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HYBRID ALGORITHM FOR THE OPTIMIZATION OF MULTIMODAL FREIGHT TRANSPORT SERVICES: MARITIME APPLICATION

Diego Crespo Pereira
Alejandro Garcia del Valle
Rosa Rios Prado
Nadia Rego Monteil
David del Rio Vilas

University of A Coruna
C. Mendizabal s/n
Ferrol (A Coruna) 15403, SPAIN

ABSTRACT

Multimodal transportation is generally accepted as an efficient alternative to road transportation in terms of costs, fuel consumption, environmental externalities and road congestion. This work presents a novel optimization approach to the multimodal network design for freight transportation with applications to a case in Spain. Optimization is conducted in order to maximize the internal rate of return. Service utilization rates are evaluated by means of a parameterized model implemented in TransCAD.

1 INTRODUCTION

Multimodal transport is acknowledged as a more sustainable transport mode than road transport due to its lower greenhouse emissions and its economies of scale. Thus, several public initiatives in the recent years have intended its advancement. The European Transport White Paper (European Transport Commission 2001) describes the necessary measures to obtain a sustainable European transport in 2010 by promoting a balanced growth of all the transport modes and paying attention to the multimodality. The development of the MARCO POLO program, the promotion of Short Sea Shipping and Motorways of the Sea, the improvement of connections between ports and railroad and the improvement in service quality are the main goals of the European transport policy in order to reach the objectives of the White Paper, especially for freight transport.

In 2011 a new Transport White Paper was published (European Transport Commission 2011), reinforcing the need of the multimodal transport and the implementation of actions to support it. One of them is the optimization of the multimodal chain performance in different terms (raising flows, energy efficiency, profitability, etc.). The goal is to achieve a freight flow from road to other modes in a percentage of 30% in 2030 and 50% in 2050. To do so, efficient and ecologic freight corridors and investments in infrastructures have to be promoted. But also, EU proposes to enhance the attractiveness of multimodal services for the shippers in terms of profitability.

This context provides an ideal framework for the development of initiatives for the optimization of multimodal transport chains. This paper focuses in the optimization of maritime route services as part of a multimodal road-maritime network. Section 2 presents a bibliographic review of simulation and optimization techniques applied to transport. Section 3 reviews and summarizes the transport model employed in this paper, based on the model presented by Rios-Prado et al. (2012). Section 4 describes the algorithm. The algorithm is employed to search for *good* solutions of ports selection, number of routes, fares and capacity design in terms of profitability for the carriers and freight flow absorption. Finally, section 5 presents results obtained in the application of the algorithm to the design of a hypothetical Spanish maritime service that could absorb some of the flows that are currently being transported by road.

2 STATE OF THE ART

Simulation and optimization are salient tools in the supply chain management field as a means for increasing performance and reducing the environmental impact of freight transport. Modeling and simulation technologies have been applied at different decision levels and for various decision problems, such as the operational improvement of terminals (Longo 2010), transport networks (Frick 2011) or routing applications (Juan et al. 2010). Transport and logistics services design is an area that can largely benefit from the adoption of modeling and simulation approaches.

The models employed for transport planning applications can be divided in those concerning passengers or freight. The case of Passenger Transport Modeling has been widely studied, generally using the Classical Model of the Four Stages (Ortúzar and Willumsen 2011). In this method, the geographical area under consideration is divided in Traffic Analysis Zones (TAZ), which are the smallest regions in which passenger flows are aggregated. This methodology adopts an approach with four main steps:

1. Trip Generation. The trips generated in each TAZ are estimated.
2. Trip Distribution. This step connects each of the trips generated in the previous stage with its destination TAZ. The result is a matrix travel between each pair of origin and destination TAZs (commonly called Origin-Destination Matrix, from now on OD Matrix).
3. Modal Split. It gives the transport mode that a trip uses (obviously, in the case that more than one transport mode is available for this trip).
4. Traffic Assignment. This step gives the links of the network used for a trip.

This model can and has been adapted to the case of carried goods. However, several challenges are faced for a successful adaptation, mostly related to the difficulty of modeling policy makers' preferences. Thus, despite of the research effort carried out in the last decades, the freight transport modeling methods are less developed than those applied in passengers modeling (Ortúzar and Willumsen 2011). Freight transport decisions are business management decisions made upon complex criteria. They can be affected by several factors such as those identified by Kreutzberger (2008) spanning the cost of the transported goods, the transport reliability, the frequency of shipments and the transport time.

