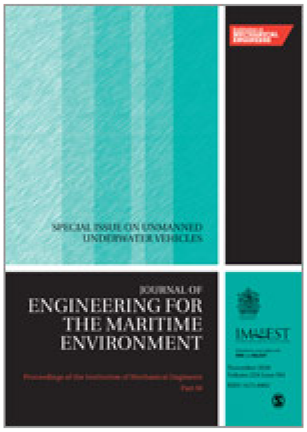

Ship emissions reduction using weather ship routing optimisation

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	distance.

SHIP EMISSIONS REDUCTION USING WEATHER SHIP ROUTING OPTIMISATION

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Abstract

A significant proportion of global carbon dioxide emissions are attributed to ocean-sailing ships and shipping emissions are predicted to double in less than 30 years. This paper investigates the benefit of using weather ship routing optimisation, assessing the ship emissions for minimum distance routes and optimised routes. A heuristic pathfinding algorithm is used to obtain the minimum cost (i.e. optimised route) in terms of sailing time, using high-resolution wave forecasting. The assessment of fuel consumption and ship emissions calculations were inspired by the STEAM2 bottom-up approach, in conjunction with the estimation of the power increase needed to overcome speed decrement due to waves. Several scenarios covering the Western Mediterranean Short Sea Shipping routes (from 24 to 600 nautical miles and using a real Ro-Pax vessel) are compared in terms of emissions between the minimum distance route and the optimum. The ship routing optimisation reveals a reduction up to 30% of ship emissions during severe storms on longer routes. Nevertheless, all the cases studied show emissions mitigation when ship routing optimisation is used. The expected increase of extreme weather events, in terms of frequency, intensity and duration due to climate change, suggests a gradual gain of implementing weather ship routing optimisation in all types of routes, regardless of the distance.

Keywords: weather ship routing, fuel consumption, shipping emissions, climate change, Short Sea Shipping

Introduction

Greenhouse gas emissions from shipping increased by 9.6% from 2012 to 2018, amounting to some 1076 million tonnes. Even though there has been an improvement of 11%, in terms of carbon intensity over the aforementioned years, the increase in maritime sector activities has overrun this gain. Notwithstanding the efforts to improve maritime transport efficiency, shipping emissions are predicted to increase by 50% by 2050 (vis-a-vis 2018) as a consequence of escalating transport demand.[1]

The world is currently facing a pandemic, which will probably show a temporary decline in the amount of worldwide emissions. Nevertheless, it must be considered that emissions projections for the upcoming years may not be influenced by this situation. Therefore, initiatives that include a cost-effective, potential reduction in shipping emissions have to be strengthened. For instance, slow steaming, the use of contra-rotating propellers and propulsion efficiency devices, can deliver fuel savings and, thus, reduce emissions.[2,3,4] Furthermore, other strategies are valuable in terms of mitigating emissions, such as the use of low sulphur fuels,[5] burning alternative fuels such as liquified natural gas (LNG),[6] the use of electric auxiliary propulsion during slow speed sailing[7] or the installation of abatement techniques such as scrubbers, inter alia. Bui et al. proposed a multi-criteria decision-making method for the selection of technological alternatives for environmental regulatory compliance.[8] Among the strategies to be applied at a later stage than vessel design, Weather Ship Routing (WSR) (defined as the development of an optimum sailing course and speed for ocean voyages based on forecasted sea conditions), [9] is a robust alternative for reducing external and internal costs. This means that, by avoiding adverse weather conditions using WSR, a reduction of the fuel consumption and the mitigation of ship emissions can be achieved.

