports

PortsK: set of destination ports

S: set of ships categories

Parameters

I_{max}: number of origin ports

γ: minimum load factor required

β: criteria weight

C_s: capacity of ships belonging to category s

C_{max}: capacity of the largest ship

D_{ij}: demand from origin port i to destination port j

Decision Variables:

X_{is}: weekly frequency of service operated with ships of category s from origin port i to the hub

R_i: unused capacity for services operating from origin port i to the hub

L_{is}: weekly capacity of services from origin port i to the hub operated on ships of category s

Fi: weekly frequency of feeder services serving port i

Model Formulation:

$$\max \frac{\sum_i F_i}{7 * Imax} + \beta \sum_i \frac{Cmax - R_i}{Cmax} \quad (1)$$

Subject to:

$$L_{is} = C_s X_{is} \quad \forall i \in I \qquad \forall s \in S \qquad (2)$$

$$\sum_j D_{ij} \geq \gamma \sum_s L_{is} \qquad \forall i \in PortsI \qquad (3)$$

$$R_i = \sum_s L_{is} - \sum_j D_{ij} \qquad \forall i \in PortsI \quad (4)$$

$$F_i = \sum_s X_{is} \quad \forall i \in PortsI \quad (5)$$

$$X_{is} \in Z^+ \quad \forall i \in PortsI \quad \forall s \in S \quad (6)$$

$$X_{is} \leq 7 \quad \forall i \in I \quad \forall s \in S \quad (7)$$

The goal of the problem, as stated in (1), is to maximise the weighted sum of the average daily frequency and average used capacity. The term R_i indicates the global unused capacity for ships entering port i. This value is computed as the difference between the sum of the capacity of the ships entering port i and the sum of the demand assigned to them. The two terms of the objective function need to be adimensional when β=1, i.e., each term should take values in [0,1]. To obtain this effect, instead of maximising the actual used capacity, we maximise the second term of (1) which is a linear increasing function of the used capacity (Cmax being the capacity of the largest ship) which is always comprised between 0 and 1. In (2), for each origin port the total capacity of the service connecting it to the hub operated by ships of category s is computed as the frequency of service multiplied by the capacity of service s. The minimum load factor required is ensured by constraint (3), while the unused capacity on the services connecting origin port i to the hub is computed by (4). The total service weekly frequency from origin port i to the hub is defined in (5). Constraint (7) imposes that each feeder connection can be carried out at most once a day. Finally, the variables domain is specified in (6).

5.2. A Mixed Integer Linear Programming Model (MILPM) model for Service Timetabling

In the second phase, a second Mixed Integer Linear Programming Model (MILPM) is proposed to provide a feasible schedule that maximises the 'weekly service coverage' of each port while minimising waiting time at the hubs. The model takes as input the weekly frequencies and ships capacity categories for each feeder service determined by the first model and provides the optimal weekly schedule as output. One of the main innovative aspects of this model is to consider the frequency of services between an origin/destination port and the hub of reference, as the sum of the frequencies of services operating directly from the port itself and those operating from the ports nearby. This is a crucial element for the definition of an effective weekly timetable able to maximise the weekly coverage of a port. As described in Section 3, the latter is defined as the number of days in a week, in which at least one feeder leaves from that port or a port nearby. To be clearer, if port "x" and port "y" are nearby ports it does not make sense scheduling their services on the same day(s), thus leaving the remainder of the week uncovered. It is much more rational for their services to be spread throughout the week so as to guarantee good coverage of the whole area every day. In so doing, transporters can decide to use the most convenient port of departure for their goods depending on the day they plan to send them.

Before presenting the mathematical formulation of the model let us introduce the following sets, parameters and decision variables:

Sets:

I: set of feeder services from origin to origin hub

J: set of mother services between hubs

K: set of feeder services from destination hub to destination

PortsI: set of origin ports

PortsK: set of destination ports

Days: set of days in the time horizon

Parameters:

T_{max}: end of the time horizon (one week)

t_i: sailing time for service i ∈ I

s_j: sailing time for service j ∈ J

τk: sailing time for service k ∈ K

δi: loading time for ship operating service i ∈ I

σj: loading time for ship operating service j ∈ J

αk: loading time for ship operating service k ∈ K

H_i: capacity of ship operating service i ∈ I

C_j: capacity of ship operating service j ∈ J

B_k: capacity of ship operating service k ∈ K

πi: port from which service i ∈ I starts

p_k: port from which service k ∈ K starts

e: very small positive constant

M: very large positive constant

Decision Variables:

$T1_i$: departure time from the origin port for service i ∈ I

$T2_i$: departure time from the hub for service i ∈ I

$U1_j$: departure time from the destination port for service j ∈ J

$U2_j$: departure time from the hub for service j ∈ J

$V1_k$: departure time from the hub for service k ∈ K

$V1_k$: departure time from the destination port for service k ∈ K

W_{ij}: binary variable taking value equal to 1 if service i ∈ I is in connection with service j ∈ J

A_{kj}: binary variable taking value equal to 1 if service k ∈ K is in connection with service j ∈ J

Pt_i: connection waiting time for service i ∈ I

Pu_j: connection waiting time for service j ∈ J

$DayI_{id}$: binary variable taking value equal to 1 if service i ∈ I is operated on day d

$DayK_{kd}$: binary variable taking value equal to 1 if service $k \in K$ is operated on day d

$CovI_{\gamma d}$: binary variable taking value equal to 1 if a service is operated from origin port γ, or from a port nearby, on day d

$CovK_{\varepsilon d}$: binary variable taking value equal to 1 if a service is operated from destination port ε, or from a port nearby, on day d

