THE OPTIMIZATION OF A FLEET FOR THE SEA MOTORWAY: VIGO-ST. NAZAIRE

(Motorways of the sea)

Alba Martínez López[1],
Department of Naval Engineering, University of A Coruña
Edificio de Talleres, (Campus de Esteiro), C/Mendizábal, 15403, Ferrol, A Coruña.
Spain
amartinezl@udc.es
Phone: +34 981337400 - 3848

Pilar Caamaño Sobrino
Integrated Group for Engineering Research
Edificio de Talleres, (Campus de Esteiro), C/Mendizábal, 15403, Ferrol, A Coruña.
Spain
pcsobrino@udc.es
Phone: +34 981337400 - 3863

Laura Castro Santos
Department of Naval Engineering, University of A Coruña
Edificio de Talleres, (Campus de Esteiro), C/Mendizábal, 15403, Ferrol, A Coruña.
Spain
laura.castro.santos@udc.es
Phone: +34 981337400 - 3890

Blanca Priego Torres
Integrated Group for Engineering Research
Edificio de Talleres, (Campus de Esteiro), C/Mendizábal, 15403, Ferrol, A Coruña.
Spain
blanca.priego@udc.es
Phone: +34 981337400 - 3864

ABSTRACT

The WEST-MOS project (2005), among others studies, had indicated a high feasibility for the Sea Motorways which joint the Atlantic coasts of France and Spain. As a consequence of this, in 2006 a Bilateral Commission (French and Spanish) was established to evaluate possible projects that articulate Sea Motorways between both countries in the Atlantic. The requirements of frequency and minimum cargo unities moved per year were quite demanding but the project selected received additional resources. The first project selected by this Commission was the Sea Motorway Vigo-St.Nazaire.

This work is focused in the technical and operative optimization of the fleet which would cover this route. The objective functions are the maximization of the savings in time and costs for the multimodal chains (articulated

1 Author for correspondence and presenting the paper

through this Sea Motorway) against the road transport. In order to achieve this objective functions a mathematical model has been developed taking into account the different alternatives of fleet and the operation of it.

This led to the integration of different kinds of variables into the model. The main variables of the problem are: the kind of the vessel (container or ro-ro), the kind and amount of cargo units (trucks, containers), maneuver means for the ship, the handling system used for the port operations, the number of vessels of the fleet and the adequate speed for the vessels. Otherwise it was necessary to determine auxiliary variables related to the naval architecture and naval engineering in order to calculate the main variables and the objective functions. These are the dimensions of the ships, the cargo capacity, building costs, the Arrangement of engine room, the kind of propeller, the kind of main engines and the number of shaft units.

The optimization will take into account the constraints derived from the operation requirements (Bilateral Agreement) and the technical restrictions (Naval Architecture and Naval Engineering). This process has been carried out using Evolutionary Algorithms and Trust-Region-Reflective Optimization (MATLAB). The two methods have been employed to test the performance and the goodness of the results obtained.

The optimization concludes with the determination of a numerical value for some variables (such as the speed) or with the decision about the optimum alternative among the possible alternatives (such as the kind of ship). Another important result achieved in this work is that the time invested in the intermodal chain and their costs are only dependent on very few controllable variables.

Keywords: Sea Motorway, Fleet Manager, Nonlinear Optimization Model, Evolutionary Algorithms

THE OPTIMIZATION OF A FLEET FOR THE SEA MOTORWAY: VIGO-ST. NAZAIRE

1. INTRODUCTION

Maritime transport in the E.U. (European Union) had the most important impulse with the concept of Sea Motorway. This concept appeared for the first time in the transport White Paper of 2001, and it was defined as a group of ports and intermodal services that are used for short distance maritime transport in a particular zone of the E.U. The main objective of the Sea Motorway concept is to contribute to preventing the traffic congestion on the European roads.

In 2003, the European Commission reviewed the extension of TEN-T, including Sea Motorways and it determined projects which should be finished before 2020. One of them was the N21 project. This project was aimed to the development of the Sea Motorways concept, thus the promoted motorways were four and one of them was the Western European Motorway, which connects Spain and Portugal with the Irish Sea and the North Sea through France . Since this moment, different European and National projects and studies were focused in the identification of the inputs which condition the competitiveness of the multimodal transport mode through Sea Motorways against the road transport. Most of them made a great effort to identify recommendable ranges of distance to establish Sea Motorways with a guarantee of successful against the road transport (EMMA project, 1998, WEST MOS project, 2008, INECEU Project, 2004, Martínez et al., 2005, Jiang et al., 1999, Ametller, 2007).

Due to the geographic location of Spain and Portugal as a Peninsula (which means an additional difficulty for the transport to the rest of Europe) the interest in the development of Sea Motorways was very high. Thus the recommended thresholds of the distance obtained from the mentioned studies were applied to different routes from these countries to France, mainly, due to the importance of the commercial flow between them (19.39% of the total exportations and the 11.71% of the total importations of Spain in 2009 were from or to France in according to the data from the Spanish Ministry of Industry). The results showed that most of the routes with France in the Atlantic coast (excepting the closest ports to the Pyrenees) were competitive against the road transport (Martínez et al., 2011, INECEU, 2004, among others).

Otherwise, in 2005, the E.U. published a study on the potentials of Sea Motorways, it was carried out by the Coordination Platform for the maritime transport (Atlantic transnational network, 2006) in the sixth Research Framework Programme. The conclusions of this study allow confirming the high potential between the central French coast and the ports of the north of Spain, both for ro-ro traffic and for container traffic. This affirmation has reinforced the previous objective of developing the Sea Western European Motorway before 2020. As a consequence, in October 2005, a collaboration agreement, 'Declaration of intentions about Sea Motorways', was signed between France and Spain. With this agreement, a Commission (CIG, July 2006) for the analysis and selection of projects developed on the Sea Motorways between both countries was created. The selected Sea Motorways received additional resources (at least the 30% of the operative cost for the first three years) but they must meet quite demanding conditions (BOE Nº265, 2006) regarding the frequency of the service and the total amount of cargo units transported per year.

The first project that has been approved in this framework (30 October of 2009) was the route Vigo-St.Nazaire (with Acciona-Transmediterranea shipping company). Among other advantages, this route has a geographic location favourable to articulate competitiveness multimodal chains and it had already offered maritime linear service. This is because there is an important ro ro (roll on- roll off) traffic between Vigo and St. Nazaire due to the production of PSA Peugeot Citroen factory (with a yearly production of 380000 cars located in the Vigo hinterland). Despite the favourable situation, the Sea Motorway is not currently, operating. At the end of 2010 the shipping company Acciona-Transmedierranea ceded its concession to the new Shipping Company (French Spanish Maritime Company) with agreement with PSA Citroen. The main argument of Transmediterranea was that the PSA Citroen production was essential to ensure the feasibility of the Sea Motorway.

In 2010 a second Sea Motorway project was approved: St.Nazaire-Gijón operated by GLD Atlantic. This route is successfully operating from September of 2010 despite the fact that: Gijón moves less general cargo and containers than Vigo (see Table 1), there is not a car factory in its hinterland and their geographic location is not as favourable as the Vigo´s one to articulate competitive multimodal chains.

Table 1: Volume of General goods and in containers in 2009 (Tn)

	Total	In Container
Gijón	587,401	175,016
Vigo	2,607,037	1,582,047

The key, according to the Port Authorities, is the fleet necessary to cope with the requirements of cargo units and minimum frequency demanded by the Agreement (the same for both cases).