There is abundant literature on the field of simulation and optimization applied to transport modeling. The majority of previous papers are limited to the analysis of a single mode of transport. Fagerholt (2010) presented a methodology for the strategic planning of a shipping company. Optimization is achieved by solving a route planning problem considering a “rolling horizon” in which information is updated. In the long term, the solutions can solve strategic problems on fleet size and contracts terms. Chou, Song and Teo (2003) raised the problem of optimizing shipping routes where there are two types of sub problems, namely the direct service and the transfer service. Mu and Dessouky (2011) presented their work to optimize the time plans for rail transport. They combine local search heuristics to find optimal feasible solutions in the short term with a heuristic that optimizes the overall total delay.

A noteworthy example solving the multimodal transport problem is the work of Yamada et al (2009). This work optimizes a particular network of multimodal transport for the exchange of goods. On the other hand, Andersen et al (2009) present an optimized model for tactical design of service networks for several companies, with special attention to the effect of timing and coordination of services as parameters for improvement.

Apart from the infrastructures and operational configuration of the service, economic aspects such as prices policies heavily affect the performance of the service. Several works that have focused on this aspect have been reviewed by Ortúzar and Willumsen (2011), although they are often treated separately from other service design aspects.

3 TRANSPORT MODEL

The model presented in this paper has been applied to the design of a new multimodal maritime and road service, although it could be easily extended to other options of multimodal transport such as the combined railway and road one. A new maritime service is modeled and parameterized in terms of a set of design variables that influence the expected return from the point of view of the carrier. In order to facilitate the implementation of the model, a transport planning software (TransCAD) has been used.

TransCAD is a GIS widely employed by transportation professionals. It allows to store, display, manage and analyze transportation data. It can be used for all transportation modes and also allows to use multiple transportation planning applications, from simple short path methods to mode choice or assignment methods.

This work adopts the parameterized model for multimodal freight transport presented by Rios-Prado et al. (2012). Based on the classical four steps method, it allows to evaluate the absorption by the maritime/road mode of unimodal road traffic flow. In this paper a hybrid algorithm procedure will be presented that maximizes the IRR (Internal Rate of Return) of a hypothetical maritime regular service that would operate among a series of Spanish ports. This sections summarizes the conceptual model.

3.1 Input Data.

The input data to the model contains the following elements:

- The traffic analysis zones (TAZ). They are defined as the geographical areas capable of attracting or generating freight shipments. They are represented by the subscripts i for origins and j for destinations.
- The OD matrices. They contain the total cargo in tons shipped from each origin TAZ to each destination TAZ. They were obtained from historical data and their future values are generated assuming constant rates. They are referred as $F_{t,i,j}$ where t represents the period of time (commonly years).
- The transport network cartography in a GIS format. It contains all the links and nodes in the transport network with their travel times, distances and associated costs. Each transport alternative (in our case multimodal or unimodal) is given by the subscript k.
- The fares and costs of each transport mode.

3.2 Transportation Network.

The model network contains the information about the infrastructure that is employed to carry out the freight trips. It defines all the available links between each origin and destination. In practical applications a geographic information system (GIS) is used, containing all the information and also enabling to introduce new layers of data.

The nodes of this network include the origin and destination TAZs of the freight flows along with the ports covered by a set of regular maritime routes. The road infrastructure comprises all the roads and highways available for freight transportation in the studied geographical area and the maritime lengths are all the links between the ports that are visited in the regular routes. A first parameter to be subject to optimization is the **number of routes** that will be defined in the network. Another aspect that characterizes the maritime routes is their capacity, given by the **number of vessels** assigned to each regular route along with the capacity of the vessels given by the characteristics of the vessels chosen for the service. The maritime routes definition is completed by setting the sequence of ports that will be covered and the fare for each route.

3.3 Transport Model.

The transport model is based on the classical Four Steps Model, but in this case OD matrixes are taken as model inputs (so the first two steps are not considered) and a final step for the economic assessment is incorporated. Figure 1 represents a flow diagram of the whole transport model employed.

