

# ENHANCEMENT OF MARITIME SAFETY AND ECONOMIC BENEFITS OF SHORT SEA SHIPPING SHIP ROUTING

M. Grifoll<sup>1</sup>, M. Castells<sup>2</sup>, and F.X. Martínez de Osés<sup>2</sup>

<sup>1</sup>Department of Civil and Environmental Engineering (DECA), Universitat Politècnica de Catalunya, BarcelonaTech, Spain, manel.grifoll@upc.edu

<sup>2</sup>Department of Engineering and Nautical Science, Universitat Politècnica de Catalunya, BarcelonaTech, Spain, mcastells@cen.upc.edu, fmartinez@cen.upc.edu

**ABSTRACT:** The relevance of ship routing system is increasing according to the mitigation of carbon emissions and enhance the maritime safety. New generation of high-resolution meteo-oceanographic predictions provides useful tools for ship routing. However, scientific efforts have been focused on inter-oceanic routes. This contribution investigates the economic benefits and improvement on safety navigation of ship routing of Short Sea Shipping (SSS) routes. The investigation is supported with the development of a ship routing system based on path finding algorithms and meteo-oceanographic predictions. The optimal ship routing analysis is investigated in a relative short distance maritime route between Barcelona and Palma de Mallorca (Spain). A\* algorithm and Dijkstra algorithm are implemented and compared in order to obtain the optimal path under an energetic wave event. The methodology is based on the inclusion of the added resistance due to waves. The results reveal how the wave direction has a relevant role in the optimum path due to the relative direction with the ship and the enhancement of the safety of navigational. Results show that the economic benefits using ship routing in SSS is estimated, in terms of time, during energetic wave episodes. 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, wave models, safety navigation*

## 1 INTRODUCTION

A major factor of competitiveness in the maritime industry is the minimization of fuel consumption for shipping 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). Academic research has focused the ship routing optimization through pathfinding algorithms (e.g. Takashima et al. (2009), Mannarini et al. (2013), Szałpczyńska and Śmierzchalsk (2009), Larsson and Simonsen (2014) and Hinnenthal (2008)) 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 relative short-distance the route shipping optimization remains unexplored, for instance in the framework of the Short Sea Shipping. In this case, the

spatial resolution of the meteo-oceanographic predictions is a severe restriction.

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. This leads to a multi-criteria problem solved with advanced optimization algorithms (e.g. NAMOA, genetic algorithm, etc.).

The objective of this contribution is to implement and discuss a ship routing algorithm in a relative short distance route in the Western Mediterranean sea (e.g. Barcelona – Palma de Mallorca; 132 nautical miles) using high-resolution wave numerical products and assess the enhancement of maritime safety and economic benefits (in terms of time). 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, and possibly the individual characteristics of a ship for a particular transit (Bowditch, 2002).

The article is structured into the following sections: after the introduction (Section 1), the Methods (Section 2) include the description of the algorithms used for route shipping, the wave numerical model description, the estimated of the speed loss due to waves and the grid discretization. The results are presented in Section 3 including the discussion of the wave effect on the ship routing. Finally, the conclusions and future developments are underlined in the last section (Section 4).

## 2 METHODS

### 2.1 Short Sea Shipping

The European Commission and Member States have observed that transport in Europe is growing at a high rate and that by 2020, the figures for inter-European transport including the EU new Member States will show a growth of over 50% in volume and that these values would be absorbed mostly by road transport. However, road transport poses rather more environmental problems than maritime transport, including a higher rate of congestion, pollution, noise and accidents.

Although Europe needs all modes of transportation to ensure the necessary mobility for people and business, Short Sea Shipping (SSS) integrated into an efficient transport chain appears to be a potential choice to avoid congestion, improve accessibility and to provide seamless transport routes. SSS accounted for 1.8 billion tonnes (Eurostat, 2016) in European Union (EU). Short Sea Shipping made up to 59% of total maritime transport of goods 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 2014. This means nearly 29% of the total of EU SSS tonnages for all sea regions in the same year.

### 2.2 Algorithms description and grid discretization

The pathfinding algorithms used in this work are the well-known Dijkstra Algorithm (Dijkstra, 1959) and A\*Algorithm (Dechter and Pearl, 1985). These algorithms are applied at gridded scheme where each grid point (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) distance is used for the spherical coordinates of the grid nodes.

