IJSTL is an international peer-reviewed journal addressing all methodological aspects in the field of shipping and transport logistics, particularly those that require empirical or mathematical analysis with managerial implications. IJSTL is dedicated to publishing original, high-quality and methodologically rigorous research papers that address significant management issues pertinent to shipping/transport logistics. IJSTL also publishes informative and critical book reviews of newly published books with scholarly and practical contributions that advance the state-of-the-art of the theory and practice of shipping/transport logistics.

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- Container positioning in liner shipping
- International trade and shipping
- Managing intermodal transport
- Market analysis in sectors of shipping and transport logistics
- Modelling and analysis of problems pertinent to shipping and transport logistics
- Risk analysis in transport logistics and physical distribution infrastructure
- Service quality in shipping and transport logistics
- Strategic alliances and relationship management in shipping and transport distribution
- Strategic management for managing shipping and transport logistics
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- Warehouse and terminal operations and management

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- Excellence in Research for Australia (ERA): Journal list 2012
International Journal of Shipping and Transport Logistics

Country: United Kingdom

Subject Area: Decision Sciences | Business, Management and Accounting | Social Sciences

Subject Category:
- Business and International Management
- Management of Technology and Innovation
- Management Science and Operations Research
- Transportation

Publisher: Inderscience Enterprises Ltd. Publication type: Journals. ISSN: 17566517, 17566525

Coverage: 2010-2013

H Index: 7

The SJR indicator measures the scientific influence of the average article in a journal, it expresses how central to the global scientific discussion an average article of the journal is. Cites per Doc. (2y) measures the scientific impact of an average article published in the journal, it is computed using the same formula that journal impact factor ™ (Thomson Reuters).

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04/08/2014
### Journal Rankings

**Subject Category:** Transportation  
**Year:** 2013

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## Journal Rankings

**Ranking Parameters**

- **Subject Area:** All
- **Subject Category:** Business and International Management
- **Country:** All
- **Year:** 2013
- **Order By:** SJR

**Display journals with at least:** Citable Docs. (3 years)

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**Subject Category: Business and International Management**

**Year: 2013**

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### Journal Summary List

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30 September 2014

Dear Prof. Alba Martínez López,

Ref: IJSTL-48542

This letter serves as the official acceptance notice that your paper entitled “Definition of Optimal Fleets for Sea Motorways: the Case of France and Spain on the Atlantic Coast” has been critically reviewed by referees with favourable results. Final decision for the revised version of your paper is made. We are pleased to formally accept the paper for publication in the International Journal of Shipping and Transport Logistics (IJSTL). Your manuscript is scheduled to be published in 2015.

Should you have further inquiries regarding the publication of this paper, please feel free to contact Ms. Barbara Curran, the Journal Manager of Inderscience Publishers at barbara@ielan.com

Yours Sincerely,

Dr Venus Lun

Director of Shipping Research Centre
Department of Logistics and Maritime Studies
The Hong Kong Polytechnic University

Editor-in-Chief
International Journal of Shipping and Transport Logistics
Dear Prof. Dr. Alba Martínez López

The paper is scheduled in an issue in 2015. The date and issue number for publication are not yet finalised. You will receive a pdf via email with full citation and page numbers when the issue is sent to press.

The paper can be seen listed as forthcoming at:

Thank you for your patience.

kind regards
Barbara

Barbara Curran
Journal Manager
Inderscience Publishers
www.inderscience.com

From: Submissions [mailto:submissions@journalservice.net]
Sent: 14 March 2014 10:06
To: Barbara Curran
Subject: FW: publication date

Dear Barbara,
Ref: IJSTL-48542, entitled "Definition of optimal fleets for Sea Motorways: the case of France and Spain on the Atlantic coast"

Could you please help?

Best regards,

Joane
submissions@inderscience.com

From: Alba Martínez López [mailto:alba.martinezl@udc.es]
Sent: Thursday, March 13, 2014 6:33 PM
To: 'Submissions'
Subject: RE: publication date

Dear Joane

We have not received any mail from the Dr. Y.H. Venus Lun...could you help us with this issue?
Dear Editor,

FW for your kind attention.

Best regards,

Joane

submissions@inderscience.com

Do you have any estimation of the publication date for our work : IJSTL-48542?. The author’s final review was completed on 4th February and we did not hear anything from you since then

Any information about this would be very appreciated.

I take advantage of the opportunity to send you cordial greetings

Sincerely,

Prof. Dr. Alba Martínez López

(PhD. Naval Engineer and Naval Architect)
The Integrated Group for Engineering Research
University of A Coruña
Bien!!!

Laura Castro Santos
laura.castro.santos@udc.es

Integrated Group for Engineering Research (GII)
http://www.gii.udc.es/
University of A Coruña (UDC)
Edificio de Talleres Tecnológicos (Campus de Esteiro)
Rúa Mendizábal, s/n
15403, Ferrol, A Coruña (Spain)
Phone: (+34) 981337400 ext 3890

El sábado, 1 de febrero de 2014 a las 03:28, Submissions escribió:

Dear author(s) Pilar Caamaño-Sobrino, Alba Martinez-Lopez, Laura Castro-Santos, Blanca Priego-Torres,

Ref: Submission "Definition of optimal fleets for Sea Motorways: the case of France and Spain on the Atlantic cost"

Congratulations, your above mentioned submitted article has been refereed and accepted for publication in the International Journal of Shipping and Transport Logistics. The acceptance of your article for publication in the journal reflects the high status of your work by your fellow professionals in the field.

You need now to login at http://www.inderscience.com/login.php and go to http://www.inderscience.com/ospeers/admin/author/articlelist.php to find your submission and complete the following tasks:

1. Save the "Editor's post-review version" on your local disk so you can edit it. If the file is in PDF format and you cannot edit it, use instead your last MS Word revised version, making sure to include there all the review recommendations made during the review process. Rename the new file to "authorFinalVersion."

2. Open the "authorFinalVersion" file and remove your reply or any response to reviewers that you might have in the front of your article.

3. Restore the author's identification, such as names, email addresses, mailing addresses and biographical statements in the first page of your local file "authorFinalVersion."
4. IMPORTANT: The paper is accepted providing that you, the author, check, edit and correct the English language in the paper. Please proofread all the text and make sure to correct any grammar and spelling mistakes.

5. Save your changes in the file "authorFinalVersion" and use the "Browse." and "Upload" buttons to upload the file on our online system.

6. Click on "Update Metadata" to correct the title, abstract and keywords according the recommendations received from the Editor. You must make sure that the title, abstract and keywords are totally free of English Spelling and Grammar errors. Do not forget to click the "Update" button to save your changes.

7. Once you have updated the metadata, check the box "Yes."

8. Upload a zipped file with the Copyright Agreement forms signed by each author. We need a signed author agreement form for every author and every co-author. Please insert the full names of all authors, reflecting the name order given in the article.

9. To see a sample of real articles that have been published in the International Journal of Shipping and Transport Logistics visit http://www.inderscience.com/info/ingeneral/sample.php?jcode=ijstl.

Finally click on the "Notify Editor" button to let the editor know that you have completed the six tasks.

Your continuing help and cooperation is most appreciated.

