Ship-weather routing applied to Short Sea Distances: study of the feasibility of SIMROUTEv2 algorithm

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Abstract

Pathfinding algorithms to determine optimal ship routing for transoceanic distances have been widely used. However, the economic and marine environmental benefits of using ship routing for short distances have been little studied.

The main objective of this contribution was to evaluate the feasibility of the SIMROUTEv2 ship-weather routing algorithm in Short Sea Shipping routes, considering ship speed and weather conditions. A ship routing system was developed to obtain the optimal route and the minimum distance route from the A* pathfinding algorithm. The methodology considers the impact of added resistance of ships in waves in terms of time. Moreover, the basis for further development of an optimal route applied to relatively short distances and its systematic use in the Short Sea Shipping (SSS) maritime industry were established. Ship routing for four routes related to five ports in the Western Mediterranean Sea was analysed, with special emphasis on Short Sea Shipping activities and Ro-Pax and Ro-Ro services. The results highlight the benefits of using ship routing systems in short distances.

Keywords. *Ship routing, pathfinding algorithms, Short Sea Shipping, wave models, safety navigation, feasibility analysis*

Introduction

The European Community transport system has been overused because of the increase in intra communitarian commercial exchanges. Inland modes of transport have always predominated over maritime transport. The main problem regarding road transport is the massive number of trucks needed to transport a specific volume of goods. Fewer trucks on the roads would result in fewer pollutants in the atmosphere, lower traffic volume and fewer traffic accidents. This number would be reduced by using maritime transport, which would result in a significant reduction of emissions. From an environmental perspective, the actions of previous years have led to high emissions of polluting gases, resulting in an imbalance of gases in our atmosphere. This problem must be addressed since the vast majority of European Union countries are facing this issue. The solution hinges on an intermodal system, which emphasises maritime routes in general and Short Sea Shipping (SSS) in particular. Integration of SSS into an effective transport chain is a potential choice to avoid road congestion, enhance accessibility and provide ideal maritime routes.

Academic research has focused on ship routing optimisation 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 rely on meteo-oceanographic forecasts (i.e. wind, waves or currents predictions). There is a large number of ship-weather routing algorithms, but the algorithm used for evaluation of SSS routes is the brand new SIMROUTE v2 algorithm (Grifoll et al. 2016). Currently, its feasibility is based on spot checks on very specific routes. The present work aims to evaluate its feasibility for ship-weather routing by testing short-distance routes for different speeds and weather conditions.

Method

The feasibility study was performed on the Western Mediterranean area. Comprehensive analysis of the weather conditions in this region at several periods of the year was carried out. A summary of the SIMROUTEv2 algorithm and its structural basis (route function and wave function) was also conducted.

Ro-Ro and Ro-Pax vessels were chosen due to the benefits provided by them in terms of environmental protection, transport safety and decongestion of roads. The research was focused on two existing routes and two possible new routes that could be important in the future for SSS (see Figure 1). These four routes covered most of the Western Mediterranean Sea. They had one port in common, the port of Barcelona (Port of Barcelona, 2017). This port was chosen for its geostrategic position as well as the SSS growing process, which make it Spain's leading port in Ro-Ro and Ro-Pax as far as SSS is concerned (Ro-Ro & Ferry Atlas Europe 2014/2015).

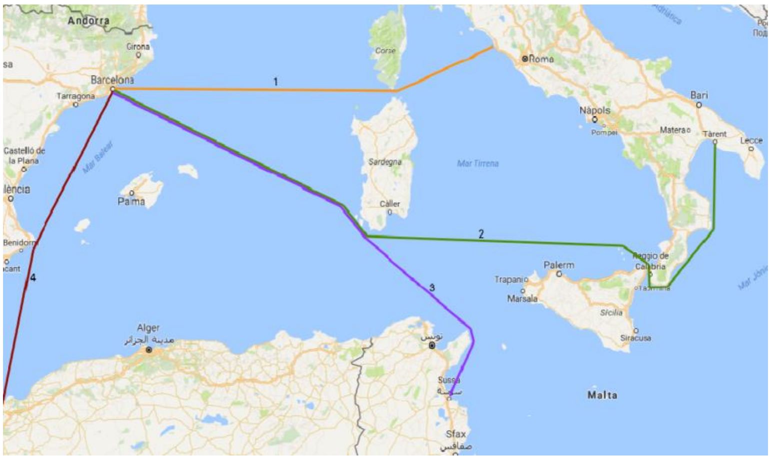

Figure 1: Tracks of the four studied routes: Barcelona-Civitavecchia (route 1), Barcelona-Taranto (route 2), Barcelona-Sousse (route 3) and Barcelona-Oran (route 4)

