Ship weather routing using pathfinding algorithms: the case of Barcelona – Palma de Mallorca

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ABSTRACT

Weather ship routing has become a recognized measure to target safe, sustainable and economical ship activities. Academic research has focused the ship routing optimization through pathfinding algorithms which take into account the meteo-oceanographic forecasts (i.e. wind, waves or currents predictions). This contribution shows the results of the numerical simulations carried out during the development of a weather ship routing applied to a ferry service in the Mediterranean Sea: Barcelona – Palma de Mallorca. From a methodological point of view, the pathfinding A* algorithm is applied to optimize the travel time considering the wave action. Under severe weather conditions, a reduction of the 6% of the travel time is obtained comparing the optimized route and the minimum distance route. The results show also a non-significant correlation between the travel time reduction and wave height. In consequence the benefit of ship routing depends not only of the wave height but also in the spatial sequence of the storm.

1. INTRODUCTION

A major factor of competitiveness in the maritime industry is the minimization of fuel consumption for ship routes. This agrees with an increase of the world tendency to reduce air emissions in the framework to mitigate the climate change effects. From the shipping industry point of view this may be achieved with an optimum route plan design (Simonsen et al., 2015). The ship routing is defined as the development of an optimum sailing course and speed for ocean voyages based on nautical charts, forecasted sea conditions, captains' experiences and the individual characteristics of a ship for a particular route. Academic research has focused the ship routing optimization through pathfinding algorithms

(Takashima et al., 2009; Mannarini et al., 2013; Szłapczyńska and Śmierzchalsk, 2009; Larsson and Simonsen, 2014 and Hinnenthal and Günther, 2010) which take into account the meteo-oceanographic forecasts (i.e. wind, waves or currents predictions). Some of these contributions have been tested through a "proof-of-concept" based in oceanic distances (Simonsen et al., 2015). However, at short-distances (for instance in the framework of the Short-Sea Shipping or Ferries activities) the weather ship routing implementation and benefit is not yet fully investigated (Grifoll et al., 2018). In this case, historically the spatial resolution of the meteo-oceanographic predictions (grid resolution of the numerical model) is a severe restriction to design feasible ship routing.

The benefits expected of the best possible route is associated in terms of criteria like estimated time of arrival (ETA), fuel consumption, emission minimization, safety (i.e. parametric rolling or surfriding) and comfort (passengers seasickness). The objective of this contribution is to show the numerical test carried out during the development of a weather ship routing applied to a short distance. From a methodological point of view, the work presented in this contribution prove the suitability of the implementation of a pathfinding algorithm (i.e. A*) for the optimum ship routing in a relative short maritime distance: Barcelona – Palma de Mallorca. The ship route comparison (minimum distance versus optimal route) shown in this contribution evidences the benefit in terms of travel time. As a consequence, the percentage of services, which the travel reduction is significant, is assessed using wave predictions.

2. METHODOLOGHY

The pathfinding algorithm used in this contribution is the A* (Dechter and Pearl, 1985). 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 distance is used for the spherical coordinates of grid nodes. A* solves routing 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. In particular, A* selects the path that minimizes the total cost function $F(n)$:

$$F(n)=G(n)+H(n) \qquad (1)$$

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. 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. In our case, the heuristic function is the minimum distance between origin and destination. The description of the operating principle of the code (pseudocode) is shown in Grifoll and Martínez de Osés (2016).

Wave action is the major factor that affects the ship motions, decreasing the propeller thrust and adding a resistance in comparison to absence of waves. A simple formula to include ship speed reduction into waves is suggested by Bowditch (2002). The final speed is computed in function of the non-wave affected speed plus a reduction in function of the wave parameters:

$$v = v_0 - f(\theta) \cdot H_S^2 \qquad (2)$$

Where H_S is the significant wave height and f is parameter in function of the relative ship wave direction (θ; see Table 1). The wave predictions used are provided by the operational systems distributed by the Puertos del Estado (see more information of the forecasting system in Grifoll et al, 2018).

Ship wave relative direction (θ)	Wave direction	f(kn/ft^2)
$0° \leq \Theta \leq 45°$	Following seas	0.0083
$45° < \Theta < 135°$	Beam seas	0.0165
$135° \leq \Theta \leq 225°$	Head seas	0.0248
$225° < \Theta < 270°$	Bean seas	0.0165
$270° \leq \Theta \leq 360°$	Following seas	0.0083

Table 1 – Values of the coefficient f in function of the ship wave relative direction (θ).

