Abstract

This contribution investigates the economic benefits of using weather ship routing on Short Sea Shipping (SSS) activities. The investigation is supported with the development of a ship routing system based on pathfinding algorithms, the parametrization of the wave effect on navigation and using high-resolution meteo-oceanographic predictions. The optimal ship routing analysis is investigated in a European SSS system: the link between Spanish and Italian ports. The results show the economic benefits using ship routing in SSS during energetic wave episodes. The rate of costs savings may reach the 15% of the total costs under particular bad weather conditions in the navigation area. The work establishes the basis of further developments in optimal route applied in relatively short-distances and its systematic use in the SSS maritime industry.

Keywords: Ship routing; pathfinding algorithms; Short Sea Shipping; cost reduction; wave effect on ship; A*

Introduction

Short Sea Shipping (SSS) accounted for 1.8 billion tones (Eurostat, 2017) in European Union (EU). SSS made up to 59% of total maritime transport of goods (in tone-kilometer) to and from the main ports within the EU. Looking at the Mediterranean scenario, the SSS of goods between main EU ports and ports located in this basin came to 582 million tons in 2015. This means nearly 29% of the total EU SSS tonnages for all sea regions in the same year. In terms of tonne-kilometer, still in 2014, road freight transport accounted for a share of 75.3%. Although SSS is overwhelmingly superior to all other transport modes in terms of fuel consumption and expenditure, the need to reduce further the quantity of consumed fuel remains strong due to the detrimental influence of the marine fuel quality on climate change and local air quality. From the shipping industry point of view this may be achieved with the design of ship route scheduling (Fagerholt and Lindstad, 2007; Fagerholt and Ronen, 2013), ship energy and efficiency (Longva *et al*, 2010) and weather routing (Simonsen *et al*, 2015). Academic research has focused the weather ship routing optimization through pathfinding algorithms (e.g. Takashima *et al*, 2009; Mannarini *et al*, 2013; Szłapczyńska and Śmierzchalsk, 2009; Larsson and Simonsen, 2014 or Hinnenthal and Günther, 2010) which take into account the meteo-oceanographic forecasts. Some of these contributions have been tested through a "proof-of-concept" based in oceanic distances (e.g. Simonsen *et al* 2015). However, at short-distances (for instance in the framework of the SSS activity) the application of ship weather routing and the derived economic benefits is not yet fully investigated. In this case, historically the spatial resolution of the meteo-oceanographic predictions (grid resolution of the weather forecasting model) was a severe restriction to design feasible ship routing at short distances.

The objective of this contribution is to assess the economic benefits of weather ship routing in SSS routes. In particular, the analysis focus on the SSS connection between Eastern Spain and Italy (Western Mediterranean Sea). The economic benefits can be estimated through the time saving and its implications in fuel consumption and additional costs. The saving cost is computed through the minimization of sailing time using the implementation of a shortest path algorithm. The benefit of using weather ship routing is compared with the minimum distance ship routing without the consideration of wave effects in the navigation. Wave predictions of a high resolution numerical model are used to evaluate the added resistance due to waves.

This contribution is organized as follows. After the Introduction (Section 1), in Methods (Section 2) the pathfinding algorithm is presented, the waves effect in navigation, the scenarios considered (bad weather episodes) and the methodology to estimate the cost of navigation. Section 3 (Results) shows the results of the application of the method at three selected routes. The scenario described in this paper is focused in the sea connection between Italy and Spain, which is an example of successful implementation of the concept of SSS. Thus, the intra-European trade link between Valencia – La Spezia (case 1), Barcelona – Livorno (case 2) and Alicante – Livorno (case 3) are chosen to examine the economic benefit of using weather ship routing. Finally, the discussion, conclusions and future works are highlighted in Final Remarks (Section 4).

Methods

Ship Routing Algorithms

The implementation of ship routing produces multi-objective problem which involves parameters such as the expected time of arrival (ETA), risk minimization or fuel consumption. The first generation of weather routing algorithms were focused to reduce time of navigation (Spaans, 1986) but more recently there are concerns on competitiveness, consumption and emissions reduction (for instance Vettor and Soares, 2015). This leads to a multi-criteria problem solved which may be solved with advanced optimization algorithms (e.g. NAMOA, genetic algorithm, etc.). In this sense, most of the ships are equipped with weather routing systems to plan a route with the lowest fuel consumption while arriving with certain time slot or storm avoidance (Simonsen *et al*, 2015). However optimization techniques are not always systematically used in ship routing design. Research based on the routing and scheduling of ships shows a growing in the number of contributions in last years (Christiansen *et al* 2013), dealing with a broad area from distribution problems to fleet deployment or weather routing, inter alia.

In the framework to assess the impact of the ship routing in short routes, preliminary tests in the route Barcelona-Palma de Mallorca (Spain) were carried out in Grifoll (2016) comparing the solution of A* algorithm (Dechter and Pearl, 1985) with well-known Dijkstra algorithm (Dijkstra, 1959). Results obtained using both algorithms were the same but A* algorithm presented a significant reduction of the computational time due to a decreasing number of nodes opened. Due to this, the pathfinding algorithm used in this work is the A* Algorithm. This algorithm is applied at gridded scheme where each gridpoint (node) is connected to a set of vicinity points. To each connection (edge) a weight related with the distance is assigned. The great circle (orthodromic) track is used for the spherical coordinates of the grid nodes even that navigation in short distances use to be through line rhumb. A* solves problems by searching among all possible paths to the solution (goal) for the one that incurs the smallest cost (least distance traveled, shortest time, etc.), and among these paths it first considers the ones that appear to lead most quickly to the solution. A* is formulated in terms of weighted mesh: starting from a specific node of the mesh, it constructs a tree of paths starting from that node, expanding paths one step at a time, until one of its paths ends at the predetermined goal node. At each iteration of its main loop, A* algorithm needs to determine which of its partial paths to expand into one or more longer paths. It does so based on an estimate of the cost (in our case the travel time) to go to the goal node. Specifically, A* selects the path that minimizes the total cost function $f(n)$:

$$f(n)=g(n)+h(n) \tag{1}$$

where n is the last node on the path, $g(n)$ is the cost of the path from the start node to n, and $h(n)$ is a heuristic that estimates the cost of the cheapest path from n to the goal. The heuristic is a problem-specific. For the algorithm, to find the actual shortest path, the heuristic function must be admissible, meaning that it never overestimates the actual cost to get to the nearest goal node. The heuristic function used in weather ship routing is the sailing time associated to the minimum distance between origin and destination. The description of the operating principle of the code is presented in Grifoll and Martínez de Osés (2016).

Effects considered on navigation and bad weather episodes selection

Wave action is the major factor that affects the ship energy performance (James, 1957 and Hu *et al* 2014). Wave field affects the ship motions decreasing the propeller thrust and adding a resistance in comparison to absence of waves. In this case, the effective speed comes by equating the propulsive forces and the resistance forces. In a still water scenario, the ship should overcome the frictional resistance because of the viscosity of the water. When the ship is sailing, the resistance increases because of the deformation of the free water surface. In this case, the added resistance is still governed by the ship hydrodynamics, but complex interactions arise between ships and both waves and currents and wind (Delitala *et al*, 2010). This resistance is proportional to the square of the incident wave height and mainly due to the heave and pitch amplitudes and the phase shift between them (Guedes *et al*, 1998). A simple formula to include ship speed reduction due to waves is suggested by Bowditch (2002) inspired in early formulations that considered wave and ship directions (Haltiner *et al*, 1962). The final speed is computed in function of the non-wave affected speed (v_0) plus a reduction in function of the wave parameters:

$$v = v_0 - F(\theta) \cdot Hs^2 \qquad (2)$$

Where *Hs* is the significant wave height and *F* is parameter in function of the relative ship wave direction (Θ; see Table 1).

Table 1. Values of the coefficient *F* in function of the ship-wave relative direction.

The incidence of extreme episodes of heavy or bad weather in the Western Mediterranean, in general terms uses to vary along the year and is characterized by a decrease of annual rainfall and an increase in the annual temperature during summer time in much of Mediterranean area (Christensen and Hewitson, 2007). From a general point of view, there can be observed strong winds during the year from N in the Gulf of Lion; and from NW over Ebro Delta region (Bunker, 1972; Grifoll *et al*, 2016). Another heavy situation is related to the cyclogenesis activity associated at low pressure system in the NW Mediterranean Sea. In this case, strong winds are originated by large pressure differences between continental land and the low pressure in the Gulf of Lion or Gulf of Genoa (Lionello *et al*, 2006). This case originates complex and energetic wave episodes in the NW Mediterranean Sea. Examples of both meteorological situations have been considered in the ship routing simulations. For case 1 a characteristic easterly wave in the Gulf of Lion is considered (see wave climate in Figure 1). These conditions correspond to a meteorological synoptic situation of a low pressure system located in the NW Mediterranean Sea leading waves that comes from the east. The period of analysis corresponds at 30th and 31st of November 2014. For case 2 and 3, a meteorological synoptic situation with N wave storm in the NW Mediterranean Sea is considered (Figure 2 and 3). The strong winds produce large waves at south of Gulf of Lion; more than 6 m of *Hs* during the period of 9th and 10th of December 2014. The wave climate shown in the mentioned figures corresponds to the forecasting service provided by *Puertos del Estado* (see description in Appendix A). These predictions are used to estimate the wave effect on ship navigation according to the equation 2.

Costs estimation of navigation

Dealing with the interest posed by this contribution to apply weather routing to short sea traffics, it is noticeable to remark that maritime sailings using a reduced number of hours and in any case less than 24 hours, require very well organized operations at ports for the purpose of not compromise the compliance of the line schedule (Fagerholt and Lindstad, 2007; Ting and Tzeng, 2003). In other words, it is important to maintain the lay time in port operations and to avoid demurrages due to delays for example coming from bad weather. The cost of these demurrages should be paid by the responsible of the navigation, usually the carrier in the case of a liner.

For cost calculation purposes a characteristic ship obtained from a field research carried out on the ships involved in Ro/Ro and Ro/Pax traffics calling at Barcelona port is used. This representative ship has been obtained from averaging data of all Ro/Ro and Ro/Pax ships, in service at May 2017 calling at Barcelona Port (see Table 2).

Table 2. Ro/Ro-Pax type ships’ particulars, those call in Barcelona Port. (May 2017)

Based on different authors (Stopford, 1997; Tzannatos, 2014; Andersson and Ivehammar, 2016) costs distribution can be divided into several main groups. The total costs are in function on ship size and age in open seas. Traveled distance and speed are factors closely related to engine consumption and then conditioned by the fuel costs. Others costs to be considered are capital costs, crew costs and RMIA (i.e. repairs, maintenance, insurance and administrative) costs. These costs are limited to the navigation phase, considering only the ship in open seas. Port costs like taxes, fees, discharge operation or demurrages are not considered.