Model formulation:

$$\max \sum_{\gamma \in PortsI} \sum_{d \in Days} CoverI_{\gamma d} + \sum_{\varepsilon \in PortsK} \sum_{d \in Days} CoverK_{\varepsilon d} - e\left(\sum_{i \in I} Pt_i + \sum_{j \in J} Pu_j\right) \quad (8)$$

Subject to:

$$T2_i = T1_i + t_i \qquad \forall i \in I \quad (9)$$

$$\sum_{j \in J} W_{ij} = 1 \qquad \forall i \in I \quad (10)$$

$$W_{ij} \leq 1 + e\left(U1_j - T2_i - \delta_i - \sigma_j\right) \qquad \forall i \in I \qquad \forall j \in J \qquad (11)$$

$$Pt_i \geq U1_j - T2_i - M(1 - W_{ij}) \qquad \forall i \in I \qquad \forall j \in J \qquad (12)$$

$$\sum_{i \in I} W_{ij} * H_i \leq C_j \qquad \forall j \in J \qquad (13)$$

$$DayI_{id} \leq 1 + e(24d - T1_i)) \quad \forall i \in I \qquad \forall d \in Days \qquad (14)$$

$$DayI_{id} \leq 1 - e(24d - T1_i)) \quad \forall i \in I \qquad \forall d \in Days \qquad (15)$$

$$CoverI_{\gamma d} \leq \sum_{\substack{i \in I \\ p_i = \gamma}} DayI_{id} \quad (16)$$

$$U2_j = U1_j + s_j \qquad \forall j \in J \quad (17)$$

$$\sum_{j \in J} A_{kj} = 1 \quad \forall k \in K \quad (18)$$

$$A_{kj} \leq 1 + e\left(V1_k - U2_j - \alpha_k - \sigma_j\right) \qquad \forall k \in K \qquad \forall j \in J \qquad (19)$$

$$Pu_j \geq V1_k - U2_i - M(1 - A_{kj}) \quad \forall k \in K \qquad \forall j \in J \quad (20)$$

$$\sum_{k \in K} A_{kj} * B_k \leq C_j \quad \forall j \in J \quad (21)$$

$$\mathrm{DayK_{kd}} \leq 1 + \mathrm{e}(24\mathrm{d} - \mathrm{V1_k})) \quad \forall \mathrm{k} \in \mathrm{K} \qquad \forall \mathrm{d} \in \mathrm{Days} \quad (22)$$

$$\mathrm{DayK_{kd}} \leq 1 - \mathrm{e}(24\mathrm{d} - \mathrm{V1_k})) \quad \forall \mathrm{k} \in \mathrm{K} \qquad \forall \mathrm{d} \in \mathrm{Days} \quad (23)$$

$$\mathrm{CoverK_{\varepsilon d}} \leq \sum_{\substack{\mathrm{k} \in \mathrm{K} \\ \pi_\mathrm{k} = \varepsilon}} \mathrm{DayK_{kd}} \quad (24)$$

$$\mathrm{V2_k} = \mathrm{V1_k} + \tau_\mathrm{k} \qquad \forall \mathrm{k} \in \mathrm{K} \quad (25)$$

$$0 \leq \mathrm{T1_i} \leq \mathrm{Tmax} \qquad \forall \mathrm{i} \in \mathrm{I} \qquad (26)$$

$$\mathrm{U1_j} \geq 0 \; \forall \mathrm{j} \in \mathrm{J} \qquad (27)$$

$$\mathrm{V1_j} \geq 0 \; \forall \mathrm{k} \in \mathrm{K} \qquad (28)$$

$$\mathrm{DayI_{id}} \in \{0,1\} \quad \forall \mathrm{i} \in \mathrm{I} \quad (29)$$

$$\mathrm{DayK_{kd}} \in \{0,1\} \quad \forall \mathrm{k} \in \mathrm{K} \quad (30)$$

$$\mathrm{CoverI_{\gamma d}} \in \{0,1\} \quad \forall \gamma \in \mathrm{PortsI} \quad (31)$$

$$\mathrm{CoverK_{kd}} \in \{0,1\} \quad \forall \mathrm{k} \in \mathrm{PortsK} \quad (32)$$

The objective function, reported in (8) is a hierarchical function that first tries to maximise daily service coverage, O1, and then to minimise waiting times for connection, O2. The role of the multiplier *e* is to ensure that if a solution S1 has a higher value of O1 compared to S2 it would be preferred whichever the corresponding values of O2. In other words, the secondary objective intervenes in the comparison of the solutions only when the value of O1 is the same. This technique of dealing with hierarchical objective functions has been broadly adopted in the literature since the pioneering works of Plane and Hendrick (1977) and Daskin and Stern (1981), which applied this hierarchical approach to optimise fire departments and emergency medical services locations. In both cases, the primary objective is to minimise the number of facilities necessary to cover all the customers/patients and the secondary objectives are related to improving the quality of the service offered. Both problems are similar to the problem addressed in this paper in which the primary objective is to maximise ports daily coverage while the secondary objective concerns the quality of the service offered in terms of minimising waiting times. A more recent application of this hierarchical approach has been proposed by Aringhieri et al. (2017) who describe an application to surgery patients scheduling.