Therefore, the main aim of this paper is to provide an optimization model able to define the most suitable fleets for the Sea Motorway traffic. This model will be useful for the decision making regarding the fleet and the most suitable cargo units. Due to the cited problem with the case of the Sea Motorway Vigo-St.Nazaire, this one will be taken as an example of the optimization.

The optimization will consider the competitiveness of the multimodal routes established through the Sea Motorway. To this aim, a mathematical model will be developed taking into account the main objectives of the competitiveness: the maximization of the difference in time and cost (per Tone transported and per travel) between the unimodal mode and the multimodal mode. Afterwards the optimization will be carried out through Evolutionary Algorithm (Differential Evolution). The results will be checked by comparison with the optimization through the algorithm: Trust-Region-Reflective Optimization.

The study will define not only the technical parameters which are necessary to define the vessels and their operation (kind of vessel, cargo capacity, architect features, speed, etc.) but also the kind of cargo units and the most suitable cargo handling systems which should be used to favour that the multimodal chain against the road transport. Therefore, the results achieved by the optimization model are not only useful for the shipping companies (which want to operate in a Sea Motorway) or for the Port Authorities with interests in the establishment of a Sea Motorway, but also for the cargo owners which need a transport service for small volume of cargo with high frequency (for example SMEs).

This paper is structured as follows: Section 2 is devoted to the revision of the literature of the field. A review of the main works related with the one presented here is done. The method used to solve the problem of the determination of the best fleet is explained in Section 3. The mathematical model developed to perform the simulations that are necessary to obtain and compare solutions is proposed at Section 4. The results obtained after the optimization are explained in Section 5. Finally, the conclusions obtained in this work are presented in Section 6.

2. LITERATURE REVIEW

As it had been seen before the studies and projects carried out about the competitiveness between multimodal chains articulated through SSS (Short Sea Shipping) and unimodal transport are very numerous. Most of them take as inputs the vessels of the fleet which are currently operating in linear shipping (ro ro - Roll-on, Roll-off- vessels of 1600 m of roads for trucks or even ferries). This is so because the approaching is based on the change of service of the current fleet (INECEU project, 2004, WEST MOS project, 2008 among others) or because the forecast is that shipping companies will invest in ro-ros for the SSS due to that, so, the truck will become a client instead of a competitor (WEST MOS, 2008).

All these projects and others (Castells, 2009, TRA2006-09939 Project,2009) agree that the weakest point of the multimodal chain is the time invested in the transport. For that reason, the majority of the projects to improve the vessels of the SSS transport are focus on the possibility of using higher speeds in ro ros (Castells i Sabra, 2009, UK Marine Motorways study, 2003, SPIN-HSV,2005, among others). All of them concluded that the High Speed Crafts are not suitable to keep the competitiveness in cost. However many projects recommended minimum thresholds of speeds for the vessels: 28 kn (WEST MOS, 2008), between 23 and 30 kn (Castells i Sanabra, 2009), 20 kn (EU-Cargoxpress, 2009).

Otherwise the importance of the cost against the time in the cargo transport is very dependent on the features of the cargo owner (Nellthorp et al., 2001). However for a small volume of cargo and high frequency (it often means high added value) the importance of the time rises (TRACE, 1999; TRA2006-09939 Project, 2009) up to a value. Thus the most of the projects of competitiveness of SSS try to minimize the transport cost only ensuring that the difference in time with the road transport is below a value very dependent on the distance (according the results from the study of stated preferences carried out in Spain by TRA2006-09939 Project, 2009 it was necessary a cost save of 20% to accept two days delay on the delivery time in the transport service to Italy).

Despite the fact that there are not so many projects focused on the technical improvement of the fleet, it is important to point out the amount of projects related with the improvement of the cargo handling systems in the vessels (IN HO TRA, 2004, IPSI, 1999) and the compatibility of the vessels (ro ros and containers) with the port facilities (Mbiydzenyuy, et al., 2010). Many of these projects lead the design of a new kind of vessel as container vessels as ro ros (EU Cargo express, 2009, INTEGRATION, 2005). From the private initiative, it is interesting to emphasize the new ro ro vessels designed for SSS traffic: European High Speed Cargo Vessel (2002, IZAR and ROLLS ROYCE) with cargo capacity of 1700 m of cargo road at 42 kn) and the new ferries: ENVIROPAX Project designed by Kvaerner Masa-Yards (2001) with capacity of 2480 m of road.

Regarding to the optimization of a fleet for SSS we must point out the study carried out by Ametller, X, (2009) where the influence of the cargo capacity of the vessels on the multimodal transport is analyzed. In this study only a kind of vessel: ro ro is analyzed concluding that the highest competitiveness in cost for the multimodal chains (articulated through Barcelona- Civitavecchia) was achieved by ro ros of 9500 Gross Tonage.

The application of optimization algorithms to SSS problems is a topic of high interest at the moment. Specially in scheduling problems like the vehicle routing problems, stowage Problems (Martins, T., 2009) and the combination of them (Triunfante, et al., 2010). In these works the authors use genetic algorithms to solve the proposed problems. In works related with the optimization of the design of the vessel other types of optimization algorithms have been used instead of evolutionary or genetic algorithms. For example, Ametller, X. (2009) used a Backtracking algorithm (exhaustive search algorithm suitable for problems with reduced search space) to define the optimum size of the vessels for SSS. Another work presented by Mbiydzenyuy, G. et al. (2010) used an integer linear optimization model to determine the most suitable kind of vessel for SSS in terms of the cost regarding the port facilities used.

3. THE METHOD

In this section we will explain the method used to optimize a fleet of vessels for the Sea Motorway from Vigo to St. Nazaire. This method is divided in two phases. The first one devoted to the definition of the mathematical model used to simulate different fleets, this mathematical model defines all the variables and relations between them that are necessary to define the fleet and its features. For that, it is necessary to pay attention to the importance of the correct definition of the vessels in the model from a technical point of view. This is important because the technical features condition the operative efficiency of the vessel (in time and cost for the multimodal transportation) but also the technical viability of the fleet (the solution must be realistic). The second phase of the model will be dedicated to the optimization of the fleets. In this work we will use two different optimization algorithms: an evolutionary algorithm, specifically a Differential Evolution and a local search algorithm, in this specific case the Trust-Region-Reflective Optimization algorithm. These two algorithms will be compared in terms of the goodness of their solutions.

Due to the importance of the correct definition of the mathematical model, the first step will be to identify the different kinds of variables which must be integrated in the model. Afterwards the relationships among them will be defined. The variables can be split out into three types regarding their roles in the optimization:

-The cases are the discrete variables which should be selected as a result of the optimization (for main and auxiliary variables).They can only reach a collect of values which means all cases. Some of them have been noted as:

$PP = \{1,.., p\}$	Set of the cargo type studied for the cargo units (see figure 2)
$Q = \{1,.., q\}$	Set of type of vessels
$BB = \{1,.., b\}$	Possibility of the installation of bow thrusters in the vessel
$G = \{1,.., g\}$	Cargo handling systems
$EE = \{1,.., e\}$	Set of ages for the vessel
$NN = \{1,..n\}$	Number of shaft lines
$D = \{1,.., d\}$	Set of land destinations of the multimodal chains

-Optimization variables are the continuous variables which will be determined by the optimization.

-The data are all of the inputs no controllable, imposed by the frame work, the route features, etc. Some of these inputs are:

X_d : Probability of different land destinations for the cargo of the vessel. Paris, Lille and Rennes have been taken as extremes of the multimodal chains (D)

DR_d^V : Road distance from Vigo Port to the land destinations (D) in Km.