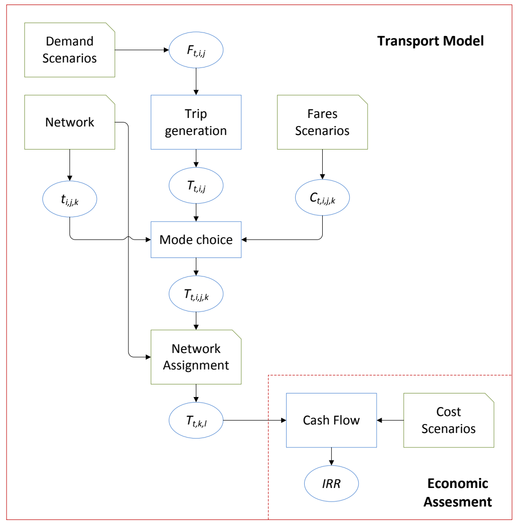

Figure 1: Transport model diagram.

Trip Generation. The first step of the model requires the transformation of the OD matrices in tons of freight ($F_{t,i,j}$) into OD matrices of trips ($T_{t,i,j}$). In this case it is assumed that all the cargo will be transported by containers. Containers constitute a standardized unit of transport which represents a high intake of the global trades. It allows to simplify the model since all the different cargo will require the same handling equipment and will occupy the same space in the transport vehicles or ships. In order to transform tons of cargo into containers average weight per container rates were employed.

Modal Split. In the modal split step the fraction of the flow between each origin-destination pair per transport mode is obtained. This is a crucial step because it is the one in which the competitiveness of the multimodal option is evaluated. Several mathematical models have been developed aiming at reflecting the choices that would be made by the freight shippers (Ortúzar and Willumsen 2011). Were a single shipper the only service user, optimization methods could be used to select the best option. However, when a large number of agents use the service, their differences in choice criteria should be taken into account because they lead to a split in mode choice. Probabilistic models are then required , such as the Probit or the Logit models. Their aim is to reflect the variety in choices among users of a transport network and how some key decision factors affect them.

The most extended Logit models family is the Multinomial Logit Model (MNL). The MNL calculates the probability of each transportation alternative for each trip as:

$$P_{i,j}(k) = \frac{e^{V_{i,j,k}}}{\sum_{k \epsilon A_K} e^{V_{i,j,k}}} \tag{1}$$

Where

- $P_{i,j}(k)$ Probability of alternative k for a trip from origin i to destination j.
- $V_{i,j,k}$ Utility of alternative k for travelling from origin i to destination j. It is modeled as a function of time and cost and fitted to historical data by means of logistic regression.
- A_K Set of transport alternatives. In this case 2 alternatives are considered.

These probabilities are used to calculate the number of trips that uses each transport alternative:

$$T_{t,i,j,k} = T_{t,i,j} \cdot P_{i,j}(k) \tag{2}$$

The utility function incorporates all the factors affecting the mode choice. The two most important ones are cost and time (Kreutzberger 2008). At this stage, cost is referred to the cost faced by the shipper, thus including both the fares for using each option as well as the direct inventory costs. The travel time takes into account both the time in movement and the waiting times in the ports as well as the legal limits on truck drivers shifts. The terms of the utility function reflect the balance between direct costs and time.

Road transport fares for the shipper have been estimated using the model provided by the Spanish Freight Road Transport Observatory (Ministerio de Fomento Gobierno de España 2012). Their model takes into account all the costs for the road transport operators as well as their profits. Road transport is also the choice for the multimodal transport Between ports and TAZs.

For the maritime transport, the following costs were considered:

- The **fare** per kilometer and unit of cargo (TEU) charged to the shipper for using the maritime route. This fare represents the income of the shipping company and should pay for all the costs involved in the operation of the ship. These costs are not directly included in the mode choice model but in the economic evaluation. They are:
  - Capital cost: It takes into account the price of the vessel, amortization, life time, etc.
  - Maintenance (Insurance and Repair costs): all vessels need maintenance and reparations during their life time. Also an insurance policy is needed.
  - Crew Costs: this is the cost due to the salary and expenses of the crew.
  - Fuel cost: it is a function of the fuel type and the vessel's consumption.
- Port operation cost: This is the cost of the cargo handling in ports.
- Inventory cost: There are two different costs. One due to the waiting time in port, and another one due to the time onboard.
- Port taxes: each port has fares for using its berth and equipment.

All cost variables were forecasted by means of constant update rates and could be changed in the model from one scenario to another.