Constraints (9), (17) and (25) allow computing arrival time at the hub for each service. Constraints (10) and (18) guarantee that each feeder service is in connection with a mother service. A feeder service can be in connection with

a mother service if and only if there is enough time for loading/unloading operations before the mother service departs (constraints (11) and (19)). Constraints (12) and (20) allow computing waiting times at the hub. Constraints (13) and (21) ensure that mother services are not overloaded. The day in which a service is scheduled is determined by constraints (14), (15), (22) and (23). Constraints (16) and (24) imply that a port can be considered covered on day d if there is a feeder service leaving from it, or a port nearby, on day d. Finally, constraints from (26) to (32) specify variables domain.

Further constraints may be added to provide fair scheduling plans. For instance, if a service is scheduled twice a week and we want to avoid it operating on two consecutive days. Supposing that i1 and i2 are the two services to be scheduled, it is possible to obtain a fair distribution of the trips over the week, imposing a minimum distance between the two starting times as stated in constraint (33). To do this we introduce the parameter $\mathrm{shift_k}$ as the minimum shift between two services operating on the same line, which strictly depends on the frequency of services on that line. If, for instance, a feeder is scheduled twice a week, $\mathrm{shift_k}$ is taken as =72, while if it is scheduled three times a week, $\mathrm{shift_k}$ is =36.

$$\mathrm{T1_{i2}} \geq \mathrm{T1_{i1}} + \mathrm{shift_k} \quad (33)$$

Furthermore, we want to avoid cases in which two services are scheduled one at the beginning and one at the end of the week, therefore almost overlapping if the cyclicity of the schedule is considered. To overcome this issue the following constraint (34) has been added:

$$\mathrm{Tmax} - \mathrm{T1_{i2}} + \mathrm{T1_{i1}} \geq \mathrm{shift_k} \quad (34)$$

6. Application data and results

In order to verify the ability of the proposed two-step optimisation approach to provide an optimal feasible schedule for the organisation of the transport service, the two models have been tested on a set of test-instances, each characterised in terms of specific demand and supply configurations. Both mathematical models have been implemented in Xpress-ive modelling language while instances have been solved by Xpress 7.9, running on a PC with an i7-5500U processor at 2.4 GHz and 16 GB of memory. Since both models were able to solve to optimality (and in

very few seconds) the real application, there was no need to design an ad-hoc heuristic method. Very large instances could require recurring to heuristic approaches, but we did not further investigate this issue since such large instances are not realistic in Ro-Ro hub-and-spoke network contexts.

This section describes the main application data that characterise the analysed scenario and the main results from testing the two models.

6.1. Application Data

Main demand and supply data characterising the selected test scenario are described below.

Demand Data

The demand data for this study refers to the O/D flows for the 98 port-to-port connections introduced in Section 2. Traffic data between the ports included in the network were collected with a monthly detail for the period 2008-2012, thus before the political crisis that has long characterised the Eastern Mediterranean region. The O/D matrices were built through a challenging data collection process which directly involved the selected ports and the shipping companies operating therein. Starting from the total annual O/D matrices, several seasonal O/D matrices were detailed to take account of variations in demand during the year. Afterwards, each seasonal matrix was in turn detailed in terms of the average, peak and soft weekly matrix. The average weekly matrices, differentiated by traffic season, were used to run the model for service frequency selection. The latter is supposed to run seasonally (typically two or three times a year) when shipowners or shipping operators must define how many ships to dedicate to a given market. Using an average weekly matrix allows to size the system to guarantee a load factor that ensures the convenience of the service for those who operate it. Conversely, using the peak weekly matrix would involve the strong risk for significant economic losses due to the likely occurrence during the planned period of load factor below the threshold value that ensures the convenience of the service. This application considers as input data the average weekly matrix for the peak season in 2012. Tables 3 and 4 show, respectively, the average weekly O/D traffic volumes from EU to MENA and from MENA to EU ports for the selected test scenario. O/D traffic volumes are provided in terms of linear meters (lm) of rolling cargo. Since freight rates in Ro-Ro shipping are typically charged per linear meters, both port and maritime operators tend to record the data in this form.

Table 3: Average weekly O/D matrices from EU to MENA (linear meters) - Peak season - Year of reference: 2012.

O/D	Mersin	Latakia	Beirut	Damietta	Alexandria	Port Said	Limassol	Sum
Valencia	1,125	246	213	162	94	67	63	1,970
Barcelona	1,351	154	366	146	72	42	57	2,188
Marseille	6,705	90	644	375	244	161	10	8,229
Sète	785	0	242	0	0	0	0	1,027
Genoa	217	0	1,102	415	252	168	9	2,163
Spezia	550	0	93	127	66	43	0	879
Naples	280	0	181	64	31	29	0	585
Sum	11,013	490	2,841	1,289	759	510	139	17,041

Table 4: Average weekly O/D matrices from MENA to EU (linear meters) – Peak season - Year of reference: 2012.

O/D	Valencia	Barcelona	Marseille	Genoa	Spezia	Naples	Sum
Mersin	3,087	516	1,742	390	450	400	6,585
Limassol	37	18	0	0	0	0	55
Latakia	31	42	0	0	0	0	73
Damietta	137	97	36	238	82	309	899
Alexandria	82	45	23	145	53	185	533
Port Said	55	31	15	96	39	126	362
Beirut	15	57	92	166	0	43	373
Sum	3,444	806	1,908	1,035	624	1,063	8,880

Supply data

Supply data include information on ports, ships, and network.