DR_d^{St} : Road distance from St.Nazaire Port to the land destinations (D) in Km.

$C_{4,p}$: Price €/Km (data from Ministerio de Fomento of Spain, 2010),regarding the type of cargo unit $G_{1,p}$ (PP).See figure 2.

P_p : Weight of the cargo units. (Tn)

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 amortization.

C_3^f : The average cost of an official (crew) per year.(€)

C_3^s : The average cost of a sailor per year.(€)

C_3^c : Cost IFO 380 (€/l)

DT_2 : Diesel density (gr/l)

$R_{5,q}$: Percentage of dockage due demanded by Port of Vigo to stimulate the SSS traffic. It depends on the number of travels and the kind of vessel (Q).

TIE: Loading/unloading time (h)

$R_{6,q}$: Percentage of cargo due demanded by Port of Vigo to stimulate the SSS traffic. It depends on the number of travels and the kind of vessel (Q).

$C_{2,p}^c$: Cargo dues in the port. It depends on the kind of the cargo unit (PP)

C^c : Pilotage due.

C_1^c :Towing due.

C_2^c :Mooring due.

DT_1 : Engine Consumption ($\frac{gr}{HP.h}$)

$C_{2,p}^{c4}$: Loading/unloading dues (€/unit). It depends on the type of cargo unit (P).

V_3 : Speed of the trucks (Km/h)

DM: Maritime distance between ports (miles)

$V_{2,g}$: Loading speed of the cranes. It depends on the cargo handling system used (G).

U_g : Number of operative cranes per vessel. It depends on the cargo handling system used (G) and the length of the vessels.

TI_1 : The average waiting time for a pilot.

TI_2 : The average waiting time for the towing service.

On the other hand, conceptually, two kinds of controllable variables will be handed in the model: the auxiliary ones (related to the naval architecture and naval engineering) and main variables. The calculation of the first ones is necessary, together with the definition of the second ones, for the calculation of the objective functions (see Figure 1).

The auxiliary variables are also dependent among them, as for instance the engine room arrangement (number of shafts, kind of main engines, etc.). Some of the auxiliary variables are:

G_3 : Maximum cargo capacity of the vessel (in units). It depends on the kind of cargo unit.

N: The number of yearly travels carried out by the fleet.

CC: Building cost of the vessel. It depends on its technical features and on its dimensions. Therefore it depends on the most of the auxiliary variables).(€)

TPM: Deadweight of the vessel. It is very dependent on the dimensions and forms of the vessel.(Tn)

NTR: Number of persons for the crew.

GT: Gross tonnage of the vessel. It also depends on the forms and dimensions of the ships (Tonnes)

PB: Propulsion power per vessel (HP)
L: Length of the vessel (in meters)
B: Breadth of the vessel (in meters)
D: Depht to upper deck (meters)
NLE_n: Number of shaft lines of the vessel. It is a consequence of the optimization. The different arrangements for the engine room of the vessel (dependent on the necessary propulsion power, dimensions of the vessels, etc.) will determine the most suitable case (N).

Despite the numerous controllable variables handed in the model (150 without taking into account the data) only 8 of them have been identified as no dependent (main variables). The main variables optimized will be able to define 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 (Rawson et al 2001, Alvariño R.et.al, 1997).

The discrete main variables are the age of the vessels E_e (in the cases EE) and the variables shown in the figure 2 (where the different cases for them are collected in PP, Q, B, G). In addition to this, the continuous main variables are:

G_2: Necessary cargo capacity of the vessel (in cargo units).
VB: The speed of the vessel (in knots).
NB: Number of vessels of the fleet (in units).

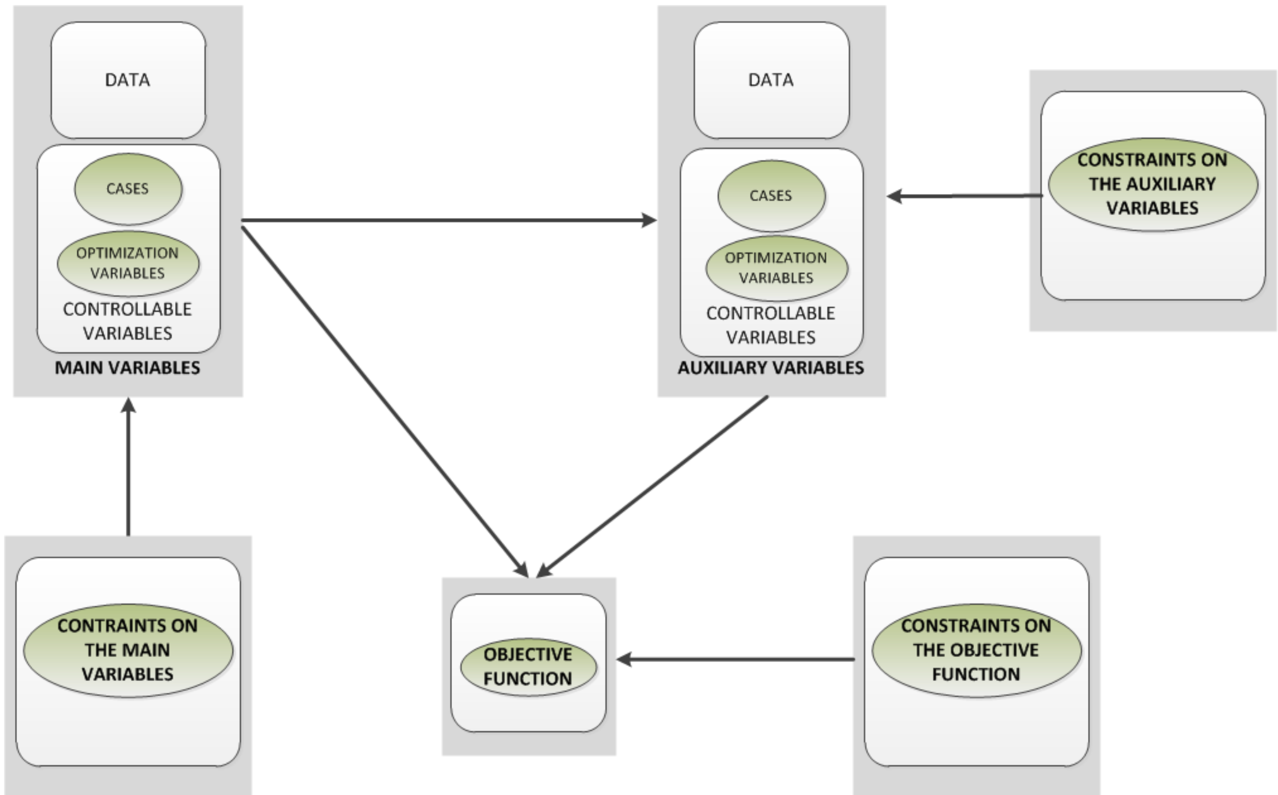

Figure 1: Integration of the variables in the optimization model

The discrete main variables are the age of the vessels E_e (in the cases EE) and the variables shown in the figure 2 (where the different cases for them are collected in PP, Q, B, G). In addition to this, the continuous main variables are:

G_2: Necessary cargo capacity of the vessel (in cargo units).
VB: The speed of the vessel (in knots).
NB: Number of vessels of the fleet (in units).