3. RESULTS

This section presents the numerical results obtained using the previous methodology applied at the Barcelona − Palma de Mallorca route (Mediterranean Sea). The horizontal grid

resolution has been 1.5 minutes with a connection of 24 edges per each node. An initial cruise ship speed of 20 knots has been considered and 25 wave energetic scenarios occurred between December 2016 and March 2017 has been selected. In order to characterize the typical wave climate, Figure 1 and 2 show the temporal evolution of two energetic episodes in terms of significant wave height: Figure 1 shows a Northeastern storm and Figure 2 Southwestern storm. The color bar represents the value of H_S and black arrows the direction of propagation of the waves. During these energetic episodes the ship routing recovered by the A* algorithm is shown (in magenta) for each snapshot. Alternatively the minimum distance is also shown in black. In both cases, the optimal route tends to avoid the most energetic areas from a wave conditions point of view. For instance, Figure 2 shows how during Southwestern storm the optimal route is displaced towards north in comparison to the minimum distance route. In this case the travel time for the optimal route is 8.1 hr, lower than the time traveled by the minimum distance route (i.e. 8.4 hr). In order to generalize the ship routing pattern, Table 2 summarizes the ship routing results considering the mentioned 25 energetic scenarios. The departure time has been selected based on the current services in the vessel routes between Barcelona and Palma de Mallorca. Differences around tens of minutes are obtained in function of the significant wave height. The maximum difference (0.55 hr) were obtained during the ship route starting at 17/01/2017 00:00, which corresponds a significant wave height of 4.5 m.

Time of departure (dd/mm/yyyy hh:mm)	max(H_S) (in m)	Duration for the optimized route (in hr)	Duration for the minimum distance route (in hr)	Difference (in hr)	Distance of the optimized Route (in nautical miles)
19/12/2016 00:00	3.2	7.0	7.0	0.0	0.000
19/12/2016 05:00	3.7	7.1	7.1	0.0	0.001
20/12/2016 06:00	5.0	8.3	8.8	0.5	5.567
20/12/2016 10:00	4.3	7.8	8.2	0.4	3.033
21/12/2016 00:00	3.4	7.2	7.3	0.1	0.867
21/12/2016	3.7	7.3	7.4	0.1	0.870

05:00						
09/01/2017 00:00	3.0		6.9	7.1	0.2	0.871
09/01/2017 03:00	3.3		7.1	7.2	0.1	1.155
11/01/2017 00:00	4.0		7.2	7.4	0.2	1.438
11/01/2017 02:00	4.3		7.4	7.7	0.3	2.685
13/01/2017 00:00	1.9		6.8	6.8	0.0	0.019
17/01/2017 00:00	4.5		7.6	8.1	0.5	2.402
18/01/2017 00:00	3.9		7.2	7.4	0.2	0.303
19/01/2017 06:00	4.0		7.3	7.3	0.0	0.020
20/01/2017 00:00	3.8		7.3	7.3	0.0	0.001
21/01/2017 06:00	5.6		7.9	8.0	0.1	0.020
21/01/2017 11:00	6.8		8.9	9.3	0.4	0.304
22/01/2017 00:00	6.8		9.1	9.2	0.1	1.353
22/01/2017 03:00	6.0		8.4	8.5	0.1	0.587
22/01/2017 06:00	5.8		8.1	8.2	0.1	0.585
05/02/2017 00:00	3.1		7.0	7.0	0.0	0.013
06/02/2017 00:00	5.4		8.6	8.7	0.1	1.352
04/03/2017 00:00	6.2		8.1	8.4	0.3	3.569
04/03/2017 02:00	5.3		8.2	8.4	0.2	3.610
04/03/2017 04:00	4.9		8.0	8.3	0.3	3.333