Dijkstra algorithm in gridded meshes picks the unvisited vertex with the lowest distance, calculates the distance through it to each unvisited neighbor and updates the neighbor's distance if smaller. Dijkstra algorithm has been used previously in ship routing applications (Mannarini et al., 2016; Montes, 2005). A\* algorithm solves problems by searching among all possible paths to the solution (goal) for the one that incurs the smallest cost (least distance travelled, shortest time, etc..) and

among these paths it first considers the ones that appear to lead most quickly to the solution. It is formulated in terms of weighted graphs: starting from a specific node of a graph, 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 estimated of the cost (total weight) still to go to the goal node. Specifically, A\* selects the path that minimizes:

$$f(n) = g(n) + h(n) \quad (1)$$

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 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 the nearest goal node. In the case of the study, the heuristic function is the minimum distance between origin and destination.

Nodal connections possibilities per node may vary in function of the grid resolution. In consequence, the sequence of edges followed by the shortest path will be limited by the grid resolution and the connected nodes. Figure 1 shows the edges connecting nodes displayed by arrows for 4 different schemes: 4, 8, 16 and 24 edges. Each arrow represents potential ship courses or directions. Different grid resolution has been tested obtaining similar conclusions than (Mannarini et al., 2013), which stated that a minimum 16 edges are required in a prototype level.

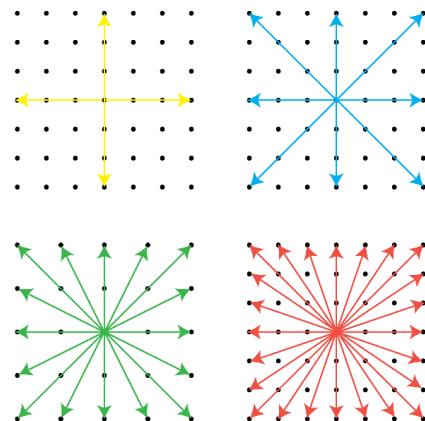


Figure 1. Scheme of the grid resolution in function of the number edges per node. In yellow 4 edges per node (top, left), in blue 8 edges per node (top, right), in green 16 edges per node (bottom, left) and in red 24 edges per node (bottom, right). For a grid cell, central node is the origin and the destination in the contiguous cell

### 2.3 Wave model description and effects on navigation

Ships are subject to difficult operating conditions, mainly because of the constant action of waves. Proper knowledge of the expected sea states is a significant factor in vessel safety.

Recently, advanced wave numerical models implementation provides high-resolution waves parameters due to an increase of the wind field resolution (Cavaleri et al., 2007). In this work, modelled wave outputs generated by the implementation of SWAN wave model system in the NW Mediterranean Sea is used (Grifoll et al., 2016) as a characteristic storm. SWAN model solves the wave action balance equation simulating wind generation and propagation in deep and coastal waters. Figure 2 shows the significant wave height and wave direction for a typical low pressure system located in the NW Mediterranean Sea. This synoptic configuration may generate strong winds and large significant wave height in the Catalan/Balearic Sea. In this academic example, the maximum significant wave height corresponds to 5 m.

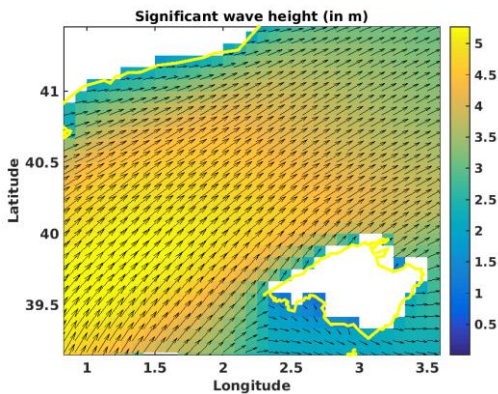


Figure 2. Significant wave height and wave direction modelled in the catalan/balearic sea. Arrows shown the propagation direction of the wave.

Wave action is the major factor that affects the ship performance and safety navigation (Hu et al., 2014). Wave field 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 to waves is suggested by (Bowditch, 2002). The final speed is computed in function of the non-wave affected speed ( $v_0$ ) plus a reduction in function of the wave parameters:

$$v = v_0 - f(\theta) \cdot H^2 \quad (2)$$

Where  $H$  is the significant wave height and  $f$  is a parameter in function of the relative ship wave direction (see Table 1).