Several ship speeds were considered: 10 knots, 16 knots, 22.6 knots (SSS average speed) and 30 knots. In order to obtain all weather conditions, the Pilot Charts of the Mediterranean Sea (National Geospatial-Intelligence Agency, 2002) and several papers by Millot (1990) were studied. In addition, an extensive search through all scripts in the Spanish Port Agency (*Puertos del Estado* website) was done. For each route, wave scripts were searched considering the following significant wave heights (Hs): Calm-Smooth sea (0 metres), Moderate-Rough sea (1.25-2.50m/2.50-4.00m) and Rough-High sea (4.00-9.00m), and the following wave directions: Following Seas (FS), Beam Seas (BS) and Head Seas (HS).

SIMROUTEv2 is based on the A* pathfinding algorithm (Dechter and Pearl, 1985). The Dijkstra Algorithm (Dijkstra, 1959) was also tested but the A* pathfinding algorithm was considerably faster (Grifoll, 2016). An optimal route was obtained from SIMROUTEv2. This route was compared with the minimum distance route considering the weather conditions. A simple formula including wave affected speed reduction was suggested by Bowditch (2002). Final speed was computed in function of non-wave affected speed (v_0) plus a reduction in function of the wave parameters:

$$\boldsymbol{v}(\boldsymbol{H_s}, \boldsymbol{\Theta}) = \boldsymbol{v_0} - \boldsymbol{f}(\boldsymbol{\Theta}) \cdot \boldsymbol{H_s}^2 \qquad (1)$$

where f is a parameter in function of the ship-wave relative direction. The values of coefficient f are shown in Table 1.

Ship-wave relative direction	Wave direction	f (in kn/ft^2)
0º≤Θ≤45º	Following seas	0.0083
45º<Θ<135º	Beam seas	0.0165
135º≤Θ≤225º	Head seas	0.0248
225º< Θ<270º	Beam seas	0.0165
270º≤Θ≤360º	Following seas	0.0083

Table 1: Values of coefficient f.

The period of time from the initial to the final node of the optimal and minimum distance routes was calculated for each case by SIMROUTEv2.

Results

This section presents an application of the above theoretical methodology. Travel times of the considered routes and travel time using the optimal route compared to the minimum distance route (calculated by SIMROUTEv2) are summarised in Tables 2 and 3. Since most of studied routes last from 1 to 3 days, differences in wave heights can occur. The wave height used in each case (Calm-Smooth sea, Moderate-Rough sea and Rough-High sea) is the main sea affecting the route for a considerable period of time.

Table 2 shows the results obtained considering Calm-Smooth sea. Wave directions are negligible in this case but were considered in the other cases (Moderate-Rough sea and Rough-High sea).

Route	Barcelona - Civitavecchia				Barcelona - Sousse				Barcelona – Oran				Barcelona - Taranto			
Ship speed (knots)	10	16	22.6	30	10	16	22.6	30	10	16	22.6	30	10	16	22.6	30
Minimum distance route (hours)	44.11	19.49	19.49	14.67	57.46	35.9	25.41	19.13	35.11	21.89	15.48	11.65	89.21	55.71	39.42	29.84
Optimal route (hours)	44.11	19.49	19.49	14.67	57.46	35.9	25.41	19.13	35.11	21.89	15.48	11.65	89.21	55.71	39.42	29.84
Saved travel time (hours)	0				0				0				0			

Table 2: Simulation results of travel time saved using the optimal route in comparison to the minimum distance route for all cases with Calm-Smooth sea (0-0.5m) and ship speeds of 10 knots, 16 knots, 22.6 knots and 30 knots.

Table 3 shows results considering all the routes, wave directions with Moderate-Rough sea and ship speed of10 knots.