Best regards,

On-line Submissions System
Inderscience Publishers Ltd.
submissions@inderscience.com

pp. Dr. Y.H. Venus Lun
### Free sample articles:
- [Sample articles for IJSTL](http://www.inderscience.com)

### Submission Status:
1. **Screening** - Your submission has been received and it is being screened to filter out unsuitable submissions. Contact submissions@inderscience.com if you require further information.
2. **Waiting** - Your submission has passed the screening process and has been admitted for peer-review where it is waiting for the review process to start. Contact the Journal Editor if you require further information.
3. **Reviewing** - The first round of the peer-review of this article is in progress.
4. **Revising** - Either the editor or the author is revising a version of the article.
5. **Done** - The review process has been completed and the article has been either accepted or rejected.
6. **Archived** - The article has been removed from the peer-review process at the request of the editor

Any submission that did not complete the five submission steps is given the status "Incomplete"
Definition of optimal fleets for Sea Motorways: the case of France and Spain on the Atlantic coast

Alba Martínez-López, e-mail: amartinezl@udc.es
Pilar Caamaño-Sobrino, e-mail: pcsobrino@udc.es
Laura Castro-Santos, e-mail: laura.castron.santos@udc.es

Paper submitted for the: International Journal of Shipping and Transport Logistics

NOTE TO EDITOR: Dear Dongping Song, First of all, we would to thank you your comments about our paper 'Definition of the optimal fleet for the Sea Motorways: the case of Vigo-St.Nazaire' (Submission code: IJSTL-44130), we really think they have helped to improve the manuscript. Attending these suggestions we re-submit the paper with the implemented comments. Additionally we have introduced in the paper the last findings regarding this project. For this reason we have decided to change the title of the paper to 'Definition of optimal fleets for Sea Motorways: the case of France and Spain on the Atlantic coast'. We hope you find it interesting. Thank you for helping us to improve our work. Best regards Dra. Alba Martínez-Lopez

Accepted Paper - Complete these Final Steps

Editor: Dongping Song <Dongping.song@liverpool.ac.uk>

Congratulations! You have completed all requested tasks. Now, your paper has been sent to copyediting, proofreading, and typesetting, which are the final steps in this editorial process and are intended to catch and correct minor errors only, and to produce the final publishable PDF version of your paper.
The perceived impacts of AEO security certifications on supply chain efficiency – a survey study using structural equation modelling
International Journal of Shipping and Transport Logistics, Volume 7, Number 1/2015
Category: MANAGEMENT JOURNALS
Luca Urciuoli and Daniel Ekwall
PDF (258.2 KB)  HTML

Measuring the efficiency of third party reverse logistics provider in supply chain by multi objective additive network DEA model
International Journal of Shipping and Transport Logistics, Volume 7, Number 1/2015
Category: MANAGEMENT JOURNALS
Ehsan Momeni, Majid Azadi and Reza Farzipoor Saen
PDF (355.6 KB)  HTML

The economic competitiveness of short sea shipping: an empirical assessment for Spanish ports
International Journal of Shipping and Transport Logistics, Volume 7, Number 1/2015
Category: MANAGEMENT JOURNALS
Ancor Suárez-Alemán, Javier Campos and Juan Luis Jiménez
PDF (590.6 KB)  HTML

A game-theoretic approach to determining the preferential berthing charges of ocean carriers
International Journal of Shipping and Transport Logistics, Volume 7, Number 1/2015
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Definition of optimal fleets for Sea Motorways: 
the case of France and Spain on the Atlantic coast

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Abstract: This work introduces an optimisation model to define the technical 
and operative features of fleets, which maximises the success opportunities in 
terms of cost and time for multimodal chains against the road. This model 
regards the relationships among technical alternatives for fleets, vessels, port 
facilities, cargo units and their influence on the activity of ‘many to many’ 
transport networks through short sea shipping. From the resolution of the 
model, it is possible to define not only the kind and number of vessels and 
cargo units, their manoeuvre means, speed and cargo handling systems, but also 
their naval architecture and engineering. A multiobjective evolutionary 
algorithm, the NSGA-II, has been applied to resolve this model as applied to 
multimodal chains between Spain and France through the Atlantic coast. Its 
application allows to verifying the utility of the model proposed. Finally, the 
most suitable fleets for the Sea Motorways Vigo-St.Nazaire and 
Gijón-St.Nazaire have been identified.

Keywords: Sea Motorway; fleet management; non-linear optimisation model; 
evolutionary algorithms; Spain; France.

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Motorways: the case of France and Spain on the Atlantic coast’, Int. J. Shipping 
1 Introduction

With the intention of finding alternatives for the traffic congestion problem on European roads, the European Union (EU) boosted its Maritime transport with the concept of Sea Motorways. This concept appeared for the first time in the transport White Paper of 2001 as a group of ports and intermodal services that are used for short distance of maritime transport in a particular zone of the EU. In 2003, in acceptance of the convenience of the Sea Motorways for general European interest, the European Commission reviewed the extension of Trans-European Transport Network (the TEN-T) by including the Sea Motorways in this network.

In this scenario the EU determined that several projects should be finished before 2020. One of these projects was the N21 project which aimed to develop the Sea Motorway concept. The Western European Motorway, which connects Spain and Portugal with the Irish Sea and the North Sea via France, was one of the four motorways selected to be promoted in the first stage of the N21 project.

As a consequence, a collaboration agreement, ‘Declaration of intentions about Sea Motorways’ was signed between France and Spain in October 2005. According to this bilateral agreement, the Sea Motorways projects selected by a Commission (CIG, in July 2006) would receive additional resources (at least 30% of the operating cost for the first three years) but they were required to meet quite demanding conditions (BOE No. 92, 2006) regarding the frequency of the service and the total amount of cargo units transported per year.

In this framework, the first project approved (30 October 2009) was the Vigo-St.Nazaire route (with Acciona-Transmediterranea as the shipping company). Among other advantages, this route was already offering a Ro-Ro linear maritime service to transport the production of the PSA Peugeot Citroen factory located at Vigo (with a yearly production of 380,000 cars). However, despite the favourable situation, the Sea
Motorway never operated. The main reason was that, after losing its agreement with PSA-Citroen in 2010, Acciona-Transmediterranea abandoned the project by arguing that the PSA Citroen production was essential to ensure the feasibility of the Sea Motorway.

In 2010 the Sea Motorway: Gijón-St.Nazaire, operated by GLD Atlantic, was also approved by the Commission. This route has been successfully operating since September 2010 despite the fact that Gijón, in comparison to Vigo, moves less general cargo annually (587,401t versus 2,607,037t in 2009; Port Authority of Gijón, 2009) and fewer containers (175,016 units versus 1,582,047 units in 2009; Port Authority of Vigo, 2009), there exists no car factory in its hinterland and Gijon is not located as far as Vigo from the Pyrenees (see Figure 4).

According to the Port Authorities, the different attitude of shipping companies to the exploitation of both Sea Motorways could be explained by the different number of standard Ro-Ro vessels necessary to cope with the requirements of minimum cargo units and the service frequency demanded by the Bilateral Agreement (the same for both cases). Thus, despite their initial advantages, Vigo-St.Nazaire would have become an unfeasible Sea Motorway due to the additional costs from the operation of a higher number of vessels to cover its longer distance. Thereby, the strategy used by the shipping companies to meet the requirements demanded by Sea Motorways was uniquely based on the modification of the number of standard vessels of the fleet, without considering the utilisation of vessels adapted to the route demands. This practice: the adaptation of the route to the fleet instead the adaptation of the fleet to the route could have led to wrong decisions being made about the feasibility of Sea Motorways.