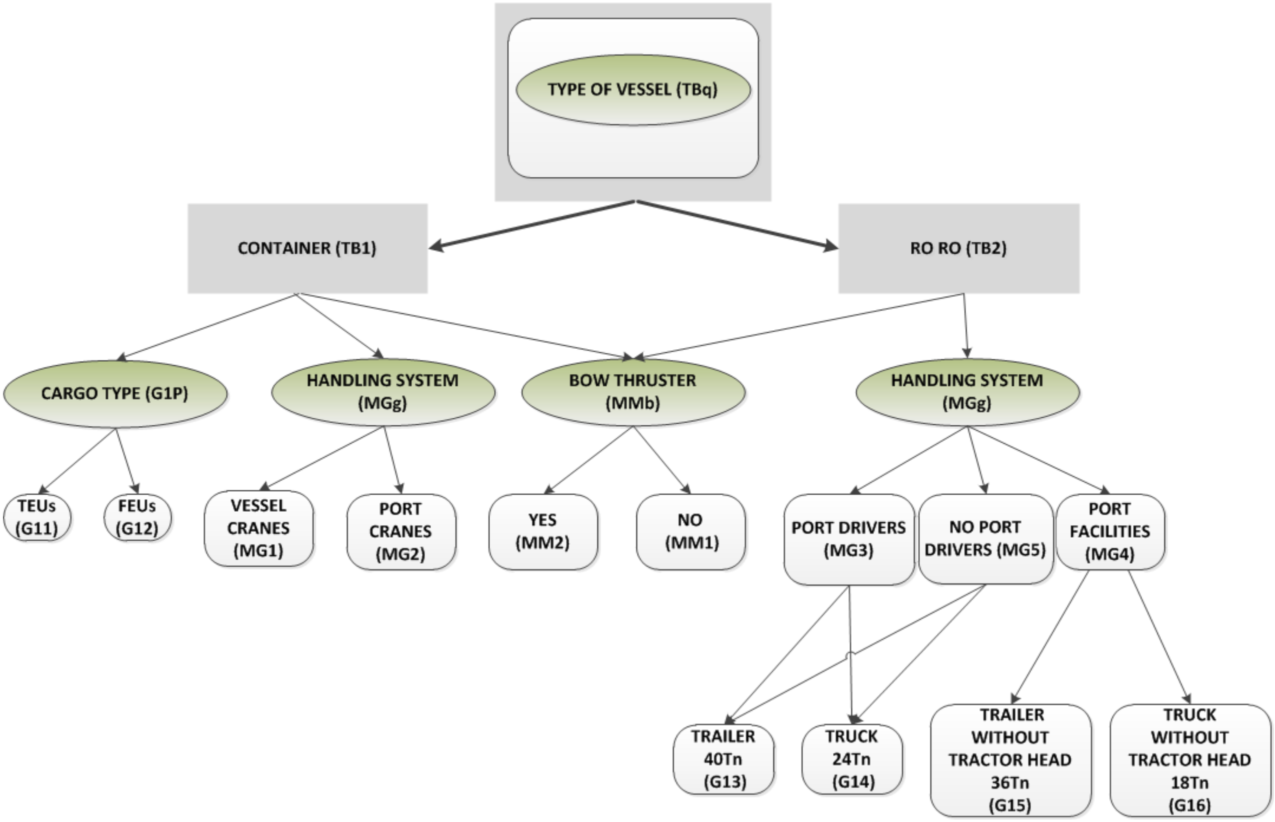

Figure 2: The discrete main variables

Once the mathematical model has been defined the optimization process is performed. From the analysis of the nature of the model we can conclude that it is a nonlinear problem with numerous nonlinear constraints either. This is a problem by itself in the optimization process through the analytic techniques. For this reason the selection of the suitable algorithm is not obvious.

The optimization problems are very frequent in real problems of engineering and logistics. For this reason the use of optimization algorithms for the resolution of them are very often from the 90's. Since that decade the quick development of the computer capacity allowed the efficient application of the Evolutionary Computation (reasonable computing time). The application of these algorithms is especially successful to problems where it is necessary the optimization of nonlinear functions with nonlinear constrains (most of real problems). This is so because their resolution through the no evolutionary algorithms is not usually effective enough (Caamaño, 2010); the algorithm tends to find local maximum or minimum (no global solutions).

Under these conditions, non linear objective functions and non linear constraints, the evolutionary algorithms work adequately in terms of the efficiency and effectiveness, specially when the topographical features of the search space is not known (as in this case). Among the evolutionary algorithms the differential evolution has been selected mainly due to two reasons: the goodness of its behaviour in the optimization of the nonlinear problems tested in optimization competitions and its wider application to engineering problems (Chang, 1998, Storn, 1996). The implementation of the Differential Evolution used in this work is available at JEAF (Caamaño et al., 2010).

However, the comparison of the results obtained to the optimization by other algorithms is recommended in order to test the solutions. Hence, a non evolutionary algorithm selected has been Trust-Region-Reflective Optimization (implemented in a function of the MATLAB library) because this algorithm is able to work with nonlinear functions (Coleman et al., 1994, Coleman et al., 1996). In addition to this, it has already been used in engineering problems to compare the results obtained by other optimization algorithms.

4. THE MATHEMATICAL MODEL

The mathematical model has been formulated taking into account that the main objective of the paper is to find the best option of fleet which articulates the most competitive multimodal chains against the road. Therefore the optimization aim is to maximize the difference in cost of the road transport regarding the multimodal chains per tonne and per travel (from one origin to one destination).

Previous studies about the decision criteria for the transport mode indicate that the preference on the time against the cost for small volume of production is obvious, but up to a value. This depends among other factors on the value of the cargo and the distance of the transport (Nellthorp et al., 2001, TRACE, 1999; TRA2006-09939 Project, 2009). Hereby a minimum difference in time between both transport systems will be assumed as enough to keep the interest of the cargo owner in the multimodal chain. Hence this time difference (favourable for the multimodal chain) will be introduced in the model as a constraint (RR13 in table 2).

Due to that the whole model is very wide (many variables and combination of cases are analyzed) only the objective function and the restrictions will be shown (in a summarized way) with their relationships with some data, auxiliary variables and main variables.

The objective function is:

$$F_1 = \max(CU - CMU)$$

Where the cost per Tonne and per travel for the unimodal transport system (CU) and the multimodal transport system (CMU) have been measured as $\frac{€}{Tn\ \text{travel}}$.

$$CU = \left(\sum_{d=1}^{3} (X_d \times DR_d^V)\right) \times \left(\frac{C_{4,p}}{P_p}\right) \qquad \forall \mathrm{p} \in \mathrm{PP}$$

$$CMU = CMU_1 + CMU_2$$

The multimodal cost integrates the cost of the road stretch (CMU_1) and the maritime stretch (CMU_2).

$$CMU_1 = \left(\sum_{d=1}^{3} (X_d \times DR_d^{St})\right) \times \left(\frac{C_{4,p}}{P_p}\right) \qquad \forall \mathrm{p} \in \mathrm{PP}$$

$$CMU_2 = \left(\sum_{c=1}^{12} (CT_c)\right) \times \left(\frac{1}{G_3 \times P_p \times N}\right) \qquad \forall \mathrm{p} \in \mathrm{PP}$$

The cost of the maritime stretch takes into account all the necessary costs (CT_c) for the calculation of the minimum required freight (to achieve the even point). These considered costs have been (Pereira, F. et al., 2007, Hunt and Butman,1995, Pardo, M. ,2009 among others) the capital costs, fixed direct costs and variable costs. The formulation used has been taken from other studies and the information provided by service companies and Port Authorities, European normative and National rules. It has afterwards been evaluated and fitted by comparison with real values (provided by shipowners, maritime companies and shipyards).