To assess the real costs from ship-owners is not easy but some other formulations describing a theoretical approach can be used. The method used in the proposal of Stopford (1997) is proposed differentiating among fuel, manning, capital and maintenance costs; however different authors have proposed alternative methods to calculate them (Anderson and Ivehammar, 2016; Tzannatos, 2005 and 2014; Mulligan and Lombardo, 2006 or Martínez de Osés and Castells, 2009).

a) Fuel costs

In the following example, speed has been considered as an implicit input that is going to compute various explicit inputs like fuel costs and sailing times. This is a model in which it is considered a speed as a fixed input, some flexibility could be lost and solutions could be suboptimal, even that wide taxonomies (Psaraftis *et al*, 2016) have been published by different authors regarding this limitation. Additionally no payload considerations have been considered in fuel consumptions, as the case of ferry traffics are considered not a clear example of binary situation (laden versus empty, voyages) in which two different fuel functions should be considered.

Based on Anderson and Ivehammar (2016, 2017) and Larsson (2010), fuel consumption for a specific journey by a Ro/Pax and Ro/Ro ship is calculated considering the hull resistance as:

$$C = \frac{R_{T}.D}{E_{MGO} \cdot \eta_{T}} \qquad (3)$$

Where

C fuel consumption, in kilogram (kg)

R_T vessel resistance, in kilonewton (kN)

D sailed distance, in meters

E_{MGO} the specific energy of Marine Gas Oil, 42700 MJ/kg is considered

η_T thermal engine efficiency

The total resistance of the vessel is calculated by a model o fur hull resistance (Larson and Raven, 2010):

$$R_T = \frac{1}{2} \cdot \rho \cdot V_S^2 \cdot (B + 2 \cdot d) \cdot L \cdot C_B \cdot C_{TS} \tag{4}$$

Where

ρ water density, in kg/m^3

V_s speed, in m/s

B beam, in m

d draught of ship, in m

L length of ship, in m

C_B block coefficient, 0.67 is used

C_{TS} resistance constant, 0.0022 is used

The equation needs the distance, which in this example will be obtained from the sailing time and proposed speed. To calculate the resistance, average data from Ro/Pax and Ro/Ro analysis making the traffic in the Western Mediterranean has been taken (see last row of Table 2).

b) Capital costs

Capital costs dependent on an additional time unit at sea, are assessed by means of different formulae based on Gross Tonnage (GT) instead of lineal metres as independent variable. The capital cost per day is based on the Compensated Gross Tonnage (CGT) factor. The formula used is taken from the Compensated Gross Ton (CGT) System, from OECD Directorate for Science Technology and Industry in its Council Working Party on Ship building (OECD 2007):

$$\mathrm{CGT} = \mathrm{A} \cdot \mathrm{GT}^{\mathrm{B}} \qquad (5)$$

Being the factors A and B for Ro/Ro ships 32 and 0.63, respectively (OECD 2007). The GT value is based on the list of Ro/Ro and Ro/Pax ship data shown in Table 2. Keeping in mind that the average price in €/CGT by category is in the case of Ro/Ro vessel of 2.253€/CGT (UNINAVE 2003) for the model ship of 30,408 GT; CGT value is 21,351.79 CGT that supposes a ship with a price of 48105594.8 €. From equation (5) applied to the price of all ships, the daily capital cost is obtained considering a credit at an interest of 5% and a useful and repayment life of 25 years (Tzannatos, 2014). The annualised capital investment cost equals 3,413,239.4 € for the average ship. Dividing this data by the 365 days in a year, the data daily capital cost is obtained. The linear regression equation found is $y = 0.63x + 2.6041$ that converted to logarithmic scale shows that ln (Capital cost) = ln (GT) 0.63 + ln (2.6401). By means of a Cobb-Douglas conversion, the daily capital cost obtained is:

$$\text{Capital cost} = 14.014 \cdot \mathrm{GT}^{0.63}\ \text{€/day} \qquad (6)$$

c) RMIA costs

Regarding the group of repairs, maintenance, insurance and administrative costs, Jansson & Shneerson (1987) suggest that this should be around 3.5% of the daily capital costs. Assuming vessel’s insurance to be equal to 2% of its initial costs and maintenance and repair on average upon the vessel’s age of 1.5%, means 3.5% of initial ship’s cost (Tzannatos, 2014). General formula to calculate RMIA costs is shown below:

$$\mathrm{RMIA} = 0.4905 \cdot \mathrm{GT}^{0.63}\ \text{€/day} \qquad (7)$$

d) Crew costs

Regarding crew cost, this unitary value is difficult to estimate due to the variability if passenger and non-passenger ships are considered. In this proposal it is considered that the number of required positions on board of a Ro/Ro ship should be 8 officers and 9 mates, that the rotation factor per each category is 2.1 and 1.5, respectively (Andersson and Ivehammar, 2016). The average salaries of 3.700 € gross/month for officers and 2.200 € gross/month per mates. The resultant formula of the crew costs is given by:

$$\text{Crew Costs} = [2.1(\text{Officers}\cdot\text{Wage}) + 1.5(\text{Mates}\cdot\text{Wage})/30]\cdot\text{Sailing time}/24 \qquad (8)$$

Results

This section provides a practical development of the theoretical methodology explained in the above section. The weather description, the distances covered and the travel times of the selected routes are summarized in Table 3 jointly with the travel time saved of the optimal route in comparison to the minimum distance route. The optimal route (plotted in magenta) and the minimum distance route (plotted in black) recovered from the A* algorithm are shown in Figures 1, 2 and 3, jointly with the wave conditions during the sequence of the ship route. These figures show hourly snapshot of the wave conditions plotted accordingly to the temporal evolution of the ship route. The color bar represents the value of *Hs* and the black arrows the propagation direction of the waves.

Figure 1. Temporal sequence of the snapshot of the case 1 (Valencia – La Spezia, hours since departure). The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the *Hs* and the black arrows the propagation direction of the waves.

The optimal route for case 1 avoids the energetic wave conditions (*Hs* equal to 3.5 m) suggesting a sailing southward in comparison to the minimum distance route. A shorter traveling of 1 hour is obtained using the ship routing algorithm. This travel time reduction represents approximately 3% of the total travel time.