Table 2– Results of the 25 ship routing simulations obtained for Barcelona – Palma de Mallorca in function of the time of departure. The minimum distance route is 133.292
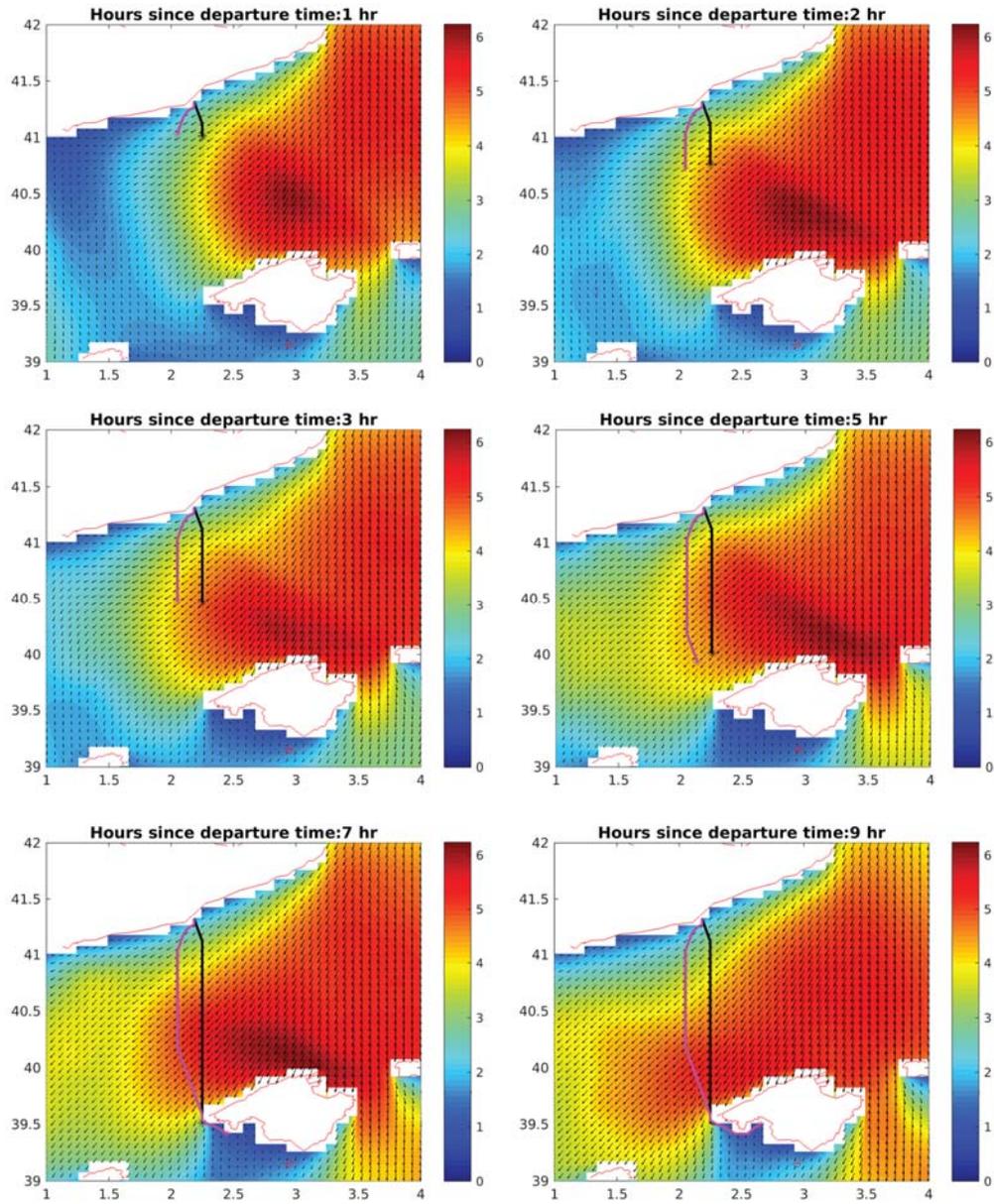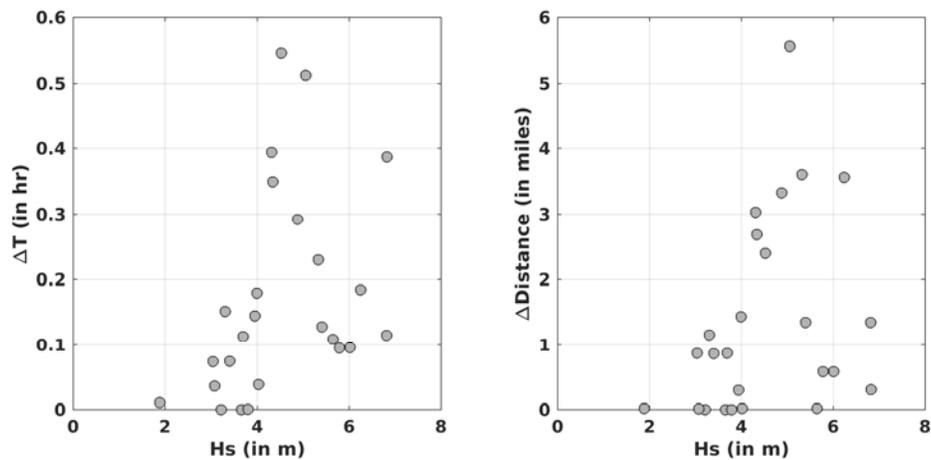
nautical miles.ig. 1 – Temporal sequence of the snapshot of the case Barcelona – Palma de Mallorca. The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the H_S and the black arrows the propagation