Network Assignment

In the network assignment step, the total flow that travels through each link of the network is obtained. As long as congestion effects in the network can be omitted or are not significant, an All or Nothing Assignment can be applied. Then, all the traffic flows between origin and destinations pairs can be assigned by the shortest path method in terms of either time, length, cost or a generalized cost function. As a result, the total number of trips (containers) that travels through each link l of the network using the mode k is stored in the table $T_{t,k,l}$.

3.4 Economic Assessment.

The steps presented before provide with an evaluation of the flows of freight that would be attracted by the defined multimodal transport service in terms of maritime routes and fares. Hence, they provide the expected incomes of an investment in that service. The next step to evaluate its profitability is to calculate the costs and the cash flow for the desired timespan. Then, an economic analysis can be performed in which the profitability of each maritime route can be analyzed by means of the IRR as follows:

$$Fare = Costs + Net\ Profit \tag{3}$$

$$Income = Fare \times \sum_{l \in MR} T_{t,k,l} \tag{4}$$

$$Earnings\ Before\ Taxes = Income - Costs \tag{5}$$

$$Earnings\ After\ Taxes = (Income - Costs) - Taxes \tag{6}$$

$$Cash\ Flow = Earnings\ After\ Taxes + Depreciation \tag{7}$$

$$\sum_{t=0}^{10} \frac{CF_t}{(1+IRR)^t} = 0 \tag{8}$$

Where MR represents the set of network links that belong to the analyzed maritime route and CF_t denotes the cash flow in the time period t (generally years). The Net Earnings account for the decreasing effect of taxes. In our case study the tax rate is the 30% of the profits (the common type of the Spanish Corporate Income Tax). The depreciation of the ship is the annual cost of the ship during its life time due to its initial and residual cost. A life time of 20 years and a 15% of residual cost were supposed in the case of study.

4 THE OPTIMIZATION ALGORITHM

Once all the components of the transport model have been introduced, an optimization problem for the maximization of the maritime transport service profitability could be formulated. The objective function in this case is the IRR, as defined in section 3.4. Its calculation would require the development of the whole transportation model presented before and thus a closed form cannot be provided. Simulation approaches are required for its calculation. The decision variables (the model parameters) presented before comprise:

- The number of maritime routes. A larger number of routes allows a higher absorption of freight flows, but it increases the operation costs of the maritime service.
- The sequence of ports in each route.
- The fares of each route. Higher fares increase margins, but they also reduce the attractiveness of the multimodal option.

Other variables that affect the solution such as the characteristics of the ships employed in each route (capacity, speed and other factors that influence costs) are established at an initial step and set constant.

The rest of the variables in the model could be assumed as fixed parameters. The next constraints should also be introduced in order to obtain solutions that verify the model assumptions:

- The fare of each route should be greater than the costs per unit of distance (the service cannot yield losses).
- The number of ships in each route should be large enough for ensuring that all the flow of freight at each link of the network can be transported.

The optimization problem thus obtained is quite complex since the objective function cannot be expressed in a close form and it involves continuous decision variables (the fares), integer ones (number of routes, ships, some of the ships characteristics) and also the ports sequences which give a combinatorial nature to this problem. Optimization procedures for this problem need to be efficient to compensate for the high complexity of the model and the large number of feasible solutions that could be obtained combining the different decision variables. Some existing techniques that could be applied to its resolution are metaheuristics (Dullaert et al. 2005), hyperheuristics (Dowsland et al. 2007) or hybrid approaches (Dridi and Kacem 2004).

A method for the optimization of a multimodal transport network with the characteristics required by this model has not been found in the literature review, so an own developed method has been adopted.

The combinatorial nature of the problem and a complex objective function, led us to adopt a combination of heuristics and metaheuristics developed specifically for this case. The proposed method combines the power of metaheuristics in the intensive exploration of the problem domain along with the calculation speed and customization provided by the heuristic methods.

Therefore we use a hybrid optimization method that combines a metaheuristic and a heuristic. The selected metaheuristic in this case is an evolutionary algorithm, specifically the Differential Evolution algorithm (Storn and Price 1997). The Differential Evolution provides a general and robust optimization method that has shown good performance in problems with a low number of dimensions (Caamaño et al. 2013) as in this case. The constructive type heuristic has been developed specifically for the problem. The genes of the evolutionary algorithm individuals correspond to the parameters of the constructive algorithm and the route fare per distance.