Indeed, the relevance role of the shipping companies in the success of Sea Motorways in particular, and of the multimodal chains in general, is amply recognised by the EU. Nevertheless, numerous authors have highlighted that the recent liberalisation of the maritime sector in the EU (October, 2008) is not sufficient to balance the advantageous situation of the road against the maritime transport. Concretely, the lack of necessary attention to the technical and operative features of maritime transport, the public financing of land transport infrastructure and the costs of externalities of the transport modes has finally led to the EU transferring responsibility for the success of multimodal transport to private initiatives (Baird, 2007; Gesé and Baird, 2013; Romana et al., 2010).

Given this reality, this paper attempts to support the decision-making of the shipping companies when they evaluate the possibility of operating a maritime route as a Sea Motorway integrated in a multimodal chain. Thereby, the main aim of this paper is to provide an optimisation model able to define the most suitable vessels, fleets and their operation for a particular Sea Motorway integrated in a multimodal chain (‘many to many’ model).

Thus, a general mathematical model will be introduced by considering the objective functions of competitiveness (Lalwani et al., 1991; Mangan et al., 2001): as the maximisation of the difference in terms of time and cost (per tonne transported and per trip) between the unimodal and the multimodal mode. Afterwards, the optimisation will be undertaken by using a multi-objective evolutionary algorithm which enables us to obtain not only the technical and operative parameters of the fleet (kind and number of vessels, cargo capacity, architectural features, speed, frequency, etc.), but also the kind of cargo units and the most suitable cargo handling systems which should be used in order to favour the multimodal chain against the road transport alternative.

Consequently, the results achieved are useful not only for shipping companies or for the Port Authorities, but also for cargo owners who need a transport service for small
volumes of cargo with high frequency (for example, SMEs). Due to the problem cited in the case of the Vigo-St.Nazaire Sea Motorway, this route will be taken as a particular case-study for the model application. Finally the model will also be applied to Gijon-St.Nazaire, this will allow the analysis of the affirmations provided by the Port Authorities and the comparison of the performance of this route against the Vigo-St.Nazaire alternative.

2 Literature review

The analyses of the competitiveness of multimodal chains through short sea shipping (SSS) versus the road haulage are numerous in the EU context (Martínez and Olivella, 2005; Paixao and Marlow, 2002; WEST-MOS Project, 2005–2008). Notwithstanding these assessments were attended from very diverse points of view, one of the reached conclusions was amply accepted by all of them: the weakest attribute of the multimodal chain is the time invested in the transport. This affirmation was also concluded by modal choice studies (Feo et al., 2010; García-Menéndez and Feo-Valero., 2009), which also determined, the relative importance of time against cost for the multimodal transport as function of the features of the cargo owner (Nellthorp et al., 2001) and the moment of the study (Bergkvist, 2001; Mangan et al., 2001). This reality motivated, on the one hand, works which took the cost of the different possibilities of the transport modes as the principal evaluation criterion (Morales-Fusco et al., 2012; Ng, 2009; Perez-Mesa et al., 2010; Sambracos and Maniati, 2012; among others), these were especially significant. On the other hand, many studies analysed those maritime routes which could operate in high speed craft (HSC) conditions (Castells i Sanabra, 2009; Engineering and Physical Sciences Research Council (EPSRC) and UK Department for Transport DfT, 2002–2003; SPIN-HSV Project, 2003–2005) with the intention of assessing if this kind of SSS service would reduce the time invested in multimodal chains. However, the HSC were finally ruled out by most of them due to their high operative costs.

Despite the wide diversity of these studies, two assumptions have been commonly accepted: firstly, the feasibility of multimodal transport is mostly based on one kind of vessel: roll-on roll-off traffic conditions for the maritime leg (Ro-Ro and Ro-Pax vessels). Secondly, the technical and operative features of the vessels, their number (the fleet) and the service conditions, which are finally provided by a shipping company, are considered as fixed initial parameters. As a consequence, these analyses often conclude distance thresholds or particular routes (such as; Bendall and Brooks, 2011; EMMA Study, 1996–1998; Martínez and Olivella, 2005; WEST-MOS Project, 2005–2008), which ensure the success of intermodal transport against road haulage by adapting the route definition to a borne SSS service.

In this context, it is argued that roll-on roll-off vessels were traditionally identified as the most suitable vessels for intermodal transport through SSS (Bernetti et al., 2002; Paixao and Marlow, 2002; WEST-MOS Project, 2005–2008; Woxenius, 2010). Nevertheless, this argument is not convincing for two reasons: the majority of the studies which support this affirmation are based on qualitative approaches and research, and studies which quantitatively compared the effectiveness of the two possible vessels for SSS (Ro-Ros and container vessels), are very scarce and focused on specific aspects of the transport (Mbiydzenyuy et al., 2010). Moreover, it is commonly accepted that the relative competitiveness of multimodal transport against the road is determined by a
combination of the operative and technical features of transport means, customer requirements and geographic characteristics (Baird, 2007; Gesé and Baird, 2013) and this combination determines the modal choice (Feo et al., 2010; Garcia-Menendez and Feo-Valero, 2009). This circumstance leads to competitiveness assessments, which take as fixed inputs the conditions of the SSS service, and the transfer of responsibility to the shipping companies (private initiative); consequently their results accept an important uncertainty level in this regard.

In parallel, studies on ship sizing and on the adaptation of the transport service to the requirements of a particular maritime route were seldom addressed to SSS (Christiansen et al., 2004). Regarding the first group, these studies explored the optimal vessel size with the intention of supporting the shipping companies by taking advantage of the effects of economies of scale (such as Culliane and Khanna, 1998, 2000; Pope and Talley, 1988), especially, on the container traffic for long distances. Notwithstanding their relevant contributions, these studies rarely consider the benefits of the shippers as an objective.

The other group, which contains research on fleet management and shipping planning by adapting the service conditions to the route demand, has reached significant results. Indeed, during the last few years, the routing, scheduling and stowage problems in container traffic (Ambrosino et al., 2004; Martins et al., 2009; Moura and Oliveira, 2009; Triunfante et al., 2010) were amply attended through the application of evolutionary algorithms (EA).

Nevertheless, despite the wide possibilities of analysis offered by these algorithms, the combined problem: simultaneous optimisation of fleets and of their operation was not treated as frequently as expected. The majority of research, which has addressed this combined problem, considers, once again, the container traffic based on hub and spoke networks (Bendall and Stent, 2001; Hsu and Hsieh, 2007) or liner routes (Cho and Perakis, 1996). These works conclude the optimal frequency, vessels size and route considering the costs related to the maritime shipping. Additionally, those that apply a multi-objective algorithm (Hsu and Hsieh, 2007), offer a significant advantage: a high flexibility, in terms of Pareto fronts, when making global decisions. Despite the fact that some studies treat this combined problem by considering seaborne as a transport leg also exist, they were focused on the resolution of very particular transport problems; the water transport between two countries (Fagerholt and Rygh, 2002) or the shipping of dry bulk minerals from extraction origin to customer sites (Mehrez et al., 1995), instead of the global problem of the relative competitiveness of multimodal chains against the road.