Ports: the port nodes in the network were characterised in terms of their physical and operating capacity in order to define the times required for ships' operations. This information was collected considering single terminals rather than whole ports as important differences may exist among terminals in terms of infrastructure and operations (Cullinane et al. 2005, Acciaro and Serra 2014). As a feeder service can be in connection with a mother service if and only if there is enough time to perform loading/unloading operations before the mother service departs, the following requirements were assumed:

- feeder ships require at least 12 hours to perform a complete loading/unloading cycle;
- the maximum port stay of a mother ship cannot exceed 16 hours in order to ensure compliance with the weekly program. In the designed layout, each mother ship is assumed to perform a complete roundtrip

service per week. In order to comply with the weekly schedule, the maximum time in port of a mother ship cannot exceed 16 hours, inclusive of times for cargo loading/unloading and berthing operations.

Ships: three classes of feeder and mother ships characterised by different load capacities were considered to calibrate the new network. The three classes were derived from a sample of more than 200 Ro-Ro and Con-Ro ships operating in the Mediterranean area:

- small feeder ships: 1,350 lm;
- medium feeder ships: 2,520 lm;
- large feeder ships: 3,320 lm;
- small mother ships: 4,600 lm;
- medium mother ships: 6,350 lm;
- large mother ships: 7,700 lm.

The capacity of Ro-Ro ships is measured using the lane meter method. The latter is a method of measuring the space capacity of Ro-Ro ships whereby each unit of space, also known as linear meter (lm), is represented by an area of deck 1.0 meter in length x 2.0 meters in width.

Network: network features concern route distances and sailing times between the various pairs of ports. The average service speed is assumed equal to 18 knots for feeder vessels and 21 for mother ships.

6.2. Application results

This paragraph describes the main numerical results obtained from the two proposed models for the test scenario.

Step 1: Results of the Mixed Integer Linear Programming Model (MILPM) for Service Frequency Selection

Given the weekly demand and the supply parameters described in the previous paragraph, the MILP model for service frequency selection has been applied to identify the optimal weekly frequency for each service included in the proposed dual hub-based network. The model outputs are the optimal services frequencies and capacities.

The model has been applied considering separately the three legs of the network:

- leg 1: includes the feeder services linking the ports of the western coastal shore to the western hub;
- leg 2: includes the mother services connecting the two hubs;
- leg 3: includes the feeder services linking the ports of the eastern coastal shore to the eastern hub.

The following assumptions have been considered:

- for each link, the highest of the two demand values characterising the two directions of the service (west to east and east to west) is taken as the reference demand for the service itself;
- the minimum load factor is taken as 0.5. A lower load factor is taken only for those services characterised by very low weekly demand (Limassol - Beirut, Port Said – Beirut, Latakia – Beirut);
- the β parameter is initially assumed equal to 1 to assign the same importance to both objectives (service quality and companies' revenues);
- every ship has to perform a complete roundtrip service (outward and return journey) and empty load units should always return to their origin port. In light of these considerations, an apparently high-frequency value can be adopted also for those routes in which existing demand does not seem to justify such a frequency.

Tables 5, 6 and 7 show the main results of the MILPM for service frequency selection for the three legs of the network. Each service is detailed in terms of optimal capacity of the selected ship, optimal weekly frequency, total weekly capacity, weekly demand and used capacity considering the two service directions (west to east and east to west).

In a second phase, the β parameter is made to vary in order to evaluate the extent to which the resulting optimal frequency and percentage of used capacity change in relation to the objective that is prioritized. When the β parameter takes values smaller than 1, more importance is given to service quality (user's perspective) while when it takes values larger than 1, priority is given to the used capacity percentage (company's perspective). Figure 4 displays, for the Eastern feeder services, the average values of the two considered objectives when the following β values are assumed: 1.8, 1.5, 1.2, 1.0, 0.8, 0.5, 0.2. The picture shows that there are no dominating solutions, i.e., there is not a value of β for which the solution is better than those obtained with other β values, for both the considered objectives. The insight found from this analysis is that there is not a value of β which is globally better. In using the proposed model to plan the maritime transport service, decision-makers must choose whether they want to give greater importance to the

quality of the service for users (imposing a β value lower than 1) or to the maximization of revenues for the companies that provide the service (imposing a β value greater than 1).

Table 5. Leg 1 - Western feeder services: frequencies and capacities.

	Feeder vessel category (lm)					West to East		East to West	
	1,350	2,520	3,320	Weekly frequency (travels/week)	Weekly Capacity (lm)	Weekly demand (lm)	Used capacity (%)	Weekly demand (lm)	Used capacity (%)
Barcelona – P. Torres - Barcelona	0	1	0	1	2,520	2,188	0.87	806	0.32
Genoa – P. Torres - Genoa	2	0	0	2	2,700	2,163	0.80	1,035	0.38
Spezia – P. Torres – Spezia	1	0	0	1	1,350	879	0.65	624	0.46
Marseille – P. Torres - Marseille	5	1	0	6	9,270	8,229	0.89	1,908	0.21
Naples – P. Torres - Naples	1	0	0	1	1,350	585	0.43	1,063	0.79
Sète – P. Torres - Sète	1	0	0	1	1,350	1,027	0.76	0	0.00
Valencia – P. Torres - Valencia	1	0	1	2	4,670	1,970	0.42	3,444	0.74

Table 6. Leg 2 – Mother services: frequencies and capacities.

	Mother vessel category (lm)					West to East		East to West	
	4,600	6,350	7,700	Weekly frequency (travels/week)	Weekly Capacity (lm)	Weekly demand (lm)	Used capacity (%)	Weekly demand (lm)	Used capacity (%)
P. Torres – Beirut – P. Torres	5	0	0	5	23,000	17,041	0.74	8,880	0.39

Table 7. Leg 3 - Western feeder services: frequencies and capacities.