Capital costs have been calculated as the addition of the amortization cost (CT_1) and the loan cost (CT_2), considering a 'usual mortgage' in the Spanish Naval building (Cervera, V., 2009).

$$CT_1 = CC \times \frac{100\% - R_1}{A_2} \times NB$$

$$CT_2 = [(R_4 \times CC) - (E_e - 1) \times (CC \times R_4) / A_1] \times R_2 \times NB \qquad \forall e \in EE$$

The fixed direct costs have been insurance cost (CT_3) which varies along the cycle life of the vessel, (Sáez Parga ,1977, Morán F.,1995)., maintenance costs (CT_4) (Morán, 1995, Stopford, M., 2009, Hunt and Butman, 1995)and personal cost (CT_5) (Pardo, ,2009, Wijnolst, 2009). Here the relationships between these costs and different variables are shown:

$$CT_3 = f(CC, E_e, R_1, A_2, NB, TPM) \qquad \forall e \in EE$$

$$CT_4 = f(CC, E_e, NB) \qquad \forall e \in EE$$

$$CT_5 = f(C_3^f, C_3^s, NB, NTR)$$

The variable costs: fuel cost (CT_6) (Polo G., 2000 , Baird, N., 1999, Rowen, A., 2003) dockage dues in port (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}). The port dues have been calculated taking into account the information provided by the Port Authorities and the Port Normative of the countries (BOE nº311, 23 December, 2011). The loading/unloading costs have been determined considering the maximum prices limited by the national normative (in Spain 'Ley de Puertos 33/2010').

$$CT_6 = PB \times \frac{DT_1}{DT_2} \times C_3^c \times TVB_1 \times N$$

$CT_7 = f(TIE, N, GT, R_{5,q}) \qquad \forall q \in Q$. (see figure 2)

$$CT_8 = f(N, G_3, C_{2,p}^c, R_{6,q}) \qquad \forall q \in Q \wedge \forall p \in PP$$

$$CT_9 = f(C^c, N, GT)$$

$$CT_{10} = f(C_1^c, N, GT, MM_b, L) \qquad \forall b \in BB$$

$$CT_{11} = f(N, GT, C_2^c)$$

$$CT_{12} = f(N, G_{3,} C^{c4}_{2,p}, MG_g) \qquad \forall p \in PP \wedge \forall g \in G$$

Otherwise, the constraints of the model are shown in the table 2. Until R9 the constraints are applied to the auxiliary variables to ensure the technical feasibility of the vessels. The constraints RR10 and RR12 are necessary to meet the minimum amount of cargo units per year and the frequency of service demanded by the Normative of Sea Motorway (BOE Nº265, 2006). The restriction RR11 ensures that the vessels do not reach the condition of High Speed Craft (High speed Craft Code MSC 36(63) and SOLAS, chapter X). This is no desirable according previous studies (INECEU project, Castells M, 2009, SPIN-HSV,2005). The restrictions RR13 and RR14 show the competitiveness of the multimodal routes articulated through this maritime route which could be reached operating with a ro ro vessel with cargo capacity of 157 trailers at 30 kn (Martínez et al., 2011).

Table 2: Constraints applied on the model

Number	Constraints
RR1	T < 10
RR2	FB > Fbm
RR3	NC or NV >= G2
RR4	Minimum B
RR5	Minimum D for container
RR6	L/B
RR7	B/D
RR8	L/D
RR9	B/T
RR10	740≥N ≥384
RR11	$VB<(3.7\times\nabla^{0,1667}/0.514)$
RR12	Minimum G2×N
RR13	(TVU-TVM)/(TVM+TVU) ≥ 0.10
RR14	(CU-CMU)/(CMU+CU)≥0.14
RR15	TVB≤NB×12

Time of the unimodal transport per travel (TVU) has been estimated in hours considering the European Normative about 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):

$$TVU = \sum_{d=1}^{3}(X_d \times \left[E\left[\frac{E\left(\frac{DR_d^V}{9\times V_3}\right)\times 0.75 + \frac{DR_d^V}{V_3}}{9}\right]\times 24 + \left[\left(\frac{E\left(\frac{DR_d^V}{9\times V_3}\right)\times 0.75 + \frac{DR_d^V}{V_3}}{9}\right) - E\left[\frac{E\left(\frac{DR_d^V}{9\times V_3}\right)\times 0.75 + \frac{DR_d^V}{V_3}}{9}\right]\right]\times 9 \right])$$

The time of the multimodal transport (TVM) per travel (measured in hours) has considered the maritime and land stretches:

$$TVM = TVB + TVC$$

The expression for the time invested in the road stretch is the same as in the unimodal transport's but the road distances are different:

$$TVC = \sum_{d=1}^{3}(X_d \times \left[E\left[\frac{E\left(\frac{DR_d^{St}}{9\times V_3}\right)\times 0.75 + \frac{DR_d^{St}}{V_3}}{9} \right] \times 24 + \left[\left(E\left[\frac{E\left(\frac{DR_d^{St}}{9\times V_3}\right)\times 0.75 + \frac{DR_d^{St}}{V_3}}{9} \right) - E\left[\frac{E\left(\frac{DR_d^{St}}{9\times V_3}\right)\times 0.75 + \frac{DR_d^{St}}{V_3}}{9} \right] \right] \times 9 \right])$$

Otherwise the time invested in the maritime stretch has been calculated as the addition of the time for the travel (TVB_1), the loading/unloading time (TVB_2)information provided by the Stowage Society of the Vigo port and the berthing time in port (TVB_3).The formulation for the calculation of the loading/unloading time (Ametller, X. ,2007) collects the information provided by Stowage Societies of the ports and consignee companies.

$$TVB = \sum_{t=1}^{3} TVB_t$$

$$TVB_1 = DM / (VB \times 1{,}85)$$

$$TVB_2 = f(TB_q, MG_g, G_3, V_{2,g}, L, U_g) \qquad \forall q \in Q \wedge \forall g \in G$$

$$TVB_3 = f(L, MM_b, NLE_n, TI_1, TI_2) \qquad \forall b \in BB \wedge \forall n \in NN$$

5. RESULTS FROM THE OPTIMIZATION

For the optimization of the model proposed in the previous section, in this work we have applied two different methods: an evolutionary algorithm and a local search algorithm. Their description, the results obtained by them and a comparison of these results are explained in the following subsections.

5.1. Optimization with Evolutionary Algorithms

Evolutionary Algorithms have shown good performance after its application to engineering problems which are multimodal, ill conditioned and where the search spaces are not known “a priori”. For that reason, in this section we will apply an Evolutionary Algorithm to try to solve the proposed problem.

A Differential Evolution algorithm (DE) (Storn et al, 1996) was used to solve the proposed problem. As we are dealing with a constrained problem, a penalty-based method was used to calculate the fitness value of the solutions. The fitness value is used to measure the goodness of a solution during the evolutionary process. The penalty-method used in this work is based on the one developed by Coello (Coello et al., 2003, Mezura et al., 2009) where the penalty amount is calculated from the amount of constraint violation of the specific solution using the following equation:

$$\phi(\vec{x}) = \alpha(t)\left[\sum_{i=1}^{n} r_i G_i + \sum\nolimits_{j=1}^{p} c_j L_j\right]$$

Where α is an annealing function which determines the amount of penalty at each generation t. In this work a linear annealing function was implemented. In this case at the beginning of the evolution the solutions receive a low penalty value and the amount of penalty increases as the generations pass. This strategy allows the exploration of the whole search space at the beginning of the evolution and it allows avoiding the premature convergence of the DE. G_i and L_j are functions of the inequality and equality constraints, respectively, as it can be seen in Table 4.