Thus, from a theory standpoint, this work addresses the relative competitiveness problem for multimodal chains through SSS against the road, but also considers the combined problem of the adaptation of the maritime fleet (Ro-Ro and container vessels) and its operation for the requirements of the ‘door to door’ transport. Thereby, using this approach, this work tries to fill the knowledge gaps identified in the literature review.

3 Methodology

The methodology followed in this work is divided into two phases. The first is devoted to the definition of the mathematical model used to simulate fleets and their operations; this mathematical model defines all variables and the relationships between them that are necessary to define the fleet and its activity in comparison with unimodal transport. The second phase of the methodology is dedicated to the optimisation of the fleets.
3.1 Mathematical model definition

From a mathematical point of view, the model is made up of three different elements: the variables, the objective functions and the constraints (see Figure 1). At the same time, the variables can be divided in three types according to their roles in the optimisation: the cases (discrete variables), the optimisation variables (continuous) and the data (no controllable inputs imposed by the specific scenario). Additionally, two kinds of variables will be handled in the model: the auxiliary ones (related to naval architecture and naval engineering) and the main variables (related directly with the objective functions and auxiliary variables). The calculation of the first ones is necessary, along with the definition of the second ones, for the calculation of the objective functions (see Figure 1).

It is interesting to bear in mind that, whereas the second classification of the variables is independent on the analysed scenario, the role of the ‘controllable’ or ‘no-controllable’ (data) variable will be imposed by each case-study. The variables and the relationships among them allow simulation of the different scenarios, which integrate the alternatives of routes (with their ports), fleets, and the cargo units. In the following sub-sections the variables, which characterise these components, are outlined.

3.1.1 Fleets

This part of the model is focused on the vessel design from a technical point of view but also calculates its impact on the time and cost of the multimodal chain. The model considers the two compatible kinds of vessels for SSS ($Q = \{1, \ldots, q\}$), Ro-Ro and container vessels. The general arrangement considered for the generation of Ro-Ro vessels is those of ‘Clipper Point’ (Royal Institution of Naval Architects, 2008) with three cargo decks. For the container vessels the general arrangement of the ‘Sea Arctica’ Royal Institution of Naval Architects, 1994) has been taken as reference. For the calculation of the technical features of vessels, the expressions published by different authors have been considered (Lamb, 2004; Rawson and Tupper, 2001; Watson, 2002; among others). Thus, the architecture of the vessel is defined through, among other values, the length ($L$), breadth ($B$), depth to the upper deck ($D$), draught ($T$), freeboard ($FB$), gross tonnage ($GT$), buoyancy volume ($\nabla$), deadweight ($TPM$), speed ($VB$), propulsion power ($PB$),

![Figure 1](image-url)
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(and through other features like the installation of bow thrusters \(BB = \{1, \ldots, b\}\)). However, the expected high speed necessary for the vessels to offer a competitive multimodal transport (Engineering and Physical Sciences Research Council (EPSRC) and UK Department for Transport DfT, 2002–2003; SPIN-HSV Project, 2003–2005) suggests a higher required space for the machine rooms and therefore a reduction of the available cargo space in the vessels. For this reason, the model introduces mechanisms (based on the available cargo volume and on the deadweight), which calculate the real maximum cargo capacity of the vessels \(G_3\), once the arrangement of the machine room has been defined. This is determined by the kind of main engines \(TMP = \{1, \ldots, m\}\) and their number \(NMP = \{1, \ldots, a\}\), the kind of propeller \(TP = \{1, \ldots, h\}\) and the number of shaft lines \(NN = \{1, \ldots, n\}\).

The competitiveness of the multimodal chain in terms of the cost is closely dependent on the capital cost (Grosso et al., 2008; Sauri, 2006) and therefore, on the building cost of the vessel \(CC\), which depends on its technical features, on its dimensions and the operative characteristics of the vessel, also depending, on the age of the vessel \(EE = \{1, \ldots, e\}\).

Other handled variables (data) for the definition of the fleet are the following:

- \(R_1\) percentage of the depreciation of the vessel value
- \(R_4\) percentage of the building cost with mortgage
- \(R_2\) interest rate of the mortgage
- \(A_1\) years of the mortgage
- \(A_2\) years of the amortisation
- \(C^a_3\) average cost of an officer in the crew per year (€)
- \(C^b_3\) average cost of a sailor per year (€)
- \(C^c_3\) cost IFO 380 (€/l)
- \(DT_2\) diesel density (gr/l)
- \(DT_1\) engine consumption (gr/HP.h)
- \(NTR\) number of persons in the crew
- \(NB\) number of vessels of the fleet.

Finally with the aim of validating the fleet design model, this has been applied to real ships (Ro-Ro and containers) with dimensions between 85 and 200 m of length between perpendiculars, and the results obtained were very close to the reality.

### 3.1.2 Cargo

In order to characterise adequately the multimodal chain it is necessary to observe all the compatible cargo units \(PP = \{1, \ldots, p\}\) along with their weight \(P_p\) for each kind of vessel: TEUS, FEUS, trailers and trucks with and without tractor head (see Figure 2).
The selection of a particular cargo unit not only defines the cargo capacity of the vessel in units \((G_2)\) but it also determines the possible cargo handling systems used \((G = \{1, \ldots, g\})\). The features of the cargo handling systems, like the number of operative cranes per vessel \((U_g)\) or the speed of the cranes \((V_g)\), are essential to know the loading/unloading time and therefore the competitiveness in terms of the time of multimodal chains. In this case, we have assumed semi-direct routes inside the port for the unaccompanied cargo units, for the rest of cargo units we have assumed direct-routes under ideal conditions (low transit times inside the port).

### 3.1.3 Routes and ports

Due to the fact that ‘many to many’ model is highly adaptable to most real ‘door to door’ haulages (Daganzo, 2005), this model has been considered for the generation of the routes (see Figure 3). Therefore, the ports of origin \((M = \{1, \ldots, m\})\) and destination \((K = \{1, \ldots, k\})\), the land origins \((Z = \{1, \ldots, z\})\) and destinations of the multimodal chain \((DD = \{1, \ldots, d\})\) with their probability of being selected as initial origin \((X_z)\) and final destination \((X_d)\) must be included in the model (see Figure 3). Once the routes are defined, they are characterised by using the maritime distance \((DM)\) and the road distances between extreme points and ports \((DR_{\text{in}}, DR_{\text{out}})\) and the road haulage distance \((DR_{\text{R}})\). Additionally, the price \((€/\text{Km})\) of the transportation by road \(C_{\text{A,R}}\) (Observatory of Road Freight Transport Costs, 2010), which is related to the type of cargo, and the maximum speed of the trucks \((V_3 \text{ in } \text{Km/h})\), is used to estimate the cost of the unimodal mode and the road stretch of the multimodal mode.
Finally, to correctly simulate the activity of the multimodal chain, it is necessary to characterise the port operations in terms of time and cost. Obviously, this activity is specific for each port, however, in most of the European ports the following variables can be considered for their definition:

- $R_{S,q}$ Percentage of dockage due required by the port to stimulate SSS traffic. This depends on the number of trips and the kind of vessel.
- $TIE$ Loading/unloading time (h).
- $R_{C,q}$ Percentage of cargo due required by the port to stimulate SSS traffic.
- $C_{S,p}^c$ Cargo dues in the port, which depend on the type of cargo unit.
- $C^c$ Pilotage dues.
- $C_1^c$ Towing dues.
- $C_2^c$ Mooring dues.
- $C_4^{C,4}$ Loading/unloading dues (€/unit).
- $Tl_1$ Average waiting time for a pilot.
- $Tl_2$ Average waiting time for the towing service.