	Feeder vessel category (lm)					West to East		East to West	
	1,350	2,520	3,320	Weekly frequency (travels/week)	Weekly Capacity (lm)	Weekly demand (lm)	Used capacity (%)	Weekly demand (lm)	Used capacity (%)
Mersin – Beirut - Mersin	1	4	1	6	14,750	6,585	0.45	11,013	0.75
Latakia – Beirut - Latakia	1	0	0	1	1,350	73	0.05	490	0.36
Damietta – Beirut - Damietta	0	1	0	1	2,520	899	0.36	1,289	0.51
Alexandria – Beirut - Alexandria	1	0	0	1	1,350	533	0.39	759	0.56
Port Said – Beirut – Port Said	1	0	0	1	1,350	362	0.27	510	0.38
Limassol – Beirut - Limassol	1	0	0	1	1,350	55	0.04	139	0.10

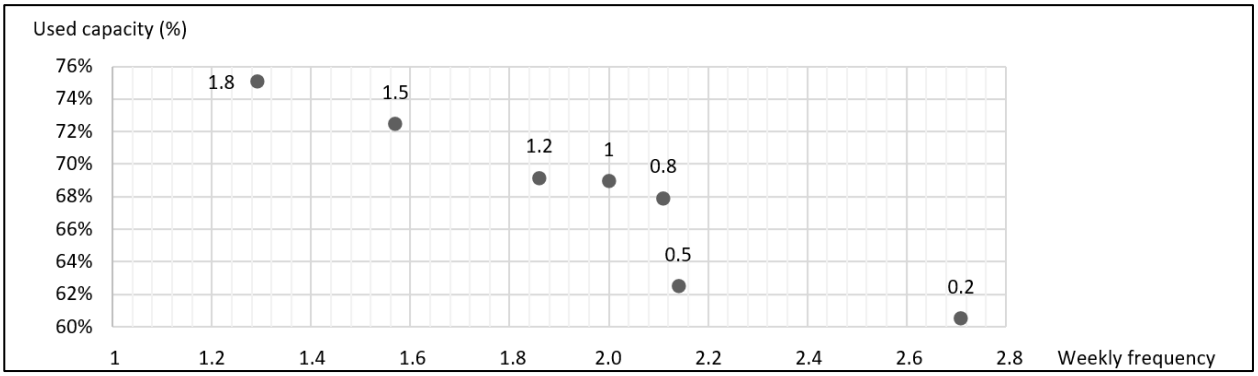

Figure 4. Variation of frequency and % of used capacity as a function of the β parameter.

6.3. Step 2: Results of the Mixed Integer Linear Programming Model (MILPM) for the Service Timetabling

The second model takes as input the optimal weekly frequencies and ships categories defined by the MILPM for service frequency selection and provides the optimal weekly schedule as output. More precisely, the model defines departure and arrival dates and times for all the services identified by the previous step in order to maximise the 'weekly service coverage' of each port while minimising waiting time at the hubs. Table 8 shows the weekly timetable for the services defined by the first model when assuming the β parameter equal to 1.

In this application, ports in the same country are considered nearby ports (with the only exception of the port of Naples, which is some distance from the other two Italian ports in the network) while the time requirements introduced in Section 6.1 are considered to ensure that a feeder service is scheduled in connection with a mother service if and only if there is enough time for loading/unloading operations before the mother service departs.

Table 8. Optimised weekly timetable.

From	To	Vessel Type	Outward				Return			
			Departure		Arrival		Departure		Arrival	
Valencia	Porto Torres	Small feeder	FRI	00:00	FRI	23:30	SAT	12:00	SUN	11:30
Valencia	Porto Torres	Big feeder	MON	00:00	MON	23:30	TUE	12:00	WED	13:30
Barcelona	Porto Torres	Medium feeder	THU	00:00	THU	16:30	FRI	07:00	SAT	23:30
Marseille	Porto Torres	Small feeder	MON	00:00	MON	11:45	TUE	00:00	TUE	11:45
Marseille	Porto Torres	Small feeder	TUE	00:00	TUE	11:45	WED	00:00	WED	11:45
Marseille	Porto Torres	Small feeder	WED	00:00	WED	11:45	THU	00:00	THU	11:45
Marseille	Porto Torres	Small feeder	THU	00:00	THU	11:45	FRI	00:00	FRI	11:45
Marseille	Porto Torres	Small feeder	SAT	00:00	SAT	11:45	SUN	00:00	SUN	11:45
Marseille	Porto Torres	Medium feeder	SUN	00:00	SUN	11:45	MON	00:00	MON	11:45
Sète	Porto Torres	Small feeder	FRI	20:00	SAT	11:15	SUN	00:00	SUN	15:15