Several initiatives have focused on the impact of WSR, in terms of cost function optimisation, using different methodologies such as genetic algorithms, pathfinding algorithms or isochrone methods, among others.[9–13] Wave action has been revealed as the major factor that affects the ship performance.[14,15] Wave fields affect ship motion, decreasing the propeller thrust and adding resistance, compared to the absence of waves. The resistance of a ship is roughly proportional to the square of the ship's speed and, as a result, the power requirement can be assumed to be proportional to the cube of its speed in calm waters, achieving even higher values in off-design conditions.[16] Consequently, in terms of fuel saving and ship emissions mitigation, vessel's speed is the key issue due to the relationship between the increase of speed and the required propulsive power. However, the impact of route optimisation on ship emissions has still not been evaluated systematically. In this sense, the main objective of this contribution is to assess shipping emissions, considering WSR optimisation. This leads to benefits such as fuel consumption reduction, which contributes to climate change slowdown. The degradation of a ship's performance due to hitting waves is also minimised by choosing an optimised route which would follow the most suitable headings. In order to carry out emission assessments for ongoing ships, there are several methodologies to be applied which include both top-down and bottom-up approaches. The aforementioned methodologies are essentially Ship Based Methods (SBM) which emphasise the collection of on-board data for each individual vessel, and Theoretical Based Methods (TBM) that obtain their results via modelling with no data recorded on-board.[17] The methodology used in this study was inspired by a TBM with a bottom-up approach, as described in Section 2. TBM, which includes input variables such as installed power per engine or engine load, was successfully applied in Ro-Pax ships by Jalkanen et al.[18,19] Furthermore, Zis et al. presented a case study using this methodology in the same type of ship operating in the Arctic Sea.[20]

This paper is structured as follows: after the Introduction (Section 1), the Methods and Tools (Section 2) include a brief description of the WSR software used, the ship emissions assessment formulation and the case description used in the analysis (i.e. short sea shipping services in the Western Mediterranean Sea). Section 3 shows the Results from the case study, including the optimised cost (i.e. sailing time) provided by the WSR software and the emissions assessed using the TBM methodology selected. The Discussion (Section 4) describes the feasibility and the limitations of the assumptions made, a comparison of the results with other contributions and the results in terms of wave field. Finally, the conclusions and future developments are underlined in the last section (Section 5).

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Methods and Tools

Weather ship routing software

Weather Ship Routing has been continuously developed in recent years. Since the seminal works presented by Bowditch[21], several academic researchers have explored different methods to find the optimal path, such as pathfinding algorithms (e.g. Dijkstra algorithm[22] or A* algorithm[23] inter alia), genetic algorithms, isochrones methods or the rise of artificial intelligence and machine learning.[16] Some of the mentioned contributions used weather data and forecasts for wave and wind fields [24,12,13,25] covering short and long distance routes, applied to different shipping vessels (e.g. Ro-Ro, dry bulk, etc.).

The weather routing software used in this work was SIMROUTE. SIMROUTE was used to obtain the optimised route in several cases in the Western Mediterranean Sea.[26,27] This software uses the A* pathfinding algorithm which is applied as a gridded mesh, where each grid point (node) is connected to a set of vicinity points. [27] In order to reduce the computational time, a heuristic function was used (i.e. minimum distance between origin and destination) to complement the cost function (i.e. sailing time). The code structure consists of a sequential execution of Matlab scripts, obtaining the optimised and minimum distance routes from the previous definition of a computational mesh according to the selected longitude and latitude domain. The optimised route considers the wave action, i.e. the optimum route may eventually lead to a shorter sailing time compared to the minimum distance route due to the potential effect of waves on navigation, which reduce the ship speed. Post-processing tools include emission assessment formulas, according to the methodology shown in the next section.

The methodology proposed is shown in Figure 1. First, several initial parameters are required: (i) route characteristics (port of departure and port of arrival) and the period to study (day/month/year); (ii) vessel characteristics (length, deadweight (*DWT*), cruising speed) and (iii) the wave field for the sailing days, planned from EU Copernicus Marine Environmental

Monitoring Service (CMEMS).[28] Second, the minimum and optimal routes are obtained for the selected period. Then, technical data from the IHS Markit Sea-Web database[29] (engine power, design speed, lowest possible specific fuel oil consumption and the engine load) are used to estimate emissions. Finally, the percentage of fuel savings and emission mitigation are obtained.