Table 1. Values of the coefficient  $f$ .

Ship-wave relative direction	Wave direction	$f$ (in $\text{kn}/\text{ft}^2$ )
$0^\circ \leq \theta \leq 45^\circ$	Following seas	0.0083
$45^\circ < \theta < 135^\circ$	Beam seas	0.0165
$135^\circ \leq \theta \leq 225^\circ$	Head seas	0.0248
$225^\circ < \theta < 270^\circ$	Beam seas	0.0165
$270^\circ \leq \theta \leq 360^\circ$	Following seas	0.083

The relation of the wave direction related on ship navigation can be described as follows (Niclasen et al., 2010):

- Head seas: Sailing against the waves is in most cases the best way to negotiate a series of large waves, but this also inflicts the most violent forces on the vessel, increasing the danger of slamming and shifting of cargo. The impact forces can be limited, to some extent, by reducing the vessel speed, or altering course.
- Following seas: There are many factors that can have a negative impact on stability and ship handling when sailing in the same direction as the waves if the waves are high compared to a vessel. The most notorious is broaching, whereby the vessel is turned violently to one side, leaving it broadside to the oncoming waves. The risk of broaching can be reduced by reducing ship speed to a fraction of the wave speed; but this again increases the risk that overtaking waves wash along upper decks from astern without this being noticed by the operators on the bridge.
- Beam seas: Sailing in beam seas can results in large roll angles and, in extreme conditions, the vessel can capsize.
- Quartering sea: Large quartering waves are unfortunate because the vessel stability is affected by the negative effects of both beam and following seas.

### 3 RESULTS AND DISCUSSION

The algorithms and methodologies presented in the previous section have been applied to a relative short maritime route: Barcelona – Palma de Mallorca. The horizontal grid resolution was established in 16 edges per node. An analytical ship speed of 13 knots is considered.

Same results have been obtained using both algorithms, although using A\* algorithm a significant reduction in the computational time is obtained due to a decreasing of the computations (less nodes are considered).

The first path corresponds to the optimum path without considering the vessel resistance due to the waves (Figure 3). In this case, the route corresponds to the orthodromic distance between the origin and the arrival. Figure 4 shows the optimum path recovered by the algorithms

considering the added resistance of the wave field in the ship speed. Differences in both routes are evident: the optimum path considering the wave field sail to the East avoiding large significant wave height.

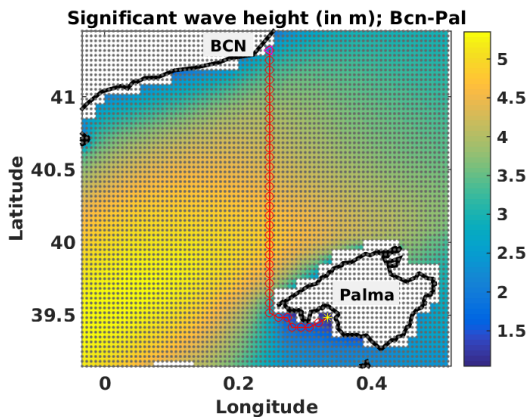


Figure 3. Optimum path recovered by the Dijkstra and A\* algorithms without considering the added resistance to the ship speed according to equation 1. Color bar and 2D color represents the significant wave height. Case Barcelona – Palma de Mallorca

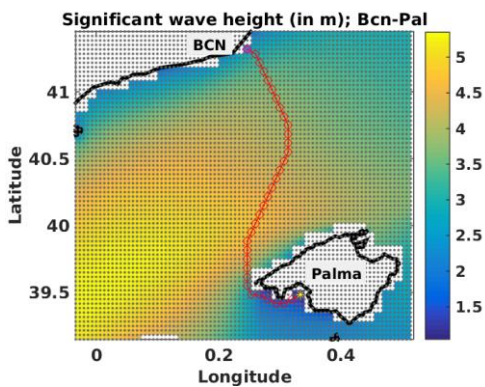


Figure 4. Optimum path recovered by the Dijkstra and A\* algorithms considering the added resistance to the ship speed according to equation 1. Color bar and 2D color represents the significant wave height. Case Barcelona – Palma de Mallorca

Considering the wave direction shown in Figure 2, seems clear how the optimum route avoid partially the most critical conditions which corresponds to head seas. The results of the function cost (in travel time) are summarized for the different paths in Table 2.