Genoa	Porto Torres	Small feeder	TUE	23:00	WED	11:00	WED	23:00	THU	11:00
Genoa	Porto Torres	Small feeder	THU	00:00	THU	12:00	FRI	00:00	FRI	12:00
La Spezia	Porto Torres	Small feeder	SAT	12:00	SUN	00:00	SUN	12:00	MON	00:00
Naples	Porto Torres	Small feeder	WED	00:00	WED	15:45	THU	06:00	THU	21:45
Porto Torres	Beirut	Small mother	TUE	23:00	FRI	19:45	SAT	11:00	TUE	05:45
Porto Torres	Beirut	Small mother	THU	00:00	SAT	20:45	SUN	12:00	WED	06:45
Porto Torres	Beirut	Small mother	FRI	00:00	SUN	20:45	MON	12:00	THU	06:45
Porto Torres	Beirut	Small mother	SAT	23:00	TUE	19:45	WED	11:00	SAT	05:45
Porto Torres	Beirut	Small mother	MON	23:00	THU	19:45	FRI	11:00	MON	05:45
Beirut	Mersin	Small feeder	SAT	06:00	SAT	16:00	SUN	05:00	SUN	15:00
Beirut	Mersin	Medium feeder	FRI	12:00	FRI	22:00	SAT	10:00	SAT	20:00
Beirut	Mersin	Medium feeder	THU	00:00	THU	10:00	THU	22:00	FRI	08:00
Beirut	Mersin	Medium feeder	SUN	12:00	SUN	22:00	MON	10:00	MON	20:00
Beirut	Mersin	Medium feeder	MON	00:00	MON	10:00	MON	22:00	TUE	08:00
Beirut	Mersin	Big feeder	TUE	00:00	TUE	10:00	WED	00:00	WED	10:00
Beirut	Latakia	Small feeder	TUE	00:00	TUE	05:40	TUE	18:00	WED	23:40
Beirut	Damietta	Medium feeder	MON	17:00	TUE	06:20	TUE	18:30	WED	07:50
Beirut	Alexandria	Small feeder	WED	12:00	THU	7:00	THU	19:00	FRI	14:00
Beirut	Port Said	Small feeder	FRI	20:00	SAT	08:45	THU	21:00	FRI	09:45
Beirut	Limassol	Small feeder	SAT	22:00	SUN	05:15	SUN	17:00	MON	00:15

7. Key success factors of the new network and barriers to its implementation

The aim of this section is to illustrate the main key success factors of the new connection structure in light of the numerical results obtained with the two-step optimisation approach. The following indicators are used to assess and compare the general performance of the two connection options (existing and optimised):

- Weekly Frequency: average weekly frequency of the services comprised in the network (journey/week). For the existing scenario, it is calculated considering the frequency indicated by shipping lines for the various routes. In the case of interline shipment, it is taken as the lowest. For the project scenario, the service frequency for a complete O/D route “port of origin – hub 1 – hub 2 – port of destination” is taken as the least of the three legs of the route.
- Number of intermediate stops: calculated as the average number of intermediate stops from origin to destination of the services comprised in the network (n. of stops per journey).
- Sailing Distance: average sailing distance of the routes in the network (nm).

For the existing scenario, the distances between each O/D pair are those for the shortest route operated by an existing shipping line (or interlines, should no connection exist operated by a single company). For the project scenario, the distances between each O/D pair are calculated as the sum of the distances of the three legs connecting the port of origin with the destination port.

- Sailing time: average sailing time of the services in the network (h/travel).

  For the existing scenario, when not available from the service information sheet, sailing times are calculated on the basis of the distance travelled assuming an average sailing speed of 18 knots. For the project scenario, they are calculated considering a sailing speed of 21 knots along the inter-hub leg and 18 knots between each hub and the ports of origin or destination.

- Port time (h/travel): includes manoeuvring and hotelling times assigned to each port of call along the route.
- Total journey time (h/travel): calculated as the sum of sailing, port, and waiting times. For each service, the latter is calculated as a function of frequency, as the time between successive sailings divided by two.
- Utilisation of the route (lm/h): indicates the average performance of the network in terms of linear meters of goods transported per hour of journey (including waiting times).

Table 9 shows the indicators values for both the existing and the optimised connection structure. It also illustrates for each indicator the related percentage variation.

Table 9. Performance Indicators.

Description	Unit of measure	Existing scenario		Optimised scenario		Variation (%)
		Mean	StDev	Mean	StDev	
Weekly Frequency	times/week	1.3	1.2	1.1	0.6	-15.4
Number of Stops	Stops/travel	3.6	0.7	1.8	0.4	-50.0
Sailing Distance	nm/travel	2016.4	561.2	1883.7	126.7	-6.6
Sailing Time	h/travel	106.1	29.5	93.4	7.0	-12.0
Port Time	h/travel	65.3	8.9	55.8	5.1	-14.5
Total Journey Time	h/travel	338.9	139.9	229.9	16.4	-32.2
Utilisation of the Route	lm/h	1.1	2.2	1.3	2.4	+18.2

Looking at the data, the optimised network option seems to perform better than the existing one. The optimised option achieves a major reduction of journey times (-32.2%) and distances travelled (-6.6%), as well as a more productive use of the route (+18.2%). The only exception is the weekly frequency indicator, for which the existing scheme seems

to show a slightly more favourable value. However, when looking at the standard deviation values of the existing network, it emerges that they deviate considerably from the mean, indicating significant heterogeneity of the sample. Conversely, the lower standard deviation values characterising the optimised scenario are indicative of greater homogeneity of the sample and thus of greater homogeneity of the service quality offered along its O/D routes.

These general results seem to confirm the general benefits to be gained from introducing the newly proposed hub-and-spoke scheme in the Mediterranean Ro-Ro market in terms of shorter distances travelled and shipping times. These factors, together with the opportunity the new system offers for achieving higher vessel load factors, may positively impact in improving the efficiency of the Mediterranean shipping supply system in terms of reducing journey times, of regularity and frequency of connection services as well as rendering it more sustainable, and more effective in relation to its ability to improve commercial relations and trade between the countries on the two shores. Furthermore, shifting freight flows to such an integrated and optimised transport scheme could reduce the environmental impact of Mediterranean transport chains and help to mitigate related emissions (Serra and Fancello, 2020; Serra et al., 2020).