Figure 2. Temporal sequence of the snapshot of the case 2 (Barcelona – Livorno; hours since departure). The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the *Hs* and the black arrows the propagation direction of the waves.

Figure 3. Temporal sequence of the snapshot of the case 3 (Alicante – Livorno; hours since departure). The optimal route is plotted in magenta and the minimum distance

route is plotted in black. The color bar represents the *Hs* and the black arrows the propagation direction of the waves.

For routes of case 2 and 3 the optimal routes recovered by the algorithm also differ in comparison to minimum distance routes. In both cases, the optimal route travels northward in comparison to the minimum distance route following the small significant wave height near the coast in comparison offshore. The travel time is reduced in more than 1 hour in case 2 (approximately 4% of the total travel time; see Table 3) and 7.5 hours in the case 3 (approximately 15% of the total travel time). The pathfinding optimization results show how longer routes in distance may be covered with less time with a consequent less fuel consumption. A summary of the results in terms of the sailing time and covered distance are shown for each selected route in Table 3.

Table 3. Travel times (in hours) and distances (in nautical miles) for selected routes.

Based on the difference in time between the minimum distance route and the optimial route, Table 4 shows the different costs (in Euros) due to the additional sailing time related to capital, insurance, maintenance, administrative procedures and crew costs considering the suggested average model of Ro/Ro ship. Fuel prices were selected in the 23rd of May 2017 in Rotterdam (Shipandbunker.com) reaching for the IFO 380 the 298 $/ton and taking the $/€ parity at same date of 1.12 $ = 1 €.

Table 4. Costs, in Euros, assumed by the model ship for the different scenarios

In Table 4, the total cost and the associated percentages (additional and sailing costs) considering the difference in time between the minimum distance and optimal routes are shown in case of avoid the additional sailing time (i.e. using a ship routing system). The rate of cost savings ranges for 3% to 15% of the total sailing costs in function of the route. Obviously, the large costs’ saving corresponds to the route where more difference between the optimal and minimum distance route were estimated: case 3 with 7.55 hours. The percentages are relevant and justify the consideration of the ship routing in relative short distances, such as SSS.

The ship routes comparison (minimum distance versus optimal route) evidences the relevance of the wave effects on navigation; in particular, the decreasing of the vessel speed due to the increase of *Hs*. Figure 4 shows the velocity profiles for the three routes tested in function of the hours since ship departure. The speed decreasing is clear comparing the continuous line (optimal route) versus the dashed line (minimum distance route). The proportionality of the vessel speed decreasing with the increasing of *Hs* is observed comparing the case 3, where the minimum route cross a high wave energetic area (see Figure 3). Also, the role that plays the head sea in the decreasing of *Hs* speed vessel is deducted from the case 1, where lower maximum in comparison to the other cases (3.5 m versus 6 m in the other cases) leads to a reduction of 1 hour (similar to the case 2 where Beam Sea predominates).

Figure 4. Velocity profiles for the three routes tested in function of the time of departure. Dashed line corresponds to minimum distance route (marked in the legend with dist.), and continuous line corresponds to optimal route.

Other concepts not contemplated are demurrage costs. Those are the waiting charges levied by ship-owners or vessel operators if their ships have a waiting time longer than a defined loading or unloading time (Wanke, 2011). In the examples showed in this contribution, it is not particularized if the terminal owner is the same own vessel operator, as those ships berth in the same place every day. In this case, the delays are not responsibility of the waiting time in the queue but from the weather. However, demurrages can suppose delays bringing to a situation in which the berth could be occupied by another ship. As an example of the demurrage costs, a 20,000 DWT bulk carrier could suppose around £ 5,000 per day (Dahal *et al*, 2007). Thus, this additional cost may be of the order of magnitude of the estimated costs shown in Table 4, so may be relevant in the benefit of using weather ship routing applied at SSS. The accurate determination of the economic benefit considering demurrage cost and the ship routing depending on the ship’s managing and terminal model is considered as future works.

Final Remarks

The cost analysis used in our contribution allows assessing the contribution of the different concepts in overall ship's management. From the results obtained, there is a lineal dependency among them and they fulfil the conditions of validity. Figure 5 shows how the main cost is the capital costs that exceed 50%, whilst fuel costs are around 25%. However, other methods would provide larger fuel consumption costs because they use the maximum power of the main engine, whilst in our case, the resistance effort to be developed (and thus the energy required) is choosen. The highest contribution of fuel consumption cost, the highest sensitivity to the price of oil.

Figure 5. Cost distribution using a characteristic SSS ship in the analyzed routes.

In this example, the ship in open seas is considered. In consequence, costs due to port operations such as demurrages or related fees are not considered. Any method, affording a reduction in navigation time, means a reduction of consumption and then a savings in emissions, reducing then the external costs parameter. In consequence, the weather ship routing impact on SSS activity can be considered as functionality within e-navigation and sea traffic management performances that will have consequences from not only economic but environmental point of view.

Psaraftis (2017) highlights that there is an increase of contributions in ship rputing those are more theoretical than practical value with a considerable gap between the methodological formulation and the reality. In our contribution, a particular effort is done in order to provide a high degree of realism in the methodology and simulations to be useful for the SSS industry. In this sense, this contribution provides a first analysis of the economic benefit of using a weather ship routing system at SSS activity: the cost savings may reach the 15%. SSS has lost some momentum in recent years because the transport modal decision is taken by private shipping companies with the consequent benefits expected from the economic activity (European Comission - DG Mobility and Transport, 2015; Suárez-Alemán *et al*, 2015). The economic benefit of ship routing systems at relative short distances justify the use of these systems in the potential multi-criteria analysis in the framework of logistic supply chains. Ship routing effect may be included in a competitiveness analysis of inter-modal routes in decision making strategies (for instance Martínez-López *et al,* 2015); or such a complementary information to other optimization techniques for shipping routes considering available vessels or fleets (Fagerholt, 2006; Cho and Perakis, 1996) and ship scheduling oriented to maximize loading operations (Cho and Perakis, 2010; Zacharioudakis *et al.*, 2011). Additional benefits not quantified in our analysis are related to an increase freight safety and passengers comfort, even reducing the seasickness probability which have a relevant influence in human factors (Beşikci *et al*, 2016; Delitala *et al*, 2010).