The proposed optimization algorithm proceeds as follow (see Figure 2):

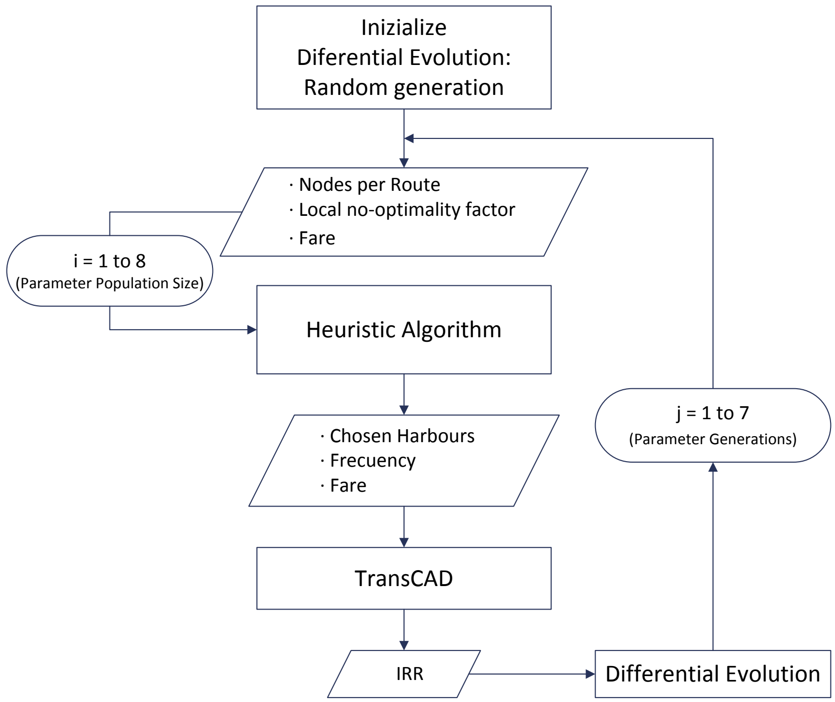

Figure 2: Heuristic algorithm

1. Initialize Differential Evolution. Random generation of the initial population which contains a number of individuals given by the Population Size parameter. Each individual has 3 dimensions (Nodes per Route, Local non-Optimality Factor and Fare).
2. The heuristic evaluates the individuals from the population, generating the corresponding routes.
3. Programmed routines within TransCAD calculate the IRR of the designed route, for all the individuals in the population.
4. Once the evaluations are completed, the Differential Evolution gives a new population by migration and recombination of the previous ones.
5. The algorithm loops for a number of times given by the Number of Generations parameter.

4.1 Evolutionary Algorithm

The evolutionary algorithm used is the Differential Evolution, implemented in the Evolutionary Algorithms Framework (EAF) developed by Caamano et al. (2010). In our study we use the parameter settings presented in Table 1. F is a parameter that controls the mutation rate, and it is a real number in the interval [0,2] and CR is a parameter that controls the recombination rate.

Table 1: Parameters settings

Parameter	Value
Population size	8
Number of Generations	8
Parameter F	0,5
Parameter CR	0,5

This algorithm is used to optimize the set of parameters that define the behavior of heuristics. The decision variables (chromosomes of the population individuals) of this algorithm are:

- Number of nodes per route: Integer value within 2 and 5.
- Local No-Optimality Factor (f): It is an integer number used so that the same harbor is not allowed twice in a route.
- Fare: For every route is within 0.3 and 0.7 €/km.

The first generation of Differential Evolution is a random generation. The initialization process takes place at the beginning of execution of the search, and the steps of mutation-recombination-selection is performed repeatedly until a condition is satisfied (number of generations, elapsed time, or quality of solution reached). In this case our criterion is the number of generations. The algorithm uses the IRR as the quality function.

4.2 Heuristic Algorithm

Every individual generated by the evolutionary algorithm is evaluated in the Heuristic Algorithm for generating a ports sequence. The variables of the individual are the input variables of the algorithm. The steps of the algorithm are:

1. Previous step: TransCAD calculates the IRR of the stretch between each possible pair of harbors. They are stored in a sorted list by descending IRR.
2. Move f positions over this list. It gives the Origin-Destination harbor pair.
3. Add the harbors to the route.
4. From 1 to (Number of nodes per route – 2):
    a. Search pairs on the list with nodes having the first or last harbor on the generated route.
    b. Select the pair with highest IRR.
    c. Add the harbor to the route.
5. Repeat steps 2 to 4 to obtain the predetermined number of routes.