direction of the waves. This route corresponds to a departure time of 17/01/2017 00:00 h.
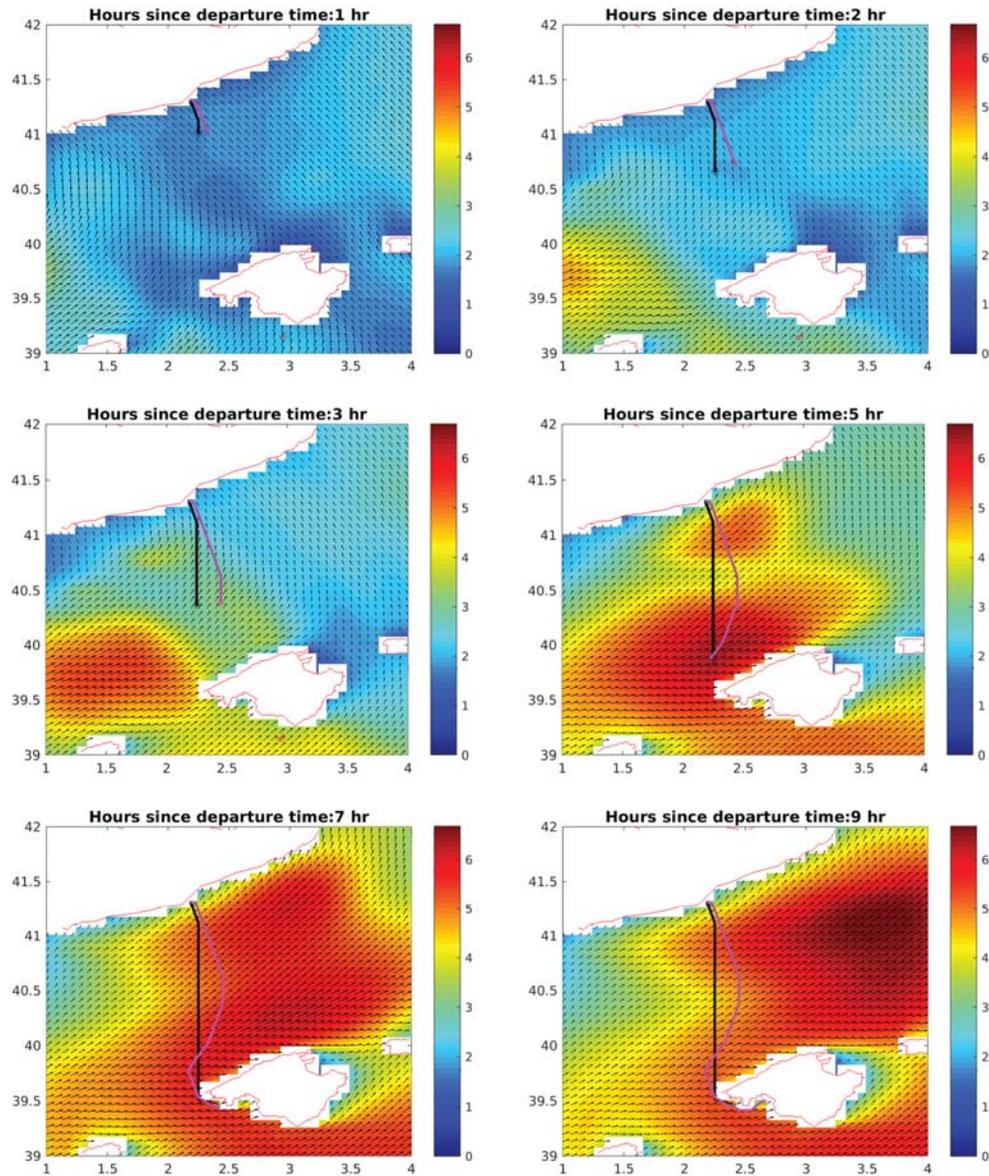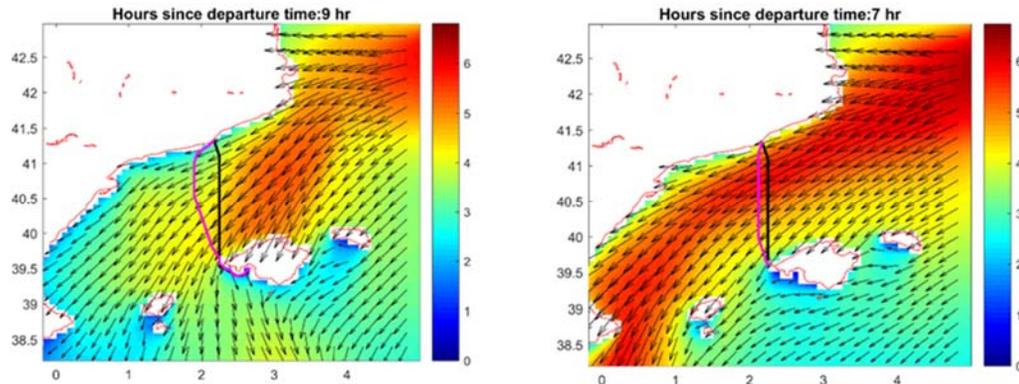
Fig. 2 – Temporal sequence of the snapshot of the case Barcelona – Palma de Mallorca. The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the H_S and the black arrows the propagation direction of the waves. This route corresponds to a departure time of 4/03/2017 00:00 h.