Route	Barcelona – Civitavecchia		Barcelona - Sousse		Barcelona – Oran			Barcelona - Taranto		
Wave direction	Head Sea	Beam Seas/ Following Sea	Beam Seas	Beam Seas	Beam Seas	Following Sea	Following Sea / Beam Seas	Beam Seas/ Head Sea	Following Sea / Beam Seas	Beam Seas/ Head Sea
Wave height average (metres)	1.50	1.58	1.11	2.0	1.48	2.45	1.69	0.76	1.27	1.34
Minimum distance route (hours)	44.94	48.39	58.1	60.47	37.14	38.64	44.58	89.59	92.84	91.70
Optimal route (hours)	44.94	48.30	58.1	60.35	36.70	38.07	41.48	89.59	92.57	91.47
Saved travel time (hours)	0	0.09 (0.17%)	0	0.12 (0.19%)	0.44 (1.19%)	0.57 (1.47%)	3.1 (7.21%)	0	0.27 (0.29%)	0.23 (0.25%)

Table 3: Simulation results of travel time saved using the optimal route in comparison to the minimum distance route for all cases with Moderate-Rough sea (1.25-4m) and ship speed of 10 knots.

As can be seen in the above tables, the travel time saved using the optimal route depends on the route, ship speed, wave direction and significant wave height. Some of the most outstanding results are presented as follows:

Barcelona-Oran route (21/01/2017). Rough-High sea: 4-9 metres. Predominant wave direction: Following sea. Initial speed: 22.6 knots (see Figure 2). This case provided the most remarkable results. Although head sea is the most critical wave direction, the following sea on that day altered the speed of the vessel substantially. The following sea had a negative effect on speed because the height of the waves was between 4 and 7 metres. The shortest path, without added wave resistance, took 15.44 hours. Travel time changed when the wave field was taken into account. Considering added wave resistance, travel time increased to 23.73 hours. However, most of the large high sea period was avoided with the optimum path. Thus, travel time decreased to 20.03 hours. This demonstrates that the algorithm optimisation leads to a 3.70 hour time saving.

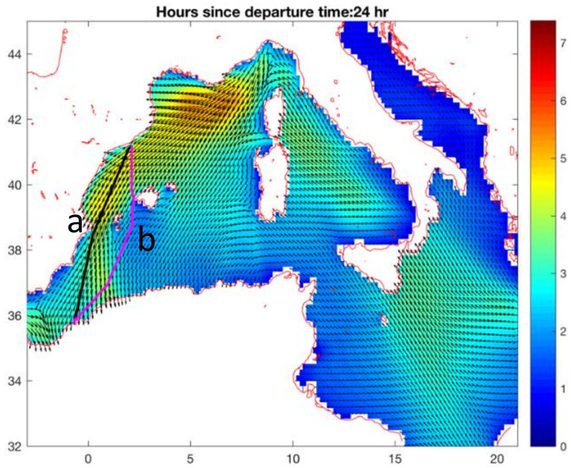

Figure 2: Minimum distance route (a) and Optimal route (b) from Barcelona to Oran on 21/01/2017. Estimated Time Departure (ETD): 20h. Initial speed: 22.6kn. Colour bar represents wave height.

Table 4 shows results of the Barcelona–Oran route on 21/01/2017 considering several ship speeds and maximum wave height encountered.

Speed (knots)	**Maximum wave height (metres)**	**Minimum distance route (hours)**	**Optimal route (hours)**	**Saved travel time (hours)**
10	6.91	The ship cannot sail because of maximum wave height conditions	50.47	The ship cannot sail because of maximum wave height conditions
16	7.29	35.66	30.03	5.63
22.6	7.04	23.7	20.03	3.7
30	6.99	16.21	14.45	1.76

Table 4: Barcelona–Oran (21/01/2017).