Table 3: Differential Evolution and Constraint Handling method parameters.

Operator	Parameter	Value
Mutation	Base Strategy	Random
	Number of vectors	1
	F	0.9
Crossover	Type	bin
	CR	0.9
Constraint Handling Method	α	$2.2 - \frac{t}{0.8 \cdot t_{max}}$
	r	100.0
	G_i	$[max(0, g_i(\boldsymbol{x}))]$
	c	1
	L_j	$\lvert h_j(\boldsymbol{x}) \rvert$

Figure 4 shows the evolution of the mean fitness value of the 30 independent runs. The value represented in this graph corresponds to the mean fitness value of the best individuals at each generation on each run. Also the standard deviation is represented, the high values of it are due to the high differences between the fitness value when the solution is a container fleet and when it is a ro ro fleet. The best container fleet obtains a fitness value of 68.10 units against the best ro ros fleet which fitness value is 34.50 units (see Table 5)

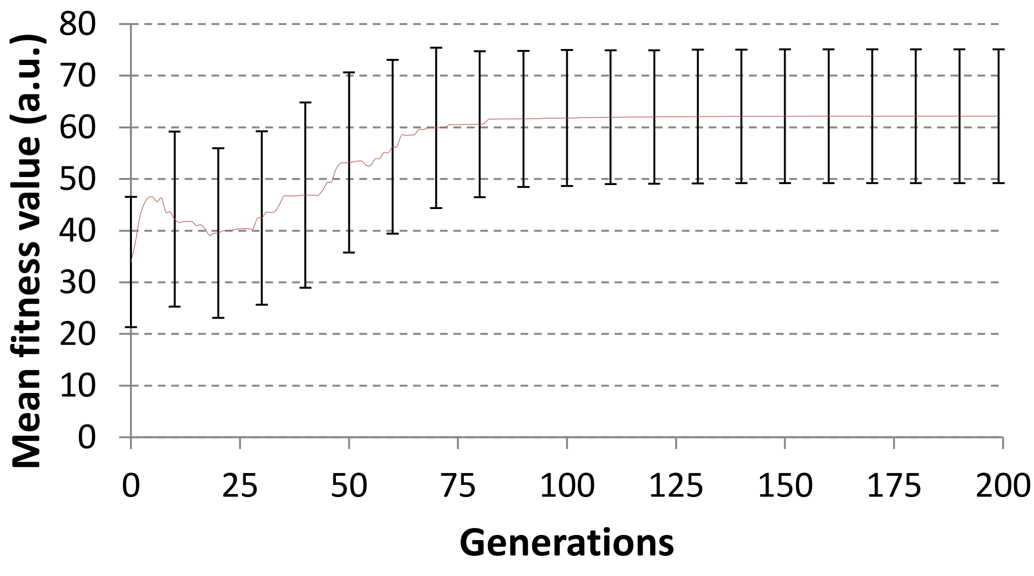

Figure 3: Mean fitness value of the best individual fitness of the 30 independent runs at each generation.

As can be seen in the results obtained the container fleet is the most competitive in terms of the cost and the same solutions have been achieved with evolutions of mixed fleet and with container fleet only.

The difference in time between the ro ros and container fleets is small in comparison to the cost difference. This is so in spite of that the number of units is quite higher for the container than the ro ro and this is according to the results achieved by Mbiydzenyuy, et al., (2010). Otherwise the better arrangement of the cargo space in the containers leads to smaller vessels and with smaller costs (capital costs and variable costs).

Table 4: The best solutions for the optimization through 'Differential Evolution' algorithm

Tests	**Containers**	**Ro ros**
Solutions	**Solution 1**	**Solution 2**
Type of vessel	**Containers**	**Ro-ro**
Kind of cargo unit	TEUs (G11)	Truck without tractor head (G16)
Amount of cargo units	210	162
Vessel speed (kn)	20.18	23.71
Age of the vessels	14	14
Bow thruster	NO (MM1)	YES (MM2)
Cargo handling system	Port Cranes (MG2)	Port facilities (MG4)
Number of vessels	3	3
Number of yearly travels	740	740
L (m)	95.32	123.91
B (m)	15.00	21.74
D to upper deck (m)	7.59	13.63
GT	2736	9977
Kind of propeller	Conventional screw (TP1)	Conventional screw (TP1)
Number of shaft lines	1	2
Kind of main engines	Diesel engine (TMM1)	Diesel Engine (TMM1)
Number of main engines	1	4
Competitiveness of the fleet		
CU-CMU (objective function)	68.10	34.50
TU-TMU	8.39	10.18

It is important to point out that despite the approach to the problem is different (the number of vessels and the route are different among many other aspects) the best solution achieved for the Ro ro is quite close to the solution obtained by Ametller, 2007. The vessels proposed as the optimum ones were of 9500 GT and in this case they are of 9977 GT (see table 5).

The results obtained also confirm that it is not necessary to reach a high speed to operate in competitive conditions for time (Castells i Sabra, 2009, SPIN-HSV,2005). In fact in this case it is no necessary to reach the 28 kn of speed for the vessel recommended in other studies (EU-Cargo Express, 2009, WEST MOS, 2008). However the thresholds for the speeds are the same as the recommended one by Castells i Sanabra, 2009 (23 kn) and by the EU-Cargo Express, 2009 (20 kn) in the case of containers. This leads to usual arrangements for the engine rooms of the vessels (avoiding the use of turbines and waterjets which rise the building cost of the vessels and theirs operative costs).

Among of that, these results confirm the importance of the speed in the loading operations in port for the competitiveness of the short sea shipping (Martínez et al, 2011, Castells, 2009) and therefore the high influence of correct sizing of the cargo capacity of the vessels (which condition the port time). This importance rises when the maritime distance decreases, and therefore the size of the fleet will be critical in order to keep the competitiveness of the multimodal chains through Sea Motorways.

The cargo units that maximizes the competitiveness of multimodal chains for both types of fleet are, as expected, the smallest units studied. This is so, because in the multimodal transport this kind of cargo units can take advantage of the effects of the scale economy during the maritime stretch.

5.2. Optimization with a Local Search Algorithm

In order to validate the results obtained by the DE algorithm, in this work we have used a Local Search Algorithm to perform the optimization of the model proposed in Section 4. The selected algorithm has been 'Trust-Region-Reflective Optimization' based on the interior-reflective method of Newton (Coleman et al., 1994, Coleman et al., 1996).Each iteration involves the approximate solution of a large linear system using the method of Preconditioned Conjugate Gradients (PCG).The algorithm has been used through the function of the MATLAB library: 'fmincon', able to hand nonlinear constraints.

For the optimization of the problem 1000 independent runs were performed. Each of them begins the search process at a random point of the search space. A first analysis of the results obtained was done to check the probability to reach valid solutions (effectiveness) through it has been evaluated. Every independent run has been analyzed taking into account the number of constrains violated (see figure 5). As it can be seen, there are not container vessels that satisfy all the constraints, i.e., the algorithm used in this work is not able to find a valid container vessel. According to the ro ro fleets, only the 3.69% of the solutions are valid. Therefore we can conclude that the effectiveness of the algorithm is very low.