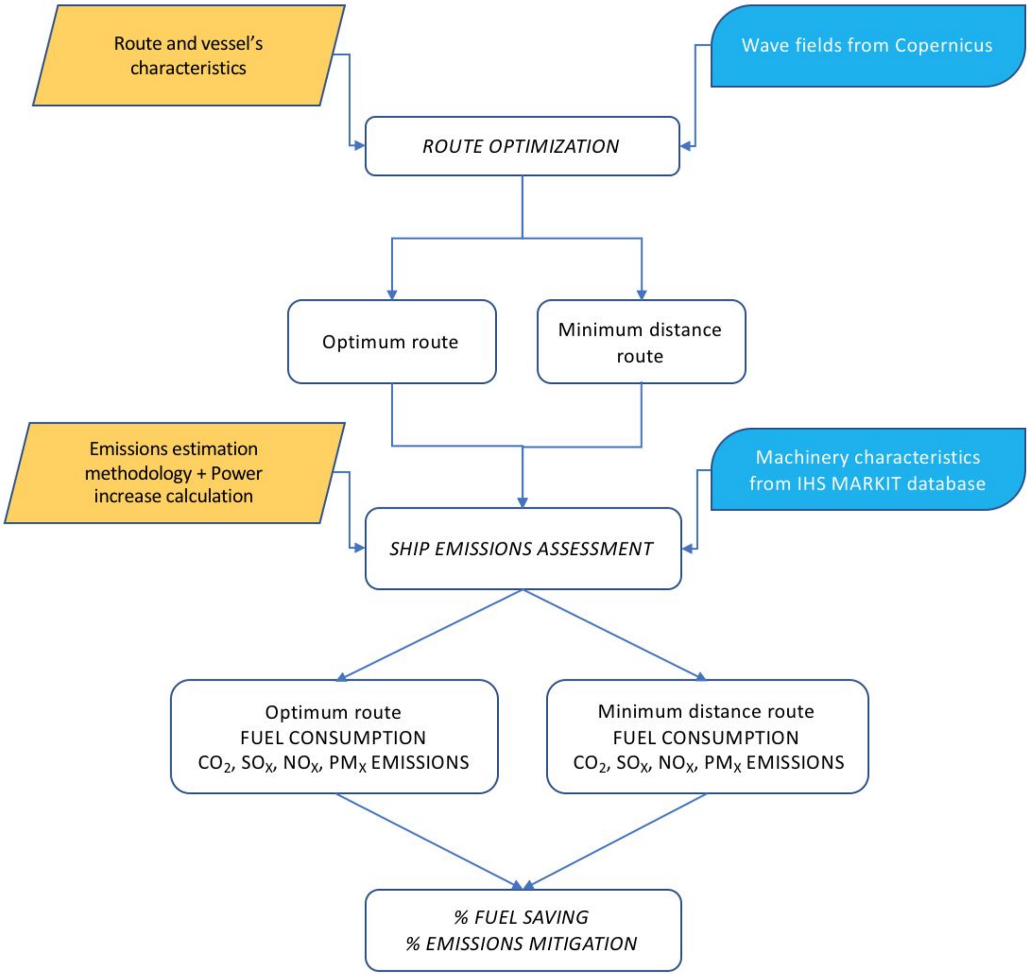

Figure 1. Methodology used including route optimisation (i.e. SIMROUTE) and ship emission assessment. Information obtained from external database in blue and parameters introduced by the user in yellow.

Daily wave information is obtained from the Copernicus Marine Service (CMEMS). As the cases selected are routes in the Mediterranean Sea, the MEDSEA product is used to provide wave information.[30,31] SIMROUTE also includes three different parametrisations of the wave effect on navigation: Aertssen,[32] Khoklov (suggested by Lubkovsky)[33] and Bowditch.[21] As can be seen in Borén et al.,[34] these formulations consider different wave parameters (i.e.

significant wave height and wave direction) and different ship characteristics, penalising ship speed as the significant wave height increases.