Considering all these aspects and the features of vessels and cargo units the model will resolve finally the number of yearly trips for the fleet ($N$).

Notwithstanding the numerous variables handled in the model (150 without taking into account the data) only eight of them have been identified as no dependent (main variables). The main variables are the ones in charge of defining the activity requirements of the vessels; these are the necessary parameters for the conceptual design of the vessels in the early step of the project (Lamb, 2004; Rawson and Tupper, 2001):
Discrete variables:
- type of vessel \( Q = \{1, \ldots, q\} \)
- age of the vessel, in years \( EE = \{1, \ldots, e\} \)
- type of cargo unit \( PP = \{1, \ldots, p\} \)
- cargo handling system \( G = \{1, \ldots, g\} \)
- bow thruster \( BB = \{1, \ldots, b\} \)

Optimisation variables:
- Cargo capacity \( G2 \)
- Speed of the vessel \( VB \)
- Number of vessels in the fleet \( NB \)

The mathematical model has been formulated by taking into account that the main objective of this work is to find the best fleet option, which articulates the most competitive multimodal chains against the road. Thereby, the optimisation objectives aim to maximise the difference in cost and time of the road transport regarding the multimodal chains, from one origin to one destination, considering all the possible origins \( Z \) and destinations \( DD \) and the probability of load distribution among them \( X_z \) and \( X_d \). The cost and time formulations have to integrate the information provided by consignee companies and the Port Authorities, as well as the European normative and national rules. Indeed, many of these expressions are highly sensitive to the selected ports and routes. However, the variables implied in their calculation are mostly standard. For this reason although these expressions are not shown with detail, their dependences are explained in this text. On the other hand, the general application expressions, which have been evaluated and fitted by comparison with real values (provided by ship owners, maritime companies and shipyards), are detailed in the following paragraphs.

### 3.1.4 Maximisation of the difference in cost

The cost of the unimodal \( CU \) and multimodal transport \( CMU \) are measured per tonne and per trip considering the probabilities of land destinations \( X_z \) and \( X_d \). The multimodal cost integrates the cost of the road stretches: door to port \( CMU_{1,1} \) and port to door \( CMU_{1,2} \) and the maritime stretch \( CMU_2 \). This last one takes into account all the necessary costs \( CTc \) for the calculation of the minimum required freight (to achieve the even point). The costs considered are the capital costs, fixed direct costs and variable costs (Hunt and Butman, 1995; Perez-Mesa et al., 2010; Sauri and Spunch, 2009).

\[
F_2 = \max(CU - CMU) \quad (1)
\]

\[
CU = \left( \sum_{z=1}^{d} \sum_{d=1}^{d} (X_z \times X_d \times DR_{zd}) \right) \times \frac{C_{z,p}}{P_p} \quad \forall p \in PP \land \forall z \in Z \quad (2)
\]

\[
CMU = CMU_{1,1} + CMU_{1,2} + CMU_2 \quad (3)
\]

\[
CMU_{1,1} = \left( \sum_{z=1}^{d} (X_z \times DR_{zmm}) \right) \times \frac{C_{z,p}}{P_p} \quad \forall p \in PP \land \forall m \in M \land \forall z \in Z \quad (4)
\]
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\[ CMU_{1,2} = \left( \sum_{d=1}^{d} (X_d \times DR_{ikd}) \right) \times \frac{C_{k,p}}{P_p} \quad \forall p \in PP \land \forall k \in K \land \forall d \in DD \] (5)

\[ CMU_2 = \left( \sum_{c=1}^{c} CT_c \right) \times \frac{1}{G_3 \times P_p \times N'} \quad \forall p \in PP \] (6)

Attending to the classical countable criterion, the capital costs have been calculated as the addition of the amortisation cost \((CT_1)\) and the interest cost \((CT_2)\) by considering a straight-line amortisation system for the first one and an arithmetical capital amortisation for the mortgage (Watson, 2002; Stopford, 2009).

\[ CT_1 = CC \times \frac{100\% - R_e}{A_2} \times NB \] (7)

\[ CT_2 = \left[ \left( R_i \times CC \right) - (E_e - 1) \times (CC \times R_i) \right] / A_4 \times R_e \times NB \quad \forall e \in EE \] (8)

The fixed direct costs are the insurance cost \((CT_3)\), the maintenance cost \((CT_4)\) and the personal cost \((CT_5)\). The first two vary along the lifecycle of the vessel (i.e., depending on the age, \(EE\)), but while the insurance cost remains practically constant (the depreciation of the vessel worth is balanced with the increase of the damage probability) the maintenance cost, which includes overhauls and repairs, increases. The vessel insurance \((CT_3)\) is mainly integrated by the hull and machinery insurance (H&M) and the protection and indemnity insurance (P&I). Notwithstanding the fact that it is highly dependent on the ship-owner history (accident risk), routes and on the insurance company, in general terms this cost is calculated considering the actual worth and age of the vessels \((CT_3, E_e)\) and their deadweight \((TPM)\). The maintenance cost \((CT_4)\) is commonly associated to the vessel construction cost \((CC)\) and the age \((E_e)\) because it suggests its technological level and its cost increases with the time (Hunt and Butman, 1995; Stopford, 2009). Finally the personal cost \((CT_5)\) (Sauri and Spunch, 2009; Wijnolst and Wergeland, 2009) takes into account the crew number \((NTR)\), the yearly salary costs, for officers \((C^a)\) and ratings \((C^b)\) by assuming a rotation index for the crew of 0.33 (Sauri and Spunch, 2009; Wijnolst and Wergeland, 2009).

\[ CT_3 = \frac{80}{100} \times CC \times \left( 1 - \frac{(100\% - R_e)}{A_2} \times E_e \right) \times NB \times \alpha \quad \forall e \in EE \] (9)

\[ \alpha = f(TPM, E_e) \quad \forall e \in EE \] (10)

\[ CT_4 = \begin{cases} \frac{53}{100} \times C_3^a + \frac{47}{100} \times C_3^b \times NB \times NTR & \text{if } TB_q = TB_1 \\
\frac{44}{100} \times C_3^a + \frac{56}{100} \times C_3^b \times NB \times NTR & \text{if } TB_q = TB_2 
\end{cases} \] (11)

The variable costs are fuel costs \((CT_6)\) dockage dues \((CT_7)\) cargo dues in port \((CT_8)\), pilotage cost \((CT_9)\), towing cost \((CT_{10})\), mooring cost \((CT_{11})\) and loading/unloading costs \((CT_{12})\). Regarding fuel costs \((CT_6)\), these are very dependent on the time of the trip \((TVB_t)\), and on the arrangement of engine rooms (Baird, 1999; Lamb, 2004) for a
determined propulsion power ($PB$): kind and number of engines ($TMP, NMP$), number of shaft lines and kind of propellers ($NN, TP$); this finally determines the fuel consumption ($DT_1$).