Barcelona-Sousse (Date: 20/12/2016). Rough-High sea: 4-9 metres. Predominant wave direction: Beam/Following seas. Initial speed: 10 knots (see Figure 3). At the start of the route between Palma de Mallorca and Barcelona, the weather conditions were challenging, with waves from 4 to 4.90 metres. The predominant beam seas had a negative effect on the stability of the vessel, leading to a reduction in speed. When the vessel was passing the area of sea surrounded by North Africa, Palma de Mallorca and Sardinia, following sea (waves from 1.50 to 3 metres) prevailed. The waves during this period had a positive impact on speed. The minimum distance route, without added wave resistance, took 57.26 hours. Travel time changed when the wave field was taken into account. Considering added wave resistance, travel time increased to 69.57 hours. However, most of the large high sea period was avoided with the optimal route path. Thus, travel time decreased to 67.41 hours. This demonstrates that the algorithm optimisation leads to a 2.16 hour time saving.

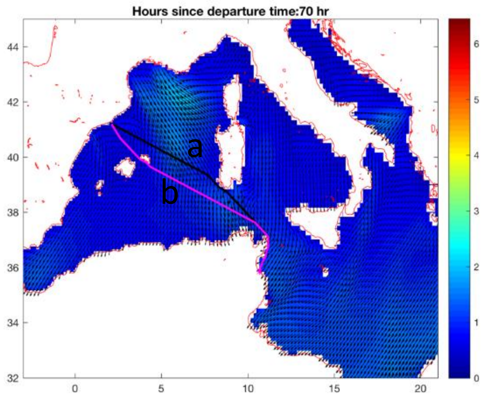

Figure 3: Minimum distance route (a) and Optimal route (b) from Barcelona to Sousse on 20/12/2016. ETD: 13h. Initial speed: 10kn. Colour bar represents wave height.

Table 5 shows results of the Barcelona–Sousse route on 20/12/2016 considering several ship speeds and maximum wave height encountered.

Speed (knots)	Maximum wave height (metres)	Minimum distance route (hours)	Optimal route (hours)	Saved travel time (hours)
10	4.90	69.57	67.41	2.16
16	5.21	39.16	39.12	0.04
22.6	5.30	27.06	27.06	0
30	5.30	20.07	20.07	0

Table 5: Barcelona–Sousse (20/12/2016). All cases.

Barcelona-Civitavecchia (Date: 20/12/2016). Rough-High sea: 4-9 metres. Predominant wave direction: Beam/Head seas. Initial speed: 10 knots (see Figure 4). This case was surprising because the track of the optimal route differed significantly from that of the minimum distance route. In the area of sea surrounded by Barcelona, Palma de Mallorca, Corsica and Sardinia, following sea prevailed. The height of the waves (4 to 4.80 metres) had a negative impact on speed. The minimum distance route, without added wave resistance, took 43.96 hours. Travel time changed when the wave field was taken into account. Considering added waves resistance, travel time increased to 50.70 hours. However, most of the large high sea period was avoided with the optimal route. Thus, travel time decreased to 49.72 hours. This demonstrates that the algorithm optimisation leads to a 0.96 hour time saving.

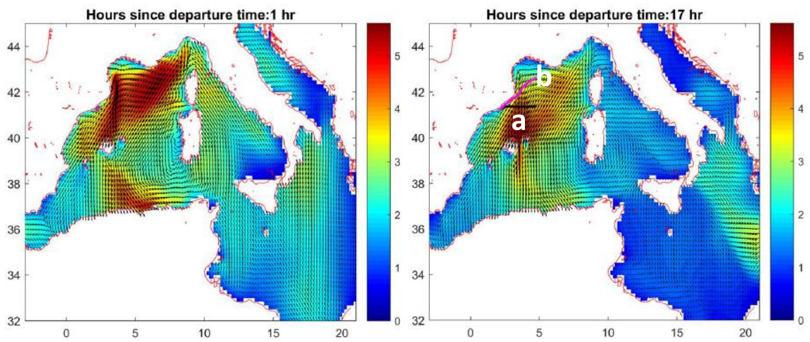

Figure 4: Minimum distance route (a) and Optimal route (b) from Barcelona to Civitavecchia on 20/12/2016. ETD: 21h. Initial speed: 10kn. Colour bar represents wave height.

Table 6 shows results of the Barcelona – Civitavecchia route on 20/12/2016 considering several ship speeds and maximum wave height encountered.