The ship route comparison (minimum distance versus optimal route) evidences the relevance of the wave effects on navigation and its effects on safety navigation and, in particular, the decreasing of the vessel speed in function of the wave characteristics. ~~The methodology used in this contribution is based on the inclusion of the added resistance due to waves. It is worth to mention that the weather routing cases reveal how the wave direction has a relevant role in the optimum path due to influence of its relative direction with the ship.~~ The cases analysed represent shorter sailing distance in comparison to applications oriented to oceanic maritime routes (e.g. Larsson and Simonsen, 2014; Hinnenthal and Günther, 2010). Our investigation is possible due to the new generation of waves and winds forecasts which has a high spatial resolution (see for instance the products of the European program of Copernicus Marine Environment Monitoring Service (CMEMS)).

From the extreme or bad weather probability point of view, different authors link these occurrences with their effect in the transport system (e.g. Molarius *et al* 2013). In this sense, Nokkala *et al* (2012) quantify economically bad weather events in terms of volume of freight and passengers reductions in the European transport systems. In this case, the EU shippers losses were estimated of the order of billions of euros due to time delays resulted by extreme weather conditions. ~~Koetse and Rietveld (2009) suggested a cost increasing in the inner navigation associated at extreme events due to the climate change.~~ As it was mentioned previously, wind generated waves can affect seriously the navigation not only from the stability point of view but from the damage to hull and freight, seasickness of passengers and the speed reduction. ~~This last means more time sailing. Depending on the ship type, the wave effect can be sharper than others.~~ The results obtained in our contribution agrees with the mentioned papers, quantify in our case the cost savings in the SSS context and highlighting the bad weather episodes effects in the maritime transport systems.

In the Western Mediterranean, storms have had a higher frequency during autumn and colder months. Usually they are generated by the Southern edge (which lies over the Mediterranean Sea) of anticyclones placed over central Europe. Considering the variability in the inter-annual pattern of storms occurrence, the investigation of the weather ship routing from an annual statistical point of view is highlighted as a future work. In this sense, a low effect of ship routing during calm conditions is expected; however to examine the recurrence of the bad weather episodes seems relevant for annual saving cost statistics (Delitala *et al*, 2010).

From a methodological point of view, the work presented in this contribution prove the suitability of the implementation of A* algorithm for the optimum ship routing in a relative short maritime distance. It is worth to note that A* was found very suitable for finding optimal path in a fairly quick time in contrast to greedy algorithms such as Dijkstra. ~~This agrees with performance analysis based on benchmarking cases comparing with less stable and high computational cost such as Ant algorithm (see test performed by Santoso *et al*, 2010). In particular the A* here has been proven efficient and robust according to a benchmarking test (e.g Barcelona – Palma) presented in Grifoll (2016).~~ Further research in the methodology include the implementation of the method for dynamic wave states, the implementation of the multi-criteria algorithm (e.g. NAMOA or genetic algorithm), the methodological inclusion of safety restrictions due to the wave conditions (surf riding or rolling motions) or the influence of currents and winds in the optimum ship routing in the SSS framework.

Appendix A. Wave forecast description

The wave predictions used are provided by the operational systems distributed by the *Puertos del Estado* (PdE). PdE together with the Spanish Meteorological Agency (AEMET) run and distribute twice-a-day wave and wind fields forecast for the Western Mediterranean Sea. Wind forecasts, used to force the wave models, come from the HIRLAM (High Resolution Limited Area Model) model, running operationally at the AEMET. The forecast horizon is 72 hours and the system generates wave hourly outputs (among other variables significant wave height (Hs), wave direction and wave period). An initialization procedure is carried out in order to ensure good initial conditions: the model is forced using wind fields 12 hours prior to forecast initialization. The wave numerical model is WAM (WAMDI, 1988), version 4 (Günther *et al*, 1992). WAM is a third-generation based on the transport of two-dimensional ocean wave spectrum without additional ad hoc assumptions regarding the spectral shape. For the Mediterranean domain the shallow water version of the WAM model is used, therefore, refraction and attenuation effects are considered for those (few) grid points located in shallow waters. The model produces the wave directional spectra for each grid point. Then, it is used to obtain further information, Hs, peak wave period (Tp), mean wave period (Tm), mean direction, Wind Sea and swell components, among others. Extended information of the WAM model implementation and additional numerical details are provided by Gómez-Lahoz and Carretero-Albiach (1997) and the mentioned web from the PdE.

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Table 1. Values of the coefficient *F* in function of the ship-wave relative direction.

Ship-wave relative direction (Θ)	**Wave direction**	***F* (in kn/ft^2)**
$0^\circ \leq \Theta \leq 45^\circ$	Following seas	0.0083
$45^\circ < \Theta < 135^\circ$	Beam seas	0.0165
$135^\circ \leq \Theta \leq 225^\circ$	Head seas	0.0248
$225^\circ < \Theta < 270$	Beam seas	0.0165
$270^\circ \leq \Theta \leq 360^\circ$	Following seas	0.0083

Table 2. Ro/Ro-Pax type ships' particulars, those call in Barcelona Port. (May 2017). DWT, GT and CGT are Dead Weight Tonnage, Gross Tonnage and Compensated Gross Tonnage respectively.