\[ CT_6 = PB \times \frac{DT_1}{DT_2} \times C_3 \times TVB_1 \times N \] (12)

Port dues ($CT_{7-11}$) must be calculated considering the information provided by Port Authorities and the Port Regulation of the different countries implied in the route. Despite of the fact that every port has their own tariffs scheme, the dockage, pilotage, towing and mooring costs are often dependent on the number of trips per year ($N$) and on the gross tonnage ($GT$), whereas the cargo dues and loading costs are mainly dependent on the number of cargo units ($G_3$). In addition to this, the compulsory use of towing services ($CT_{10}$) is usually conditioned by the manoeuvring means ($MM_b$) and length ($L$) of vessels. Additionally, the loading costs ($CT_{12}$) consider the cargo handling system selected ($MG_g$).

\[ CT_7 = f\left(TIE, N, GT, R_{s,q}\right) \quad \forall q \in Q \text{ (see Figure 2)} \] (13)

\[ CT_8 = f\left(N, G_3, C_{2,p}^-, R_{b,q}\right) \quad \forall q \in Q \land \forall p \in PP \] (14)

\[ CT_9 = f\left(C^+, N, GT\right) \] (15)

\[ CT_{10} = f\left(C_1^-, N, GT, MM_b, L\right) \quad \forall b \in BB \] (16)

\[ CT_{11} = f\left(N, GT, C_2^+\right) \] (17)

\[ CT_{12} = f\left(N, G_3, C_{2,p}^4, MG_g\right) \quad \forall p \in PP \land \forall g \in G \] (18)

### 3.1.5 Maximisation of the difference in time

The duration of the unimodal transport per trip ($TVU$) has been estimated in hours per trip, considering the European Normative on the maximum speed for trucks (European Directives 92/24/EC, 92/6/EC) and minimum breaks for the resting of the drivers (Regulation 561/2006 of European Parliament). The duration of the multimodal transport ($TVM$) per trip (measured in hours) considers the maritime and land stretches. Thus, while expressions for the time invested in the road stretches ($TVC_1, TVC_2$) are the same as the unimodal transport expression but with different road distances (see Figure 3), the time invested in the maritime stretch ($TVB$) is the addition of the duration of the trip by sea ($TVB_1$), [dependent on the vessel speed ($VB$) and the maritime distance ($DM$)], the loading/unloading time ($TVB_2$), and the berthing time in port ($TVB_3$).

\[ F_2 = \max(TVU - TVM) \] (19)
The expression of \( TVB_2 \) compiles the information provided by Stowage Societies of the ports and consignee companies which operate in the selected ports, while \( TVB_3 \) results are highly dependent on the mandatory use of pilot and towing services demanded by the Port Authorities.

\[
TVB = \sum_{i=1}^{3} TVB_i
\]
Finally, the constraints of the model are shown in the Table 1. Constraints from RR1 to RR9 and RR15 are applied to the variables to ensure the technical feasibility of vessels. The constraint RR11 ensures that the vessels do not reach the condition of HSC [High-Speed Craft Code MSC 36(63) and SOLAS, chapter X], as this is not desirable according to the results achieved by previous research (as outlined in the literature review).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Constraints applied on the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR1</td>
<td>( T &lt; 10 )</td>
</tr>
<tr>
<td>RR2</td>
<td>( F_B &gt; F_{bm} )</td>
</tr>
<tr>
<td>RR3</td>
<td>( G_1 \geq G_2 )</td>
</tr>
<tr>
<td>RR4</td>
<td>( \begin{align*} &amp; B \geq TB_q = TB_1 \ &amp; TB_q = TB_2 \end{align*} ) ( \begin{align*} &amp; 7 \times 10^{-5} \times PB + 12.47 \text{ if } PB * \leq 82,607 \ &amp; 16 \text{ if } 82,607 &lt; PB &lt; 101,381 \ &amp; 13 \text{ if } 101,381 \leq PB \end{align*} )</td>
</tr>
<tr>
<td>RR5</td>
<td>( D \geq TB_q = TB_1 ) ( 7.15 \text{ if } PB \leq 33,794 ) ( 5 \times 10^{-4} \times PB - 5.52 \text{ if } 33,794 &lt; PB \leq 53,600 )</td>
</tr>
<tr>
<td>RR6</td>
<td>( TB_q = TB_1 ) ( 4.94 &lt; \frac{L}{B} &lt; 7.50 )</td>
</tr>
<tr>
<td>RR7</td>
<td>( TB_q = TB_2 ) ( 4.26 &lt; \frac{B}{D} &lt; 2.31 )</td>
</tr>
<tr>
<td>RR8</td>
<td>( TB_q = TB_3 ) ( 1.55 &lt; \frac{B}{D} &lt; 2.31 )</td>
</tr>
<tr>
<td>RR9</td>
<td>( TB_q = TB_4 ) ( 1.34 &lt; \frac{B}{D} &lt; 2.84 )</td>
</tr>
<tr>
<td>RR10</td>
<td>( N_1 \geq N \geq N_2 )</td>
</tr>
<tr>
<td>RR11</td>
<td>( VB &lt; (3.7 \times 10^{0.160} / 0.51) )</td>
</tr>
<tr>
<td>RR12</td>
<td>( G_2 \times N \geq ) Cargo1; if ( G_{ip} = G_{11} ) Cargo2; if ( G_{ip} = G_{12} ) Cargo3; if ( G_{ip} = G_{13} ) Cargo4; if ( G_{ip} = G_{14} ) Cargo5; if ( G_{ip} = G_{15} ) Cargo6; if ( G_{ip} = G_{16} )</td>
</tr>
<tr>
<td>RR13</td>
<td>( (\frac{TVU - TVM}{TVU + TVM}) \geq IT )</td>
</tr>
<tr>
<td>RR14</td>
<td>( (\frac{CMU - CMU}{CMU + CU}) \geq IC )</td>
</tr>
<tr>
<td>RR15</td>
<td>( TVB \leq NB \times 12 )</td>
</tr>
</tbody>
</table>

Note: *PB: measured in horse power (HP).
The constraints $RR10$ and $RR12$ are necessary to meet the minimum amount of cargo units per year (Cargo1 to Cargo6) and the frequency of service ($N1, N2$: yearly trips) imposed for every case-study. Constraints $RR13$ and $RR14$ ensure the competitiveness of multimodal routes articulated through the Sea Motorway that is reached by operating with a commercial fleet ($IT, IC$). This competitiveness must be taken as the minimum which should be reached by the optimised fleet.

3.2 The optimisation framework

Once the mathematical model has been developed, it is necessary to identify, through the analysis of the problem, the most suitable optimisation process to solve it. Thus, considering the nature of the model, we can conclude that it is a mixed-integer and non-linear problem with numerous non-linear constraints. EA are metaheuristics, which have shown an adequate performance in terms of efficiency and effectiveness in this type of problems. As the problem of this work is multi-objective, the NSGA-II (Deb et al., 2002) will be used. In previous works (Martínez et al., 2012), a mono-objective approach of the same problem was also tackled.

4 Application to the case-study

The mathematical model definition is very dependent on the routes and ports selected for the study. For this reason, in this section the general model definition will be applied to the case-study (especially Subsections 3.1.3 to 3.1.6).