Speed (knots)	Maximum wave height (metres)	Minimum distance route (hours)	Optimal route (hours)	Saved travel time (hours)
10	4.78	50.70	49.72	0.96
16	5.43	31.44	30.96	0.48
22.6	5.48	21.44	21.26	0.18
30	5.40	15.64	15.60	0.04

Table 6: Barcelona–Civitavecchia (20/12/2016). All cases.

Barcelona-Taranto (Date: 18/12/2016). Rough-High sea: 4-9 metres. Predominant wave direction: Head seas. Initial speed: 16 knots (see Figure 5). In this case, the vessel altered the course and changed the direction entirely when passing between Corsica and Sardinia. This change of course was necessary due to the extensive high wave field (maximum wave height of 5.53 metres) in the area of sea surrounded by Tunisia, Sardinia and Sicily. The critical head sea had a negative effect on the vessel taking the minimum distance route because of high wave resistance. The minimum distance route, without added wave resistance, took 55.44 hours. Travel time changed when the wave field was taken into account. Considering added wave resistance, travel time increased to 60.86 hours. However, most of the large high sea period was avoided with the optimal route. Thus, travel time decreased to 58.37 hours. This demonstrates that the algorithm optimisation leads to a 2.49 hour time saving.

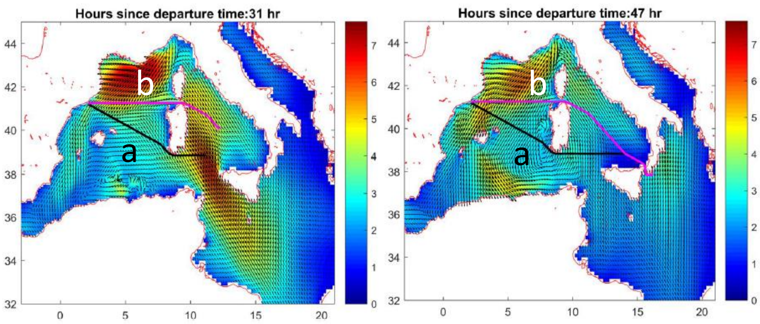

Figure 5: Minimum distance route (a) and Optimal route (b) from Barcelona to Taranto on 18/12/2016. ETD: 20h. Initial speed: 16kn. Colour bar represents wave height.

Table 7 shows results of the Barcelona–Civitavecchia route on 18/12/2016, considering several ship speeds and maximum wave height encountered.

Speed (knots)	Maximum wave height (metres)	Minimum distance route (hours)	Optimal route (hours)	Saved travel time (hours)
16	4.40	60.86	58.37	2.49
22.6	2.97	40.72	40.28	0.44
30	2.23	30.09	29.92	0.17

Table 7: Barcelona–Taranto (18/12/2016). All cases.

Conclusions

The present work studied the feasibility of the SIMROUTEv2 algorithm using a large number of cases. It was observed that if the wave field was not so wide, it was possible to avoid it and save time. Additionally, if the wave field extended along the route, the time difference between the optimal route and the minimum distance route was still more considerable. On the other hand, if the wave field was very wide and/or with a few extensions along the route (1 or 2 hours), the time saving percentage was 0%.

In the case of Calm-Smooth seas (almost negligible wave height), the optimal route was exactly the same as the minimum distance route. In consequence, the difference in time saving percentage was 0 in all cases and for all the routes. This means that the algorithm is not useful in Calm-Smooth sea conditions. In the case of Moderate-Rough sea, the algorithm can be feasible at ship speeds between 10 and 20 knots; in these cases, if the wave field is wide, time savings with the optimal route are considerable (between 0.25 and 2.5 hours). If high speed vessels (>23 knots) are considered, waves between 1.5m and 3m do not affect speed, and therefore time savings are negligible.

Finally, in Rough-High sea conditions, waves were more powerful than the vessel in most cases (maximum wave height >6 metres) for a speed of 10 knots. In this situation, the vessel is forced in reverse, which is ultimately detrimental to the engine. In some cases, the minimum distance route could not be taken by the vessels whereas the optimal route was always feasible by taking a different route while also adding travel time. For a speed of 16 knots, travel time savings varied considerably, i.e. ranging from 0.35 hours to 5.35 hours (in the extreme case of the Barcelona-Oran route), except for those cases where savings were 0 hours due to the wide wave field. In this situation, the vessel would not have taken a redirected route to avoid the waves because this would result in a significant increase in travel time. For speeds between 22.6 and 30 knots, time savings tended to be 0 hours, not including the Oran case, where the wave field extended along the route. In the Barcelona –Oran route, the optimum path avoided this field, leading to time savings between 3.70 hours and 1.76 hours, respectively.