Table 2. Travel times (in hours) for the route Barcelona – Palma de Mallorca (and vice versa).

Route: Barcelona – Palma de Mallorca	hours
Travel time for the minimum distance case (without wave resistance)	10.2
Travel time for the minimum distance case (with wave resistance)	12.6
Travel time for the optimum route considering wave resistance.	12.1
Route: Palma de Mallorca - Barcelona	hours
Travel time for the minimum distance case (without wave resistance)	10.2
Travel time for the minimum distance case (with wave resistance)	13.0
Travel time for the optimum route considering wave resistance.	12.9

The travel time of the minimum distance path (without the added resistance due to the waves) is equal to 10.2 hours (minimum distance). However, considering the added resistance due to waves for the minimum distance path, the value raise to 12.6 hours. Obviously, this value is larger than the cost obtained by the shortest path recovered by the algorithm considering waves (i.e. 12.1 hours). In consequence, the implementation of the shortest path algorithm saves 0.5 hours with the consequent reduction in fuel consumption and saving costs.

Different picture occurs when the algorithm is applied to the inverse route: Palma de Mallorca – Barcelona (Figures 5 and 6). In this case both paths recovered by the algorithms (without and with waves) do not present substantial differences. The travel times obtained are similar (Table 2) and the only differences are appreciated in the vicinity of the West cape of the Mallorca Island where the beam sea is relevant. These results are also consistent with the wave direction (see Figure 2), which for Palma – Barcelona route was basically beam sea, in comparison with Barcelona – Palma where the head sea was prevalent.

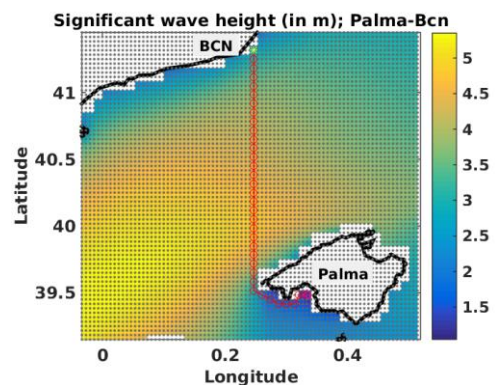


Figure 5. Optimum path recovered by the Dijkstra and A\* algorithms without considering the added resistance to the ship speed according to equation 1. Color bar and 2D color represents the significant wave height. Case Palma de Mallorca – Barcelona

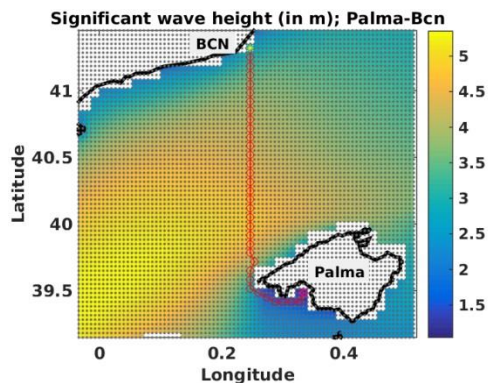


Figure 6. Optimum path recovered by the Dijkstra and  $A^*$  algorithms considering the added resistance to the ship speed according to equation 1. Color bar and 2D color represents the significant wave height. Case Palma de Mallorca – Barcelona

#### 4 CONCLUSIONS

The work presented in this contribution is an implementation of two different pathfinding algorithms, the Dijkstra algorithm and the  $A^*$  algorithm, for the optimum ship routing in a relative short oceanic distance. The methodology is based on the inclusion of the added resistance due to waves. Results obtained using both algorithms are the same but  $A^*$  algorithm presents a significant reduction of the computational time. The methodology has been applied to the maritime route Barcelona – Palma de Mallorca. 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 due to the wave characteristics.

This represent a relative short distance in comparison to mentioned applications oriented to oceanic maritime routes. This application is possible due to the new high-resolution products for waves and winds. The results showed here reveal how the wave direction has a relevant role in the optimum path due to the relative direction with the ship. Future works include the implementation of the system for dynamic wave states, the implementation of the multi-criteria algorithm (e.g. NAMOA or genetic algorithm), the inclusion of safety restrictions due to the wave conditions (surfriding or rolling motions) in the methodology or the influence of currents and winds in the optimum ship routing.

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