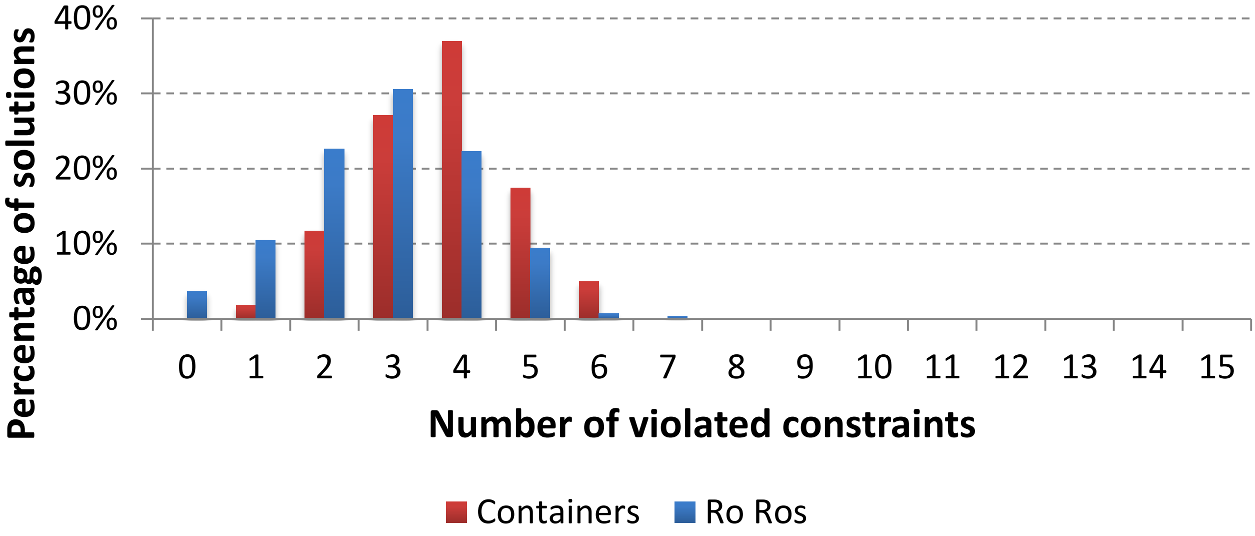

Figure 5: Percentage of solutions found with the algorithm Trust-Region-Reflective Optimization in terms of the violated constraints.

The valid solutions obtained have been two ro ros. All of them with a fitness value lower than the best solutions achieved through the evolutionary algorithm (see Table 5**Error! Reference source not found.Error! Reference source not found.**).

Table 6: Valid solutions through the algorithm Trust-Region-Reflective Optimization

Cargo units (G2)	Travels /year (N)	Speed vessel (VB)	Obj. Func. (F1)	Nº vessel (NB)	Gross Tonage (GT)	Age of vessel (Ee)	Type of vessel (TBq)	Bow thrusters (MMb)	Type of cargo unit(G1)	Cargo handling system (MGg)
313	740	26.95	26.55	3	25115	14	Ro ro	yes	Truck	No port drivers
207	740	25.38	13.55	3	21998	6	Ro ro	yes	Trailer without tractor head	Port facilities

As we have observed in the results, this algorithm has very few probabilities to reach a valid solutions and the fitness of this solution presents very low values.

As it can be seen, the DE algorithm is able to obtain valid solutions for the two types of fleets. In addition to this the DE results outperforms the Trust-Region-Reflective results for the roro fleet (higher fitness values).

Afterwards the optimization with the two methods, in order to try to improve the solutions obtained by the DE algorithm, the Trust-Region-Reflective Optimization method was again applied but using as a starting point the best solutions obtained by the DE, the best container fleet and the best ro ro fleet. After these executions the solutions were not improved. Therefore we can assume that these results are the best solutions that the algorithms can obtain.

6. CONCLUSIONS

The influence of the vessels features in the competitiveness of the multimodal chain is relevant, especially for the chains articulated through the Short Sea Shipping where the port times have a higher relative weight. However in many occasions the vessels have been taken as rigid elements adapting the feasibility of the route to the available fleet.

In this paper we try to adapt the fleet to a Sea motorway in order to maximize the competitiveness of the multimodal chains articulated through it against the road option. For this an optimization model has been developed taking into account that the final client is the owner of the load and the influence of the features of the vessel on the invested time and cost in the transport.

The mathematical model has integrated 150 different variables (continuous and discrete) need to define technically and operatively the fleet of vessels. And therefore all of them have been obtained in the optimization. These parameters have been classified as main and auxiliary according to their role in the optimization model. The formulations used in the model have included information and data provided by previous publications, companies, normative, port authorities and public institutions. Once defined all the relationships between variables, objective function and constraints we can conclude that only eight variables are not dependent and are also controllable.

Due to the difficulties for the operation of the Sea Motorway: Vigo-St.Nazaire (despite the numerous reports which support its feasibility) this one has been considered as an example for the application of the model and its optimization.

For this, 15 constraints have been applied to the model. Ten of them ensure the technical feasibility of the vessels and five are necessary to meet all the requirements of service demanded by the Normative.

Therefore the optimization problem obtained is characterized as nonlinear with nonlinear restrictions. Therefore for its resolution an evolutionary algorithm: Differential Evolution has been applied and its effectiveness and efficiency has been evaluated in comparison to the results obtained by other algorithm: Trust-Region-Reflective Optimization. The validation of the results showed that the Differential Evolution has been suitable for the resolution of this optimization problem.

From the analysis of the optimization process we can point out that it is extremely difficult to find container fleets which are able to articulate multimodal chains meeting the minimum savings in time demanded (constraint RR13). This is mainly due to the high cargo capacity of these vessels; this means wide port times per vessel. Opposite to this it happens with the meeting of the minimum saving in cost demanded (constraint RR14). In this last case it is complicate to find a competitive ro ro fleet in terms of the cost against the container fleet.

Despite of this, the evolutionary algorithm was able to find a container fleet with vessels of 210 TEUs of cargo capacity as the best solution (in cost for both kinds of vessels). On the other hand the most competitive ro ro fleet achieved has vessels with cargo capacity of 150 trucks without a tractor head. The difference between both fleets is relevant in cost (the ro ro cost is near twice times higher than the container fleet cost).

Otherwise the difference in time is quite small between both types of fleets (the ro ro fleet is faster with an advantage of less of two hours). Nevertheless the required speed for the shipping is not as high as expected in this route (28 kn) for any fleet, and it is closer by type of vessel to generalist estimations provided by previous studies. This shows again the high importance of the time invested in the cargo operations for SSS traffic.

It is also remarkable that the type of cargo units selected has been the smallest for each kind of vessel. Despite this parameter being no controllable by the transport responsible, this data can help to focus the client searching.

Finally to note that the Gross Tonnage (GT) obtained for the vessels of the ro ro fleet is very close to the results obtained for the optimization of the ro ro fleet to cover Barcelona- Civitavecchia (despite the approaching to the problem is different). However the cargo capacity estimated for container liner service for SSS provided by EU-Cargoxpress, 2009 (150 TEUs) is quite different than the one obtained in this paper.

This confirms the risk taken when technical and operative assumptions are applied to the multimodal transport without paying attention to the relationships which there are among them. Therefore it would be interesting to analyze the results of the optimization of the fleet for different maritime routes in order to meet common and non common points and so to provide wider conclusions.

REFERENCES

Ametller, X. (2007). Optimización del transporte de mercancías mediante tráfico maríti-mo de corta distancia. Tesina del Departamento de Ingeniería del transporte de la Universidad Politécnica de Cataluya.