To conclude, Table 8 shows general results of the feasibility of SIMROUTEv2 for Short Sea Shipping routes:

	10 knots	**16 knots**	**22.6 knots**	**30 knots**
Calm-Smooth	No	No	No	No
Moderate-Rough (FS)	No	No	No	No
Moderate-Rough (BS)	½	½	No	No
Moderate-Rough (HS)	½	½	No	No

Rough-High (FS)	**Yes**	**Yes**	½	½
Rough-High (BS)	**Yes**	**Yes**	½	½
Rough-High (HS)	**Yes**	**Yes**	**Yes**	**Yes**

Table 8: Feasibility analysis considering all cases. FS (Following sea); BS (Beam seas); HS (Head sea). Yes (feasible); No (not feasible); ½ (meaning that not all cases were feasible).

Future work will include the implementation of dynamic wave systems, implementation of a multi-criteria algorithm (e.g. NAMOA or genetic algorithm) including safety restrictions due to wave conditions (surf riding or rolling motions) in the methodology and the influence of currents and winds in optimum ship routing.

References

[1] BOWDITCH, N., 2002. The American practical navigator. *National Imagery and Mapping Agency*, Bethesda, Maryland, USA.

[2] DECHTER, R., and PEARL, J., 1985. Generalized best-first search strategies and the optimality of A*. *Journal of the ACM*, Vol. 32, Issue 3, 505–536.

[3] DIJKSTRA, E.W., 1959. A note on two problems in connection with graphs. *Numerische Mathematik*, Vol.1: 269–271.

[4] GRIFOLL, M., CASTELLS, M., MARTINEZ, F. X., 2016. Enhancement of Maritime Safety and Economic Benefits of Short Sea Shipping Ship Routing. A: International Seahorse Conference: maritime safety and human factors. *Proceedings of SEAHORSE 2016, International Conference on Maritime Safety and Human Factors.* Glasgow

[5] GRIFOLL, M., 2016. Ship routing applied at short sea distances. *Proceedings of 7th International Conference on Maritime Transport*, Barcelona. ISBN: 978-84-9880-591-8

[6] HINNENTHAL, J., and GÜNTHER, C., 2010. Robust Pareto optimum routing of ships utilizing deterministic and ensemble weather forecasts. *Ships And Offshore Structures*, Vol. 5, Iss. 2: 105-114.

[7] LARSSON, E., and SIMONSEN, M H., 2014. *DIRECT weather routing*. Master's thesis, Department of Shipping and Marine Technology, Chalmers University of Technology, Gothenburg, Sweden.

[8] MANNARINI, G., 2013. A Prototype of Ship Routing Decision Support System for an Operational Oceanographic Service, In: *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 7 (1), pp. 53-59.

[9] MILLOT, C., 1990. Circulation in the Western Mediterranean Sea, *Journal of Marine Systems 20*, 423-442

[10] NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY, 2002. Pilot chart of the Mediterranean Sea (November). *Atlas of Pilots Charts North Atlantic Ocean (including Gulf of Mexico).*

[11] PORT DE BARCELONA, 2017. *Press dossier February*. [viewed 05/03/2017]. Available from: http://content.portdebarce-lona.cat/cntmng/d/d/workspace/SpacesStore/9779453c-2269-4f07-9640-465862b81716/Dos-sier_en.pdf.

[12] SZŁAPCZYŃSKA, J., and ŚMIERZCHALSKI, R., 2009. Multicriteria Optimisation in Weather Routing. In: *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 3 (4), pp. 393-400.

[13] TAKASHIMA, K., MEZAOUI, B., and SHOJI, R., 2009. On the Fuel Saving Operation for Coastal Merchant Ships using Weather Routing. In: *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 3 (4), pp. 401-406.