Ship emissions assessment and inclusion into SIMROUTE

STEAM2 methodology[18,19] allows the evaluation of the exhaust emissions of marine traffic based on the messages provided by the Automatic Identification System (AIS). The evaluation of [18,19] in WSR was already discussed in Borén et al.,[17] concluding that this method uses ship specific data to obtain more accurate calculations as it is a bottom-up methodology. This methodology allows the estimation of the amount of Sulphur dioxide (SO_2), carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM_x) emitted. The required data for emissions assessment and main assumptions for the study cases are shown in Table 1.

Table 1. Required data for emission assessment methodology

Input data	Acronym	Assumptions
Installed power per engine (in kW)	$P_{Installed}$	From IHS Markit database
Engine Load	*EL*	According to[19], EL's values are around 70% to 80%
Specific Fuel Oil Consumption (in g/kWh)	*SFOC*	From the corresponding manufacturer's project guide of the engine
Design speed (in knots)	V_{design}	From IHS Markit database
Sulphur and Carbon Content of fuel (in mass percentage)	*SC/CC*	Depends on the fuel burnt
Main Engine Revolutions per Minute (in rpm)	*Rpm*	If engine data is unavailable, the ship is assumed to use a 500 rpm medium speed diesel engine by default
Molar mass of Sulphur/Sulphur dioxide/Carbon/Carbon dioxide (in g/mol)	$M(S)/M(SO_2)/$ $M(C)/M(CO_2)$	

Total emissions for each pollutant (E_{Tp}) per ship and per route is the sum of the amount of pollutant (p) emitted into the atmosphere and can be obtained by applying the following formula,[35] changing the emissions factor related to one pollutant or another:

$$E_{T_p} = P \cdot EL \cdot EF_p \cdot t \qquad (1)$$

Where P is the average output power (in kW), EL is the engine load, EF is the emission factor of each pollutant (according to Table 2) and t (in hours) is the total time sailed.

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Table 2. Summary table of the *EF* for each pollutant

Sulphur dioxide (SO_2)	$\boldsymbol{EF(SO_2) = M(SO_2) \cdot n(SO_2) = M(SO_2) \cdot n(S) = M(SO_2) \cdot \frac{SFOC \cdot SC}{M(S)}}$ *(g/kWh)*
Carbon dioxide (CO_2)	$EF(CO_2) = M(CO_2) \cdot n(CO_2) = M(CO_2) \cdot n(C) = M(CO_2) \cdot \frac{SFOC \cdot CC}{M(C)}$ *(g/kWh)*
Nitrogen oxides (NO_x)	$EF\,(NOx) = \begin{cases} 17(rpm < 130) \\ 45^{rpm^{-0.2}}(130 < rpm < 2000) \\ 9.8(rpm > 2000) \end{cases}$
Particulate Matter (PM)	$EF(PM) = SFOC_{REL}(EF_{SO4} + EF_{H2O} + EF_{OC}OC_{EL} + EF_{EC} + EF_{ASH})$ Where: $SFOC_{REL} = 0.455EL^2 - 0.71EL + 1.28$; $SFOC = SFOC_{REL} \cdot SFOC_{MANUFACTURER}$

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In general, the aforementioned power P is the power output at Normal Service Rating (*NSR*), P_{NSR}, which is the power needed to sail at cruising speed. This *NSR* is usually lower than the Maximum Continuous Rating (*MCR*), defined as the maximum output power for the engine running under safe condition in a continuous manner (P_{MCR}) to maintain design speed. The relation between the *MCR* and the installed power ($P_{Installed}$) is defined as Engine Load (*EL*). The engine manufacturer will state the *EL* for running the engine at the most efficient condition as well as the specific fuel oil consumption of the engine (*SFOC*) under such conditions, knowing that *SFOC* is the measure of mass of fuel consumed per unit of time to produce 1 kW. However, when the vessel faces different sailing situations, this *EL* and *SFOC* will change if cruising speed has to be maintained. In order to assess emissions calculations, the power delivered by the engine has to be analysed in the different meteo-oceanographic conditions. For that purpose, an instantaneous power has to be defined for each of the intervals analysed over the route. Jalkanen et al. suggest a solution for assessing instantaneous power, assuming that frictional, residual, appendage and air resistances are ship-specific constants (Eq. 3).[19] The formula for the instantaneous power ($P_{Instant}$) is, thus, expressed as follows:

$$P_{Instant} = k \cdot v_{Instant}^3 \qquad (2)$$

where k is obtained from the required methodology's data (see Table 1):

$$k = \left(\frac{EL \cdot P_{Installed}}{(V_{design})^3}\right) \qquad (3)$$

SIMROUTE provides a grid-based itinerary, the node-to-node being defined as an interval (i) and a correspondent sailing time (Δt). In consequence, the average instantaneous power per time interval, in terms of the vessel's instantaneous speed ($v_{Instant}$), was estimated highlighting that the power varies as v^3.

The emissions module considers the involuntary speed loss of the vessel due to waves. The effect of bad weather could be treated as a vessel's speed reduction for a given engine power, or an increase in engine power in order to maintain cruising speed. In this case, we consider the second option of maintaining cruising speed in order to accomplish the Estimated Time Arrival (ETA) of the vessel. Therefore, the increase in power (ΔP) needed to maintain the cruising speed as a function of the speed reduction (ΔV) due to waves is obtained by Molland et al.:[36]

$$\Delta P = \left(\frac{1}{\left(1 - \frac{\Delta V}{V_{cruising}}\right)^3} - 1 \right) \cdot P_{Instant} \qquad (4)$$

Once the power increase (ΔP) is computed, the power required to maintain speed can be calculated for each interval (P_i^{new}):

$$P_i^{new} = P_{NSR} + \Delta P_i \qquad (5)$$

The same process is followed for both routes (i.e. the minimum distance and the optimised one proposed by the software). Afterwards, considering the change in specific fuel oil consumption ($SFOC_i^{new}$), the total fuel consumption (FC) in tonnes is calculated for the routes, using Eq.6:

$$FC = \sum_{i=0}^{n} P_i^{new} \cdot SFOC_i^{new} \cdot \Delta t_i \qquad (6)$$

n being the number of intervals and t the time from node-to-node for each interval.

Using the values obtained for P_i^{new}, $SFOC_i^{new}$, the emission factors derived from Table 2 and considering the change in Engine Load per interval (EL_i^{new}), the total amount of each pollutant emission can be assessed by adapting equation *(1)* to the pollutant analysed, as shown below:

$$\boldsymbol{E_{T_p} = \sum_{i=0}^{n} P_i^{new} \cdot EL_i^{new} \cdot EF_{(p)_i} \cdot \Delta t_i} \qquad (7)$$

Considering the results obtained using SIMROUTE, additional variables are defined. The additional fuel consumed (AFC) and additional quantity of emitted pollutants (AE_p) are defined in function of the FC and E_{T_p} by the minimum distance route and the optimum route:

$$AFC = FC^{min} - FC^{opt} \qquad (8)$$

$$AE_p = E_{Tp}^{min} - E_{Tp}^{opt} \qquad (9)$$

Where FC^{opt} and FC^{min} are the total fuel consumed by the main engine during the optimum route and the minimum route, respectively; and E_{Tp}^{opt} and E_{Tp}^{min} represent the total amount of

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a specific pollutant (*p*) emitted during the optimum and the minimum distance route, respectively.

Case description

The ship emissions assessment from optimal weather-ship routing is investigated in a case-study in the Western Mediterranean short sea shipping system. The research covers ten Short Sea Shipping routes from 24 to 600 nautical miles (nm) because shorter routes should also be considered for potentially applying weather ship routing, due to the expected increase of extreme weather events. On one hand, five routes connect the Balearic Islands and the main land Spanish ports and, on the other hand, five routes connect the Mediterranean Spanish ports and Western ports in the Italian coast. The study cases, including identification, are: (R1) Barcelona – Alcúdia; (R2) Ciutadella – Alcúdia; (R3) Alcúdia – Ciutadella; (R4) Palma de Mallorca – Barcelona; (R5) Barcelona – Palma de Mallorca; (R6) Valencia – Roma; (R7) Barcelona – La Spezia; (R8) Roma – Barcelona; (R9) Livorno – Alicante and (R10) Valencia – Roma. Two periods of adverse weather conditions are considered: January 2020 and January 2021. These dates have been chosen due to the weather events that took place over those months (for instance Storm Gloria and Storm Philomena) which revealed significant differences between optimum and minimum distance routes. Wave fields for the selected periods were obtained from CMEMS. The vessel selected is a real, standard Ro-Pax whose main particulars are given in Table 3. The name of the selected ship has been anonymised for commercial data protection.