Baird, N. (1999). Marine engines and Propulsion systems. Baird Publications.

Bases reguladoras de las Autopistas del mar entre España y Francia (2006). Boletín oficial del estado español nº 265. [WWW] URL:http://boe.es [Accessed 30 November 2009]

Caamaño, P., Tedin, R., Paz-Lopez, A., and Becerra, J.A. (2010) JEAF: A Java Evolutionary Algorithm Framework. In Proceedings of IEEE Congress on Evolutionary Computation, 2010, 1-8.

Caamaño, P. (2010). Caracterización de espacios de calidad y algoritmos evolutivos en problemas de optimización con codificación real. PhD. Departamento de computación. Universidade de A Coruña.

Castells, M. (2009). Short Sea Shipping efficiency analysis considering high-speed craft as an alternative to road transport in SW Europe. Thesis. Departamento de Ciencia e Ingeniería náuticas de la Universidad Politécnica de Cataluña.

Castells, I. and Sanabra, M. (2009). Short Sea shipping efficiency analysis considering high-speed craft as an alternative to road transport in SW Europe. Tesis. Departamento de Ciencia e Ingeniería náutica de la Universidad Politécnica de Cataluya.

Cervera, V. (2009). Matemática financiera. Economía del sector marítimo. Apéndice 3. Instituto Marítimo español. Fondo editorial de Ingeniería Naval.

Chang, T. and Chang, H. (1998). Application of fiferential evolution to passive shunt harmonicfilter planning. In 8th International Conference on Harmonics and Quality of Power, 1998.Proceedings, volumen 1.

Coello, C. (2002). Theorical and numerical constraint handling techniques used with evolutionay algorithms: a survey of the state of the art. Computer methods in apllied mechanics and Engineering, 191 (11-12):1245-1287.

Coleman, T. F. and Li, Y.(1994). On the convergence of reflective newton methods forlarge-scale nonlinear minimization subject to bounds. Mathematical Program-ming,67(2):189–224, 1994.

Coleman, T. F. and Li Y. (1996). An interior trust region approach for nonlinear minimi-zation subject to bounds. SIAMJournal on Optimization.,6,(1996), 418-445.

EMMA study. 1996-1998 European Marine Motorways, the potential for transferring freight from road to high speed sea transport system. IV Framework Programme of the European Commission.

EU-CARGOXPRESS. VII Framework Programme of the European Commission (2009-2012). [WWW] <URL:http:// cargoxpress.eu/Presentation.htm> [Accessed 12 July 2010]

Feo, M. and García L. (2006-2009). TRA2006-09939: Desarrollo del transporte marítimo de corta distancia: soluciones para la creación de Autopistas del mar. Ministerio de Educación y Ciencia en el (CICYT 2006-2009)

Hunt, E. and Butman, B. (1995). Marine engineering economics and Cost Analysis. Cornell Maritime Press.

IN HO TRA. Integration of interoperable Intermodal horizontal transshipment techniques in in-termodal transport operators (2001-2004). V Framework Programme of the European Commission. [WWW] <URL:http://transport-research.info/> [Accessed 10 March 2010]

INTEGRATION Integration of Sea Land technologies for an efficient door to door intermodal transport.. 2001-2005. V Framework Program me of the European Commission. Obtenido a través de internet: http://cordis.europa.eu/

Jiang, F., Johnson, P. and Calzada, C. (1999). Freight demand characteristics and mode choice: and analysis of the results of the modeling with disaggregated relevant prefe-rence data. Journal of Transportation and statics, 2,pp 149-158.

Martínez, A. and Alonso, L. (2011). Assessment of the competitiveness of intermodal routes for the case of Spanish French atlantic coasts. Proceedings of European Conference on shipping Intermodalism and Ports. ECONSHIP 2011.

Martínez, F. X. and Olivella, J. (2005). Short Sea shipping opportunities for the Pyre-nean cargo flows. Journal of Maritime Research, 2-II, pp 65-80.

Martins, T., Lobo, V. and Vairinhos, V. (2009). Container Stowage Problem Solution for Short Sea Shipping' Proceedings of 14º Congresso da Associação Portuguesa de Análise Operacional, Universidade Nova de Lisboa,

Mbiydzenyuy, G.,Persson, J. and Henesey, L., (2010).'A decisión support Method for analysisng a short sea shipping link from a port infraestructura perspective'. Proceedings of 2010 Annual Conference of the International Association of Maritime Economists.

Mezura Montes, E. (2009). Constraint handling in evolutionary optimization. Sprin-gler Publishing Company, Incorporated.

Morán, F. (1995). Los costes de explotación del buque. Colegio Oficial de la Marina Mercante española.

Nellthorp, J., Sansom, T., Bickel, P., Doll, C. and Lindberg, G. (2001). Valuation conventions. UNITE.ITS, University of Leeds

Olivella Puig, J., Martínez de Osés, J. and Castells Sanabra, M. (2004). Intermodalidad entre España y Europa, el proyecto INECEU. Research group TRANSMAR, Departamento de Ciencias e Ingeniería náutica. Universidad Politécnica de Cataluña.

Pardo, M. (2009). La cuenta de explotación del buque. Economía del sector maríti-mo. Capítulo 7. Instituto Marítimo español. Fondo editorial de Ingeniería Naval.

Pereira, F., Ballarín, E., Rosanas, J. and Grandes M. (2007). Contabilidad para dirección. 22 nd edition, EUNSA.

Polo, G. (2000). Sobre la estructura de costes en el transporte marítimo en España. Estudios e investigaciones marinas, vol. 1, nº 1(27-45).

Port Authority of Gijón (2009). Annual report 2009. Gijón. Spain. [WWW] <URL:http://puertogijon.es > [Accessed 12 October 2010]

Port Authority of Vigo (2009). Annual report 2009. Vigo. Spain. [WWW] <URL:http://apvigo.com> [Accessed 12 October 2010]

PSA Peugeot Citroen Vigo data. [WWW] <URL:http:// vigo.psa-peugeot-citroen.com > [Accessed 1 January 2011]

Rowen, A. (2003). Machinari considerations. Ship Design and Construction Vol.1, Ch.24.The Society of Naval and Marine engineering.

Sáez Parga, A. (1977). Buques de cabotaje. Estudios de rentabilidad y economía de su explotación Ingeniería Naval. nº510,

SPIN-HSV: Shipping quality and safety of High Speed Vessels 2003-2005. IV Framework Programme of the European Commission for Research and Development.

Stopford, M. (2009). Maritime economics. Third edition. Routledge.

Storn R. (1996). Differential evolution Design of an IIR-Filter. Proceedings of the IEEE International Conference on evolutionary Computation, pages 268-273.

TRACE (1999). Elasticity handbook: elasticities for prototypical contexts. Prepared for European Commission Directorate General for transport. Contract Nº RO 97-SC2035.

Triunfante, P., Moura, A., Andrade-Campos, A. and Lobo V. (2010). Genetic Algorithms approach for containerships fleet management dependen ton cargo and their deadlines. Proceedings of 2010 Annual Conference of the International Association of Maritime Economists.

UK Marine Motorways Study (2002-2003) Engineering & Fisical sciences Research coun-cil (EPSRC) and UK Department for Transport Dft. Dft LINK Future Integrated Transport (FIT) Programme.

WEST-MOS Project: Western Europe Sea Transport & Motorways of the Sea Project. (2005-2008). co-financed by the European Union from the Trans-European Networks (TEN). [WWW] <URL:http:// westmos.eu > [Accessed 3 March 2011]