Vessel Name	**Length (m)**	**Beam (m)**	**Draft (m)**	**DWT (tons)**	**GT (tons)**	**CGT (tons)**	**Power (kW)**	**Speed (knots)**
MV Cruise Barcelona	224.97	30	6.8	7500	54,310	30,769.77	55,440	28
MV Cruise Roma	224.96	30	7.1	7500	54,310	30,769.77	55,440	28
MV Cruise Smeralda	200.65	25.8	6.6	5150	29,968	21,156.52	44,480	22
Excellent	202.78	26.8	6.7	7300	39,777	25,288.21	26,308	24
Fantastic	188.15	28	6.4	7037	35,222	23,423.01	26,280	22
Amilcar	193	26	6.5	14268	22,900	17,858.55	16,200	20.5
Snav Adriático	164.78	27.6	6	4642	31,910	22,010.19	19,360	19.5
Zurbarán	180	25	5.6	7396	22,152	17,488.80	23,756	22
Las Palmas de G.C.	116.8	20.7	5	2706	11,032	11,272.54	5352	17
Tenacia	198.99	27	5.7	8500	25,993	19,342.36	24,000	21.5
Dénia Ciutat Recreativa	150.42	23.4	5.1	5985	19,308	16,038.52	11,678	19
Sicilia	186.25	26	6.1	7000	24,409	18,591.15	18,900	24
Martín i Soler	165.3	25.6	5.5	9737	24,760	18,759.13	18,000	21.4
Abel Matutes	190	26	5.5	10863	29,670	21,023.74	18,000	21.4
AVERAGE	**184.78**	**26.27**	**6.04**	**7541.71**	**30,408.64**	**21,351.97**	**25,942.42**	**22.1**

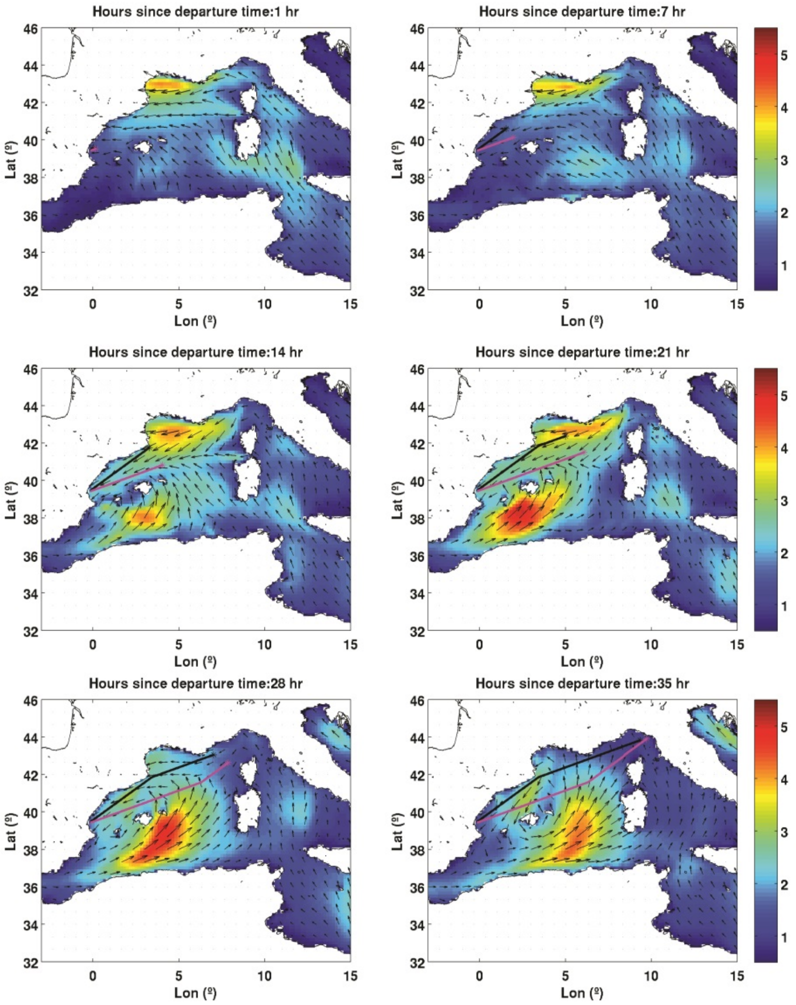

Figure 1. Temporal sequence of the snapshot of the case 1 (Valencia – La Spezia; hours since departure). The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the *Hs* and the black arrows the propagation direction of the waves.