The snapshot shown in the Figure 3 reveals that similar maximum Hs leads differentiated optimal ship routing after 4 hours of the departure. In this case, the difference of the wave climate relies in the homogeneity of the storm instead of the maximum Hs (more spatial heterogeneity in the wave conditions shown in the Figure 3.left). In this sense, From a practical point of view, it is interesting to analyze the relation between the maximum H_S and

the increase of travel time in comparison to the time given by the minimum distance route (Figure 4.Left). This Figure shows how there is not significant correlation between H_S and the decrease of the travel time ($r=0.37$; $p>0.05$). The non-significant correlation of the optimal route and the wave climate is also shown in the relation between the maximum H_S and the increasing of the distance associated to the optimal route in comparison to the minimum distance (Figure 4.Right; $r=0.31$; $p>0.05$). In consequence, the determination of the optimal route is not only due to the H_S and wave direction (as suggested in Equation 2 and Table 1), but also the spatial evolution of the storm may have a relevant role on the determination of the optimal route.

Fig. 3 – Left: maximum H_S and the increase of travel time versus the time given by the minimum distance route in the 25 scenarios investigated. Right: maximum H_S versus the increasing of the distance associated to the optimal route in comparison to the minimum distance in the 25 scenarios investigated.

Fig. 4 – Left: Snapshot of the case Barcelona – Palma de Mallorca after 9 hours of departure for a departure time of 20/12/2016 at 06:00 h. Right: Snapshot of the case Barcelona – Palma de Mallorca after 7 hours of departure for a departure time of 22/01/2017 at 03:00 h. The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the H_S and the black arrows the propagation direction of the waves.

4. FINAL REMARKS

The ship route comparison (minimum distance versus optimal route) evidences the relevance of the wave effects on navigation. Even the short distance between Barcelona and Palma the reduction in terms on time sailed using ship routing may be substantial (7% of the total time). The analysis of the 25 episodes revealed a non-significant correlation between the travel time reduction and the maximum wave height occurred during the navigation route. In consequence, the benefit of ship routing would depends not only of the maximum wave height but also other wave parameters (such as wave direction) and the the spatial sequence of the storm.

This sailing time reduction may lead to substantial economic benefit. In this sense, Grifoll et al. (2018) quantify the economic benefit of using the ship routing methodology shown in this contribution for a Short-Sea Shipping activity (among Spanish and Italian ports). In this case, the percentage of economic cost savings may reach 18% of the total costs under severe storms considering bunkering, crew costs among other factors. This economic benefit of ship routing systems at ferry services distances justifies the use of these systems in the inclusion of 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 such as fleets management (Fagerholt, 2006) or scheduling orientation (Cho and Perakis, 2010). In our contribution, the ship weather routing implementation is accompanied with the developing of high-resolution meteo-oceanographic products (such as the products

provided by Puertos del Estado). In this sense, further works include the consideration of water currents and wind effects on navigation. Also, further research in the methodology includes the implementation of the method for dynamic wave states, the implementation of the multi-criteria algorithm or the methodological inclusion of safety restrictions due to the wave conditions (parametric rolling and broaching/surf-riding).

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