Although from an overall perspective the proposed transport scheme seems to be a quite attractive transport option, it should be noted that cross-border initiatives of this kind necessarily require strong political support to be implemented. The missing link that probably requires more attention is to convince shipping companies currently operating in the area through their business networks to seriously consider the proposed alternative “Mediterranean system”. This may clash with the traditional reluctance of shipping companies to undertake new collaborative initiatives (Fancello et al., 2014) and with the marked centralised management style of the sector, symptomatic of the control culture typically implemented by maritime companies (Casaca and Marlow, 2007). In this regard, the benefits and economic advantages of the proposed system, especially in terms of opportunity to maintain and increase their existing market share, need to be clearly perceived and recognised by the operators themselves. It should also be noted that before the new network can become operational, various interventions must be implemented to guarantee the quality of the transport services offered. The ports involved should specialize more in SSS activities, which would also improve operators' perception of the reliability of the system (Medda and Trujillo, 2010). The improvements should include not only infrastructural interventions, but also administrative and legislative measures aimed at

removing the administrative barriers (documents, customs, etc.) currently related to the cross-border nature of maritime transport.

8. Conclusion

This research lies in the field of Short Sea Shipping (SSS), considered not only as a privileged mode to reduce road congestion and its related costs but also as a key factor for economic and social cohesion between countries. Focusing on the Mediterranean basin, and in order to investigate the possibility of improving the current maritime transport supply in the area by reorganising the existing transport service, this study has proposed an innovative hub-and-spoke Ro-Ro transport option connecting the north-western and south-eastern Mediterranean shores.

A key requirement for addressing this problem was to define an effective organisation of the transport service in terms of optimal service frequencies, capacities, and time-schedule so as to ensure a new feasible, reliable, and competitive transport option. The problem was modelled using two different but related mathematical models:

- a mixed integer programming model for service frequency selection to determine the optimal frequencies and capacities for mother and feeder services;
- a mixed integer programming model for service timetabling to provide a feasible schedule that maximises the weekly service coverage of each port while minimising waiting time at the hubs.

Numerical tests performed on real demand and supply data covering eight Mediterranean countries demonstrated the validity of the proposed approach for determining an optimal feasible configuration for organising the transport service within the designed transport network.

Although the proposed two-step approach was specifically designed for this case study, both the approach and the models are general and can be initialised with all possible demand and supply settings, thus making the approach easily replicable on any hub-and-spoke network and any other shipping context. Similarly, the two hub ports considered in the application were a pair used for testing the whole model but in operating realities they can be replaced by other ports.

What has emerged from this study is that rationalising in a systemic way the existing Mediterranean Ro-Ro services using the hub and spoke model would not only result in shorter total distances travelled and journey times but would also increase ships' load factor, thus making the transport service more sustainable and more efficient. Policymakers

should be aware that there is huge potential for improving SSS services in the Med area and network design measures should play a key role in policies and initiatives aimed at increasing the role of SSS as a reliable Mediterranean transport alternative within cross-border transport chains. In this regard, the outcomes of this study can provide new insights into the challenge of developing the Mediterranean freight shipping and logistics system to ensure a more efficient and sustainable trade between European and MENA countries.

References

1. Acciaro, M., & Serra, P. (2014). Strategic determinants of terminal operating system choice: an empirical approach using multinomial analysis. *Transportation Research Procedia*, 3, 592-601.
2. Ameln, M., & Fuglum, J.S. (2015). 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).
3. Andersson, H., Duesund, J. M., & Fagerholt, K. (2011). Ship routing and scheduling with cargo coupling and synchronization constraints. *Computers & Industrial Engineering*, 61(4), 1107-1116.
4. Aringhieri, R., Landa, P., & Mancini, S. (2017). A Hierarchical Multi-objective Optimisation Model for Bed Levelling and Patient Priority Maximisation. In: Sforza, A., Sterle, C. (Eds.), *Optimization and Decision Science: Methodologies and Applications*. ODS 2017. Springer Proceedings in Mathematics & Statistics, vol. 217. Springer, Cham.
5. Casaca, A.C.P., & Marlow, P.B. (2007). The Impact of the Trans-European transport networks on the development of short sea shipping. *Maritime Economics & Logistics*, 9(4), 302-323.
6. CIREM (2014). OPTIMED project - Rationalising Mediterranean sea ways: from north-western to south-eastern ports. Report on new hub-based network system, 2014. Project report. Available at http://docplayer.net/44882356-Optimed-project-rationalising-mediterranean-sea-ways-from-north-western-to-south-eastern-ports-report-on-new-hub-based-network-system.html
7. Cullinane, K., Song, D.W., & Wang, T. (2005). The application of mathematical programming approaches to estimating container port production efficiency. *Journal of Productivity Analysis*, 24(1), 73-92.
8. Cho, S.C., & Perakis, A.N. (1996). Optimal liner fleet routing strategies. *Maritime Policy & Management*, 23(3), 249–259.
9. Christiansen, M., Fagerholt, K., & Ronen, D. (2004). Ship routing and scheduling: status and perspectives. *Transportation Science*, 38(1), 1–18.
10. Christiansen, M., Fagerholt, K., Nygreen, B., & Ronen, D. (2007). Maritime transportation. In: Barnhart, C., Laporte, G. (Eds.), *Handbook in OR & MS*, vol. 14. Elsevier, pp. 189–284.
11. Christiansen, M., Fagerholt, K., Nygreen, B., & Ronen, D. (2013). Ship routing and scheduling in the new millennium, *European Journal of Operational Research*, 228(3), 467-483.
12. Daskin, M.S., & Stern, E.H. (1981). A Hierarchical Objective Set Covering Model for Emergency Medical Service Vehicle Deployment. *Transportation Science*, 15(2), 137-152.
13. Ducruet, C., & Notteboom, T. (2012). The worldwide maritime network of container shipping: spatial structure and regional dynamics. *Global Networks*, 12(3), 395–423.
14. Eurostat (2017). Maritime transport statistics - Short sea shipping of goods. Accessed at: https://ec.europa.eu/eurostat/web/transport
15. Farahani, R.Z., Hekmatfar, M., Arabani, A.B., & Nikbakhsh, E. (2013). Hub location problems: A review of models, classification, solution techniques, and applications. *Computers & Industrial Engineering*, 64(4), 1096-1109.
16. Fancello, G., Pani, C., Serra, P., & Fadda, P. (2014). Port cooperation policies in the Mediterranean Basin: An experimental approach using cluster analysis. *Transportation Research Procedia*, 3, 700-709.
17. Fadda, P., Fancello, G., Pani, C., & Serra, P. (2017). The OPTIMED project: A new Mediterranean hub-based Ro-Ro network. *Transport Infrastructure and Systems: Proceedings of the AIIT International Congress on Transport Infrastructure and Systems*. ISBN 978 1138030091.