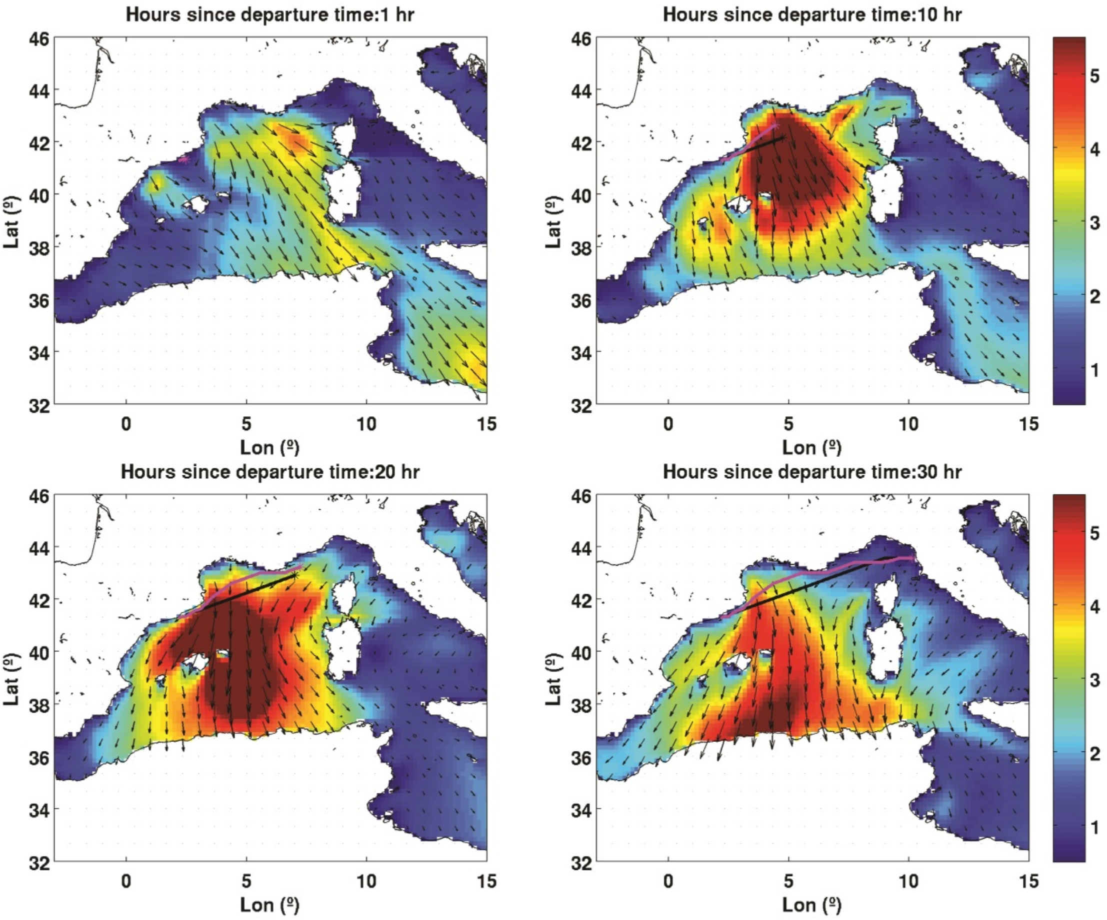

Figure 2. Temporal sequence of the snapshot of the case 2 (Barcelona – Livorno; hours since departure). The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the *Hs* and the black arrows the propagation direction of the waves.

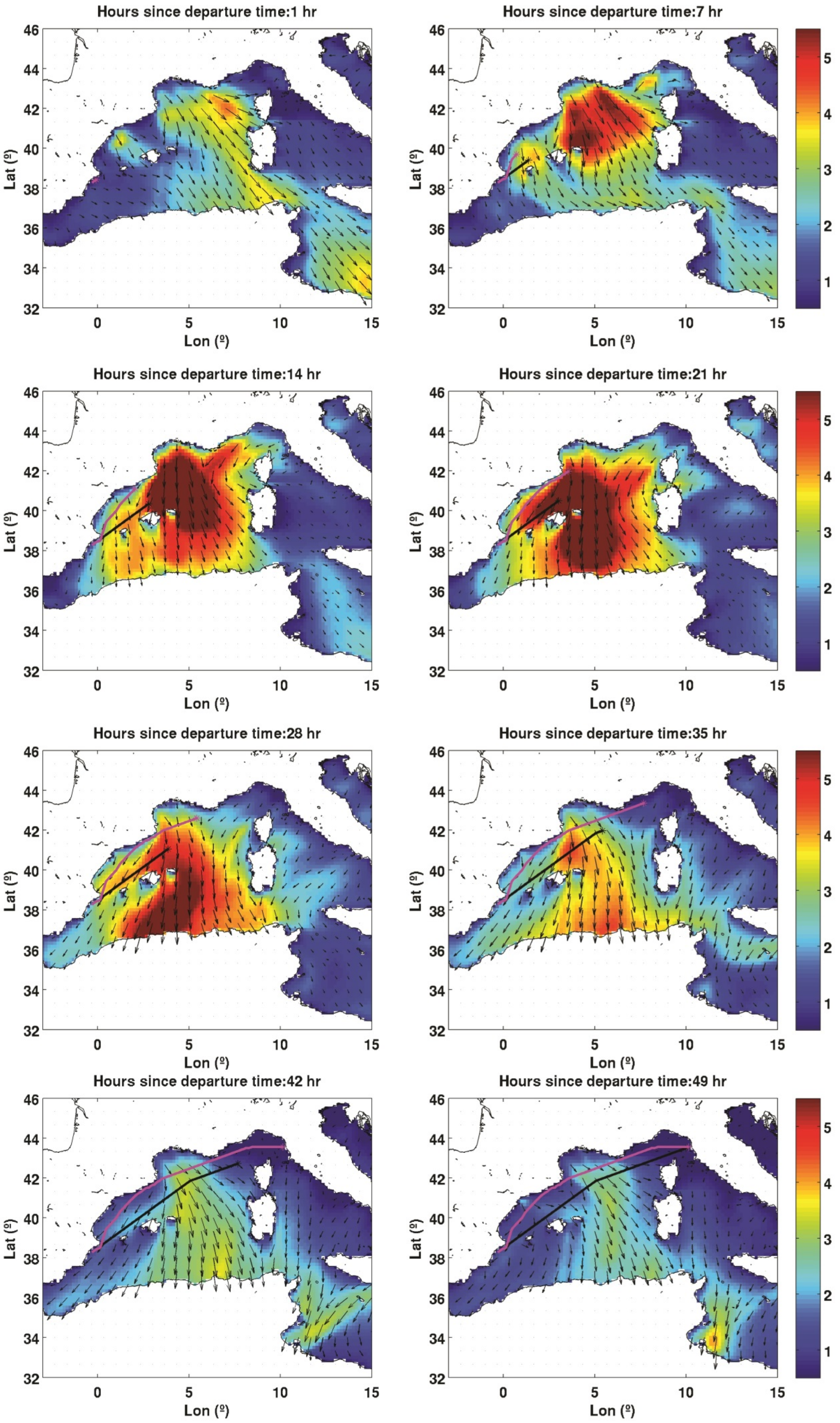
Hours since departure time:1 hr
Hours since departure time:7 hr
Hours since departure time:14 hr
Hours since departure time:21 hr
Hours since departure time:28 hr
Hours since departure time:35 hr
Hours since departure time:42 hr
Hours since departure time:49 hr
Lat (º)
46
44
42
40
38
36
34
32
Lon (º)
0
5
10
15
1
2
3
4
5