One all the ports sequences of the routes are obtained, their IRR can be estimated by means of the transport model implemented in TransCad and be sent back to the Differential Evolution algorithm for further exploration of solutions.

5 CASE STUDY : SPANISH MARITIME ROUTE OPTIMIZATION

To test the effectiveness of the optimization process, two scenarios are evaluated: one in which the solution consists of a single route and the second in which it is formed by two routes, shown in figure 3.

As another assumption, the number of annual trips was fixed to 50 (one each week): this allows routes to be serviced with a single ship. Although this frequency minimizes the number of vessels, the algorithm checks whether this is sufficient and, if not, increases it. Applying the methodology explained above, we obtain the following results shown in Tables 2 and 3:

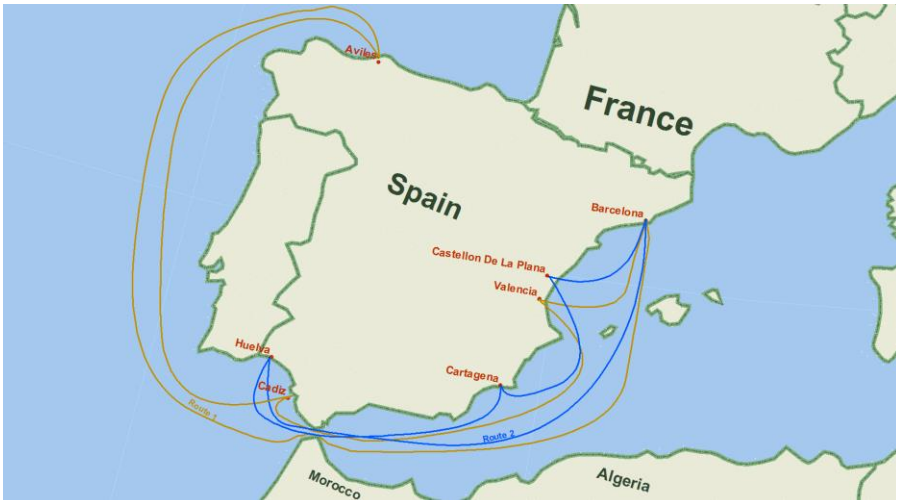

Figure 3: Case of Study

Table 2: Scenario 1.

Scenario 1	Decision Variables of the Genetic Algorithm			
	Number of ports in a route		4	
	Non-Local Optimality Factor		3	
	Fare per Route		0.67 €/Km	
	Decision Variables of the Optimization Problem			
	Routes Solution		Valencia-Barcelona-Marín-Cartagena	
	Frequency		50	
	Fares		0.67 €/Km	
	IRR			
	VAL-BCN	BCN-MAR	MAR-CART	CART-VAL
	9.54%	35.34%	30.67%	-2.72%
	IRR Overall			
	18.12%			
	Computation Time: 40 minutes			

The developed algorithm is capable of providing good solutions in terms of profitability. A 6.4% absorption rate of the interregional freight flow is achieved with the two routes , which is remarkable taking into account that multimodal transport represents a small fraction of the interregional Spanish transport nowadays. This result represents an increase in the absorption rate from the results of the previous studio conducted by Rios-Prado et al. (2012) in which only port taxes reduction scenarios were considered.

The validity of the transport model employed in this case study could not be assessed by data since it was not available. In the moment in which it was conducted and the optimization results have not been implemented. However, results are reasonable taken into account that the Spanish ports linked by the optimization process are the ones connected to the most relevant hinterlands (such as Barcelona or Valencia) and with the highest flows among regions. This case study has served as a means of demonstrating the utility of the applied methodology and the optimization algorithm, but further analysis in other case studies with more data should be carried out in order to demonstrate its forecasting capabilities.

Table 3: Scenario 3.