For the particular case of the multimodal chains between the Northern Spain and France (see Figure 4), according to García-Alonso and Sánchez-Soriano (2010), the Spanish ports are located in the same province as most of the important population/activity centres of their hinterland, and those centres are the main traffic generators in the Spanish northern coastline (therefore $X_z = 1$, for every route from the north of Spain). For this reason, in this particular case the general ‘many to many’ model suggested in the methodology (see Section 3.1.3) can be simplified to a ‘one to many’ model (Martínez and Alonso, 2011) where the probability of load distribution in the French side ($X_d$: 0.62, 0.21 and 0.17 for Paris, Lille and Rennes respectively, see Figure 4) was calculated by considering a population criterion (Ng, 2009).

Figure 4 Multimodal chains articulated through Vigo-St.Nazaire and Gijón-St.Nazaire
(see online version for colours)
The application of the general expressions (‘many to many’ model) to the case study (‘one to many’ model) implied the origin of routes is unique and coincident to the initial port (m) and which generates all the load ($X_i = 1$) and therefore the door to port distance is zero ($DR_{im} = 0$). This involves that the cost of this stretch is zero ($CMU_{1,1} = 0$, see Section 3.1.4) as well as its time ($TVC_i = 0$, see Section 3.1.5).

The calculation of $TVB_2$ (highly conditioned by the cargo handling systems $MG_g$), for this particular case-study, takes into account the port cranes ($V_{2,1} = 27$ TEUs/h; one crane operating every 37 m of vessel length), port drivers ($V_{2,5} = 8$ trailers/hour per driver, one driver every 17 trucks) and mafis (Ametller, 2007) as cargo handling systems for the cargo units ($PP$). Additionally, by considering the current activity of liner services in these ports, the waiting time for the load in port (from its arrival until the beginning of loading operations) has been assumed as coincident with $TVB_3$.

Finally, the constraints $RR10$ and $RR12$ were imposed to meet the minimum amount of cargo units per year and the frequency of service imposed for the case-study, these requirements are demanded by the applicable Normative of Sea Motorway (BOE No. 92, 2006) to Spain and France. For this: $N1 = 740$; $N2 = 384$; Cargo1 = 122,400; Cargo2 = 74,634; Cargo3 = 38,250; Cargo4 = 63,750; Cargo5 = 42,500; Cargo6 = 85,000. For the case-study, $RR13$ and $RR14$ values ($IT = 0.10$; $IC = 0.14$) were obtained with a Ro-Ro vessel with a cargo capacity of 157 trailers at 30 kn (Martínez and Alonso, 2011).

5 Optimisation process

In order to find the optimal fleet which maximises the opportunities for success of the multimodal chain versus the road, a mathematical model and an optimisation framework have been defined in previous sections. Here, the results obtained after the application of the optimisation framework to the mathematical model are shown and analysed in depth.

Figure 5  Constraints as met by containers and Ro-Ros (see online version for colours)
As aforementioned, consideration of the kind of vessels in studies exploring the competitiveness of the multimodal chain is mainly based on qualitative criteria (Paixao and Marlow, 2002; Woxenius, 2010). Hence, we do not have enough previous information to forecast the competitiveness of the multimodal transport in terms of time or cost based on one kind of vessel versus another. In other words, the dominance of one type of vessel in the investigation and the size of the group of feasible solutions during the optimisation are unknown, and therefore the difficulty of finding feasible solutions for each type of vessel is not known.

Considering the percentages of meeting all constraints (see Figure 5), we can conclude that it is more difficult to find feasible solutions for fleets of containers than Ro-Ro fleets. Hence, in an effort to avoid a premature convergence on a single kind of vessel, three independent optimisation processes will be carried out with the NSGA-II: mixed fleet, a Ro-Ro only fleet and a container only fleet. Because less than 30% of the total vessels evaluated met all of the required, constraints, the solution for the kind of fleet necessary to ensure the competitiveness of multimodal transport against the road is not obvious, and the use of optimisation processes is therefore justified.

The NSGA-II algorithm has been applied with the configuration parameters shown in Table 2. For each experiment, 50 independent runs have been carried out. The hypervolume indicator (Zitzler et al., 2000) is used for the performance comparison; with a unique value this measurement allows comparison of different runs. Given two Pareto fronts, $F_1$ and $F_2$, $F_1$ outperforms $F_2$, if the hypervolume of $F_1$ is greater than the hypervolume of $F_2$. The stop criterion of the EA is based on the number of function evaluations (FEs) and depends on the dimension of the problem. The maximum number of FEs is set to $10,000 \cdot n$, where $n$ is the dimension of the problem, in this case 8.

Table 2 Configuration parameters for the NSGA-II algorithm

<table>
<thead>
<tr>
<th>Operator</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tournament selection</td>
<td>Pool size</td>
<td>2</td>
</tr>
<tr>
<td>SBX-crossover</td>
<td>Probability</td>
<td>5%</td>
</tr>
<tr>
<td>Polynomial mutation</td>
<td>Probability</td>
<td>60%</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 shows the Pareto fronts corresponding to the two independent tests using only containers and only Ro-Ros for the sea motorway: Vigo-St.Nazaire, and the performance of the current fleet which is operating in this route. Pareto fronts are the results of the runs that maximise the hypervolume indicator in each experiment. Each Pareto front contains 100 individuals, i.e., the whole population belongs to the first Pareto front.

The container solutions strongly dominate in terms of the cost to Ro-Ro solutions but not so much in terms of the time. However, despite the fact that container vessels are the most competitive in both runs (with a container only fleet and with a mixed fleet), it is worthwhile analysing the possibilities of Ro-Ro fleets.
5.1 Results assessment

As the hierarchy of attributes considered by cargo owners for the selection of transport in the Western Corridor is mainly based on cost (Feo et al., 2010; Garcia-Menendez and Feo-Valero, 2009) and because a preference for time against cost goes up to a certain value for the transport of small volume of cargo, which often means high added value, (De Jong, 1999; Garcia-Menendez and Feo-Valero, 2009; Nellthorp et al., 2001), the vessels located on the Pareto front with maximum $F_1$ value (competitiveness in terms of the cost) have been selected for the analysis. Thus, in Table 3 the features of vessels for Vigo-St.Nazaire are shown. Additionally, the optimisation process has been also carried out for the maritime route of Gijon-St.Nazaire for Ro-Ro fleets in order to assess the affirmations undertaken by Port Authorities. According to the achieved results in the optimisation of Ro-Ro fleets, the operation of two vessels is sufficient to cover Gijon-St.Nazaire, while for Vigo-St.Nazaire three Ro-Ro vessels are necessary (see Table 3). Taking into account the Pareto fronts (see Figure 6) the number of necessary vessels in the fleets ($NB$) is always three for both kinds of vessels and for all possible fleet solutions. Despite the fact that Port Authorities were right, by paying attention to the competitiveness results reached with optimised Ro-Ro fleets for both routes, it can be shown that the results are more favourable (in cost and time) for Vigo-St.Nazaire.
The differences in time between container and Ro-Ro fleets are small in comparison to the cost difference in the Vigo-St. Nazaire route. This is so despite the fact that the cargo capacity is higher for all containers obtained in the Pareto front ($183 \leq G_2 \leq 210$) than the Ro-Ros ($146 \leq G_2 \leq 162$) due to better arrangement of the cargo space in container vessels ($79.00 \leq L \leq 82.04$) in comparison to Ro-Ros ($118.00 \leq L \leq 123.91$). These results are in accordance with the conclusions obtained by Mbiydzenyuy et al. (2010). However, they diverge from the institutional decisions to support the development of SSS uniquely through Ro-Ros (the Italian Ecobonus or the Spanish Port Normative 33/2010 that supports only Ro-Ros for SSS with a reduction of their port dues).