18. Fancello, G., Serra, P., & Mancini, S. (2019). A Network Design Optimization Problem for Ro-Ro Freight Transport in the Tyrrhenian Area. *Transport Problems*, 14(4), 63-75.
19. Fagerholt, K. (1999). Optimal fleet design in a ship routing problem. *International Transactions in Operational Research*, 6, 453–464.
20. Gelareh, S., Nickel, S., & Pisinger, D. (2010). Liner shipping hub network design in a competitive environment. *Transportation Research Part E: Logistics and Transportation Review*, 46(6), 991-1004.
21. Gelareh, S., & Pisinger, D. (2011). Fleet deployment, network design and hub location of liner shipping companies. *Transportation Research Part E: Logistics and Transportation Review*, 47(6), 947-964.
22. Huang, Y.F., Hu, J.K., & Yang, B. (2015). Liner services network design and fleet deployment with empty container repositioning. *Computers & Industrial Engineering*, 89, 116-124.
23. Imai, A., Shintani, K., & Papaditriou, S. (2009). Multi-port vs. Hub-and-Spoke port calls by containerships. *Transportation Research Part E: Logistics and Transportation Review*, 45(5), 740-757.
24. Mancini, S., & Stecca, G. (2018). A Large Neighborhood Search based Matheuristic for the Tourist Cruises Itinerary Planning. *Computers and Industrial Engineering*, 122, 140-148.
25. Medda, F., & Trujillo, L. (2010). Short-sea shipping: an analysis of its determinants. *Maritime Policy & Management*, 37(3), 285-303.
26. Meng, Q., & Wang, S. (2011). Liner shipping service network design with empty container repositioning. *Transportation Research Part E: Logistics and Transportation Review*, 47(5), 695-708.
27. Mingjun, Ji., Shen, L., Shi, B., Xue, Y., & Wang, F. (2015). Routing optimization for multi-type containerships in a hub-and-spoke network. *Journal of Traffic and Transportation Engineering*, 2(5), 362-372.
28. Mourão, M.C., Pato, M.V., & Paixão, A.C. (2001). Ship assignment with hub and spoke constraints. *Maritime Policy & Management*, 29(2), 135–150.
29. Ningwen, T., Dimas, A., Xiaowen, F., & Zhi-Chun, L. (2018). Shipping network design in a growth market: The case of Indonesia. *Transportation Research Part E: Logistics and Transportation Review*, 117, 108-125.
30. Paixão, A.C., & Marlow, P.B. (2002). Strengths and weaknesses of short sea shipping. *Marine Policy*, 26(3), 167-178.
31. Plane, D.R., & Hendrik, T.E. (1977). Mathematical Programming and the Location of Fire Companies for the Denver Fire Department. *Operations Research*, 25, 563-578.
32. Powell, B.J., & Perakis, A.N. (1997). Fleet deployment optimisation for liner shipping: an integer programming model. *Maritime Policy & Management*; 24(2), 183–192.
33. Ronen, D. (1993). Ship scheduling: the last decade. *European Journal of Operational Research*, 71, 325–333.
34. Serra, P., & Fancello, G. (2020). Towards the IMO's GHG Goals: A Critical Overview of the Perspectives and Challenges of the Main Options for Decarbonizing International Shipping. *Sustainability*, 12(8), 3220.
35. Serra, P., Fadda, P., & Fancello, G. (2020). Investigating the Potential Mitigating Role of Network Design Measures for Reducing the Environmental Impact of Maritime Chains: The Mediterranean Case. *Case Studies on Transport Policy*, 8(2), 263-280.
36. SRM (2018). Italian Maritime Economy. China, energy corridors, ports and new routes: geomaps of a changing Mediterranean. Annual report 2018. Available at: http://www.srm-maritimeconomy.com/cp/annual-report/
37. Wang, S., Alharbi, A., & Davy, P. (2014). Liner ship route schedule design with port time windows. *Transportation Research Part C: Emerging Technologies*, 41, 1-17.
38. Wang, S., & Meng, Q. (2012). Liner ship fleet deployment with container transshipment operations. *Transportation Research Part E: Logistics and Transportation Review*, 48, 470-484.
39. Zheng, J., & Yang, D. (2016). Hub-and-spoke network design for container shipping along the Yangtze River. *Journal of Transport Geography*, 55, 51–57.
40. Zheng, J., Meng, Q., & Sun, Z. (2014). Impact analysis of maritime cabotage legislations on liner hub-and-spoke shipping network design. *European Journal of Operational Research*, 234, 874–884.