<table>
<tr><td rowspan="20">Scenario 2</td><td colspan="5">Decision Variables of the Genetic Algorithm</td></tr>
<tr><td colspan="2">Number of ports in a route</td><td colspan="3">5</td></tr>
<tr><td colspan="2">Non-Local Optimality Factor</td><td colspan="3">4</td></tr>
<tr><td colspan="2">Fare per Route</td><td colspan="2">0.57 €/Km</td><td>0.62 €/Km</td></tr>
<tr><td colspan="5">Decision Variables of the Optimization Problem</td></tr>
<tr><td colspan="2" rowspan="2">Routes Solution</td><td colspan="3">Huelva-Barcelona-Cartagena</td></tr>
<tr><td colspan="3">Cadiz-Barcelona-Marín</td></tr>
<tr><td colspan="2" rowspan="2">Frequency</td><td colspan="3">50</td></tr>
<tr><td colspan="3">50</td></tr>
<tr><td colspan="2" rowspan="2">Fares</td><td colspan="3">0.57 €/Km</td></tr>
<tr><td colspan="3">0.62 €/Km</td></tr>
<tr><td colspan="5">IRR</td></tr>
<tr><td>HUELV-BCN</td><td colspan="2">BCN-CART</td><td colspan="2">CART-HUELV</td></tr>
<tr><td>20.85%</td><td colspan="2">-2.97%</td><td colspan="2">12.83%</td></tr>
<tr><td>CAD-BCN</td><td colspan="2">BCN-MAR</td><td colspan="2">MAR-CAD</td></tr>
<tr><td>13.82%</td><td colspan="2">4.47%</td><td colspan="2">1.89%</td></tr>
<tr><td colspan="5">IRR Overall</td></tr>
<tr><td colspan="5">8.48%</td></tr>
<tr><td colspan="5">Computation Time: 3 hours 30 minutes</td></tr>
<tr><td colspan="5">Absorption Rate: 6.40%</td></tr>
</table>

6 CONCLUSIONS

A parameterized model for the optimization of a multimodal transportation network has been developed and implemented aiming at evaluating the possibilities to increase the absorption rate by a multimodal transport service. Three different software packages (TransCAD, a Java Heuristic and the genetic library of the Integrated Group for Engineering Research) have been integrated in order to implement the transport model and an optimization algorithm. A novel formulation of the optimization process has been developed, by combining a metaheuristic method (the Differential Evolution algorithm) and a constructive heuristic.

The proposed method might contribute to achieve the objectives pursued by initiatives such as the European Transport White Paper (ETWP) by providing a tool for increasing the attractiveness of the multimodal transport. Results from this specific case study could not be validated and thus further data and analysis would be required in order to assess the obtained maritime routes. However, the optimization methodology has been proved useful for improving the model results and thus it could be employed in other cases in which more complete data were available.

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AUTHOR BIOGRAPHIES

DIEGO CRESPO PEREIRA is an Industrial Engineer by the UDC and holds a PhD in Industrial Engineering. He is Assistant Professor of the Department of Economic Analysis and Company Management of the University of A Coruna (UDC). He also works at the GII (Integrated Group for Engineering Research, www.gii.udc.es) as a research engineer since 2008. He is mainly involved in the development of R&D projects related to industrial and logistical processes optimization. His email address is diego.crespo@udc.es.

ROSA RIOS-PRADO works as a research engineer at the GII of the University of A Coruna (UDC) since 2009. She holds an MSc in Industrial Engineering from the UDC. She has previous professional experience as an Industrial Engineer in several engineering companies. She is mainly devoted to the development of transportation and logistical models for the assessment of multimodal networks and infrastructures by means of simulation techniques. Her email address is rrios@udc.es.

DAVID DEL RIO VILAS holds an MSc in Industrial Engineering. He is Adjunct Professor at the University of A Coruna and research engineer at the GII of the UDC since 2007. Since 2010 he works as a R&D Manager for a group of companies in the Civil Engineering sector. He is mainly involved in R&D projects development related to industrial and logistical processes optimization. His email address is daviddelrio@udc.es.

ALEJANDRO GARCIA DEL VALLE is an Industrial Engineer by the Polytechnic University of Madrid and holds a PhD in Industrial Engineering. He is full Professor at the Polytechnic School of the University of A Coruna and one of the founders of the GII at the University of A Coruna. He has led many research projects about simulation and optimization of industrial, logistical and service systems. His email address is agvalle@udc.es.

NADIA REGO MONTEIL obtained her MSc in Industrial Engineering in 2010 from the UDC, where she works as a research engineer at GII . Her areas of major interest are in the fields of Ergonomics, Process Optimization and Production Planning. Her email address is nadia.rego@udc.es.