On the other hand, by analysing the results obtained in Pareto fronts (see Figure 5), the optimisation process has found solutions that correct the weak points in both kinds of vessels. Regarding the Ro-Ro type, the moderate service speed ($23.71 \leq V_B \leq 28.00$) and the use of unaccompanied trucks ($G_{16}$ by loading with port facilities $MG_4$ in every solution of the Pareto front) leads to an improvement in the arrangement of the cargo space and finally to a reduction of costs. Thereby, the use of ferries (with accommodation for drivers) in SSS traffic (Bergantino and Bolis, 2008; Morales-Fusco et al., 2012; Woxenius, 2010) would not result appropriate. However, the proposed container fleets (see Figure 6) present a low cargo capacity by operating with port cranes ($MG_2$ in all
cases), which means reduced loading times. This confirms the importance of the speed of loading operations in port for the competitiveness of SSS (Castells i Sanabra, 2009; Martinez and Alonso, 2011; Romana et al., 2010) and therefore the strong influence of the correct sizing of the vessels on it, as the cargo capacity conditions the loading time. This importance increases when the maritime distance decreases, and therefore the size of the fleet will be critical in order to maintain the competitiveness of the multimodal chains through Sea Motorways.

The results obtained not only confirm that it is not necessary to reach a high speed to operate in competitive conditions of time (Castells i Sanabra, 2009; SPIN-HSV Project, 2003–2005) but also that it is not necessary to reach a speed as elevated as expected (less than 20 kn for container vessels) according to the results achieved in other studies (WEST-MOS, 2005–2008, among others). This leads to moderate propulsion power and therefore to the most common arrangements for the engine rooms of vessels (two shaft lines NLE\textsubscript{2} with four diesel engines NMP\textsubscript{4} for Ro-Ros and one shaft line NLE\textsubscript{1} and 1 diesel engine NMP\textsubscript{1} for all containers), and avoids the use of turbines and waterjets (the screw TP\textsubscript{1} was obtained as the most suitable propeller for all obtained vessels due to the fact that the service speed was always less than 35 kn) which raises the building cost of the vessels and their operating costs.

On the other hand, the cargo units that maximise the competitiveness of multimodal chains for both types of fleet are, as expected, the smallest units studied ($G_{11} = \text{TEUs}$ for container vessels and $G_{16}$ for Ro-Ros). This is because in multimodal transport, this kind of cargo unit can take advantage of the economies of scale on the maritime stretch.

It is important to point out that, despite the differences in the approaches to the problem, we have found similarities among the vessel sizes found for the route Vigo-St. Nazaire (494 nautical miles) and the vessels suggested by other authors. For example, Ng (2009) has considered container vessels with a cargo capacity of 250 TEUs for the SSS traffic between Baltic ports and Western European ports and Ametller (2007) has proposed Ro-Ros of 9500 GT as the most suitable vessels for Barcelona-Civitavecchia (455 nautical miles).

Notwithstanding these results, the fleet which is currently operating in Vigo-St. Nazaire route (although not in Sea Motorway conditions) which is made up of two ro-Ros of 18,978 GT at a service speed of 18 kn, is very far from the optimised fleets (see Table 3).

6 Conclusions

Evidence that the decisions of shipping companies are greatly responsible for the success of multimodal chains may be easily found in previous SSS research, as well as in the Sea Motorways performance in Europe. Despite this evidence, the relationship of issues such as the geographical features of the ‘door to door’ routes, the technical characteristics of the vessels and cargo units, the fleets and their management were seldom addressed from the standpoint of the global competitiveness of the multimodal chains against the road.

This work attempts to contribute to filling this gap by providing an optimisation model able to define those technical and operative features of the fleet, which maximise
opportunities for the success of multimodal transport in terms of cost and time. Thereby, this work introduces a general method for the construction of the model; subsequently the method is applied to obtaining the optimisation model for the study case: Vigo-St.Nazaire.

From the analysis of the optimisation process for the study case, we can point out that it is extremely difficult to find container fleets to serve on multimodal chains that are able to achieve the minimum competitiveness required in time (constraint $RR13$). This is mainly due to the high cargo capacity of these vessels, which means longer port times per vessel. The opposite happens with satisfying the minimum competitiveness required in cost (constraint $RR14$). Despite this, a container fleet with three vessels of 210 TEUs of cargo capacity has been obtained as the best solution (considering both attributes, cost and time, simultaneously) for transport chains through the Vigo-St.Nazaire route. Regarding the Ro-Ros, the most competitive fleet identified for this route, has three vessels with a cargo capacity of 162 trucks without a tractor head. The difference between the two fleets is relevant to the competitiveness of the multimodal chains in terms of cost (the cost of the Ro-Ro fleet is nearly twice as high as the container fleet) but less so in terms of time (a 17% advantage for the Ro-Ro fleet). Notwithstanding the great difficulty in finding feasible container fleets, the results obtained in this work suggest the use of containers is preferable to Ro-Ros for SSS in ideal port conditions and contradicts some national rules of European countries which support only this kind of vessel for SSS.

Additionally, the required speed for the shipping is not as high as expected for any fleet on Vigo-St.Nazaire, and it is closer to the generalised estimations provided by previous studies. This is mainly due to the greater influence of the service speed for SSS on cost than on time. Additionally, the time invested in port operations is critical for multimodal chain competitiveness, this reality leads to the fact of the specified vessels have a moderate size (especially the containers for which the weakest point is the time) which permits reduced loading times. It is also noteworthy that the type of cargo units found is the smallest for each kind of vessel. For the Ro-Ros, the cargo unit selected (trucks without master head) rules out ferries as suitable vessels for the Sea Motorways. Despite the fact that this parameter cannot be controlled by the transport responsible, this conclusion can help to focus the client’s search.

On the other hand, once the optimal fleet with its operative and technical features has been defined, future studies should focus efforts on the assessment of freight price with the variations of uncontrollable inputs over time such as the demand (utilisation ratio of vessels) and kinds of cargo units. For this, the evolution of the demand between France and Spain should be evaluated.

Finally, note that the size and number of the vessels specified for the optimised Ro-Ro fleet is very different from the Ro-Ro fleet, which is currently covering the Vigo-St.Nazaire route and that this number of vessels is higher than those obtained for the Gijón-St.Nazaire route. This could be one of the reasons for the lack of feasibility of the Sea Motorway announced by the shipping company and reaffirms, partially, the Port Authorities declarations about the different activity of both Sea Motorways. Thereby, the results confirm the risk taken when technical and operating assumptions are applied to multimodal transport analysis without paying attention to the relationships which exist among them.
References


Definition of optimal fleets for Sea Motorways


Definition of optimal fleets for Sea Motorways