Figure 3. Temporal sequence of the snapshot of the case 3 (Alicante – Livorno; hours since departure). The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the *Hs* and the black arrows the propagation direction of the waves.

Table 3. Travel times (in hours) and distances (in nautical miles) for selected routes.

	Case 1: Valencia – La Spezia (Period: 30-31/11/2014)	**Case 2: Barcelona – Livorno (Period: 09-10/12/2014)**	**Case 3: Alacant – Livorno (Period: 09-10/12/2014)**
Weather description	Waves from North-East	Waves from North	Waves from North
Travel time for the minimum distance case (without wave resistance). In hours.	32.92	23.86	35.67
Travel time for the minimum distance case (with wave resistance). In hours.	36.55	29.59	49.30
Travel time for the optimal route considering wave resistance. In hours.	35.52	28.43	41.75
Minimum distance. In miles.	529	384	574
Distance covered by the optimal route. In miles	536	396	606

Table 4. Costs assumed by the model ship, for the different additional time scenarios

	Case 1	**Case 2**	**Case 3**
Time difference (in hours)	1.03 hours	1.16 hours	7.55 hours
Additional consumption (in tons)	0.684 tons	0.771 tons	5.019 tons
Additional fuel costs (in €)	182	205.2	1335.6
Additional Capital costs (in €)	401.3	451.96	2941.61
Additional RMIA costs (in €)	14.04	15.82	102.95
Additional Crew costs (in €)	131.41	148	963.25
Total Additional costs (in €)	728.75	820.98	5343.41
Total cost for the minimum distance route (with wave resistance). (in €)	25860.35	20941.76	34891.41
Total cost for the optimal route considering wave resistance. (in €)	25131.59	20120.8	29548
Percentage of cost savings	2.82%	3.92%	15.3%

in the optimal route regarding the minimum distance route (in %)			

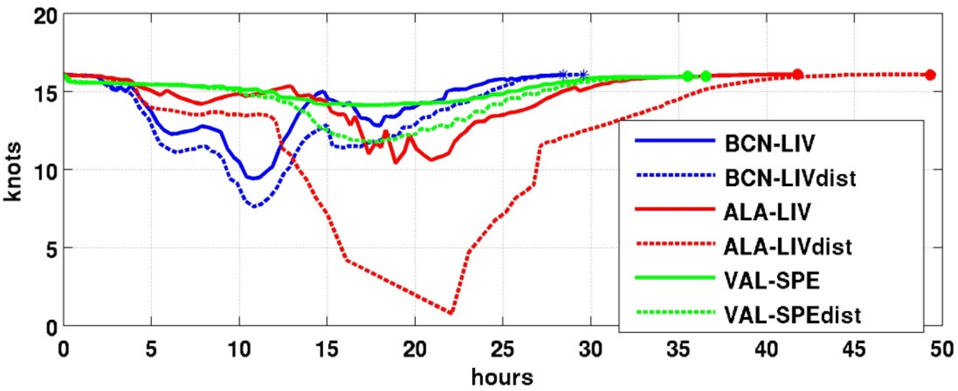

Figure 4. Velocity profiles for the three routes tested in function of the time of departure. Dashed line corresponds to minimum distance route (marked in the legend with *dist*), and continuous line corresponds to optimal route. BCN, LIV, ALA, VAL and SPE means Barcelona, Livorno, Alicante, Valencia and La Spezia respectively.

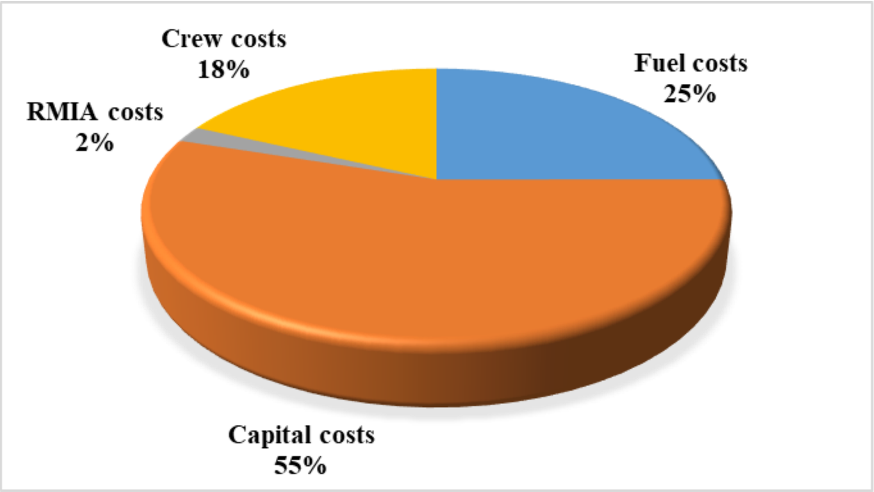

Figure 5. Cost distribution using a characteristic SSS ship in the analyzed routes.