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Table 3. Case-study vessel particulars: [29]

Gross Tonnage (GT)	DWT (Tm)	Year	Length (m)	Breath (m)	Draft (m)	$P_{Installed}$ (kW)	$EL = \frac{P_{MCR}}{P_{Installed}}$ (%)	rpm	$V_{cruising}$ (knots)
29670	5300	2010	177	26	6.3	18000	80	500	21.4

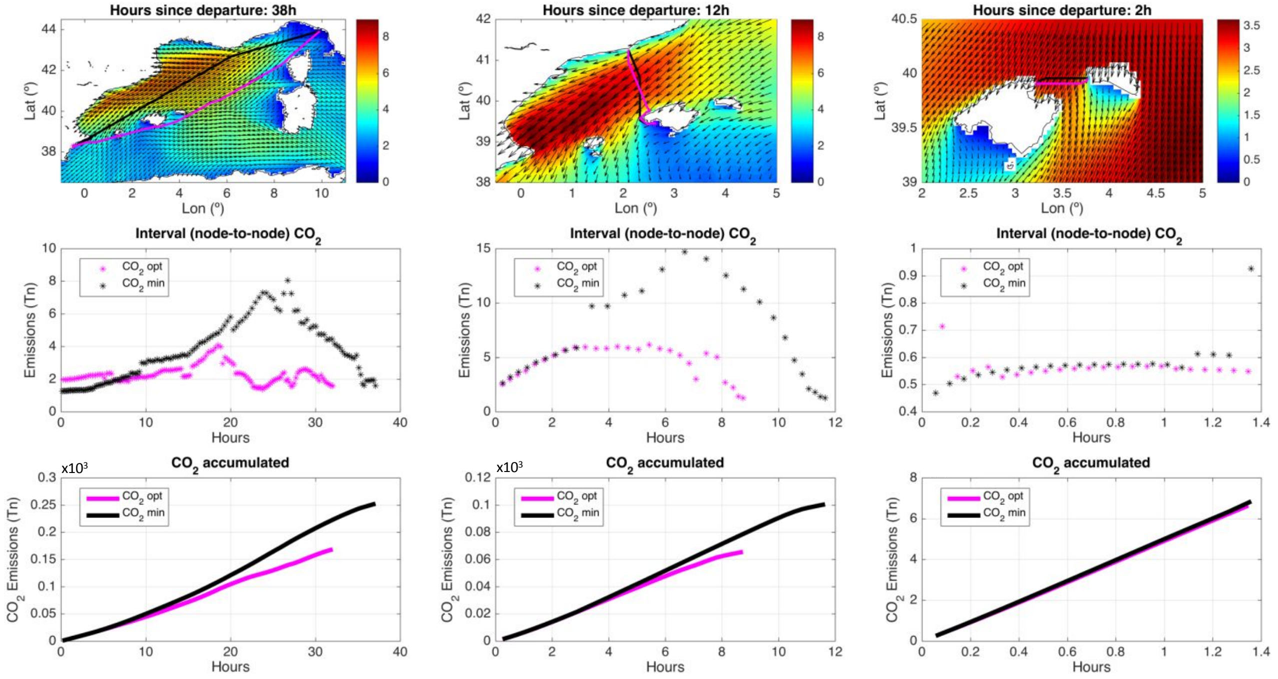
Results

Differences in sailing time and distance between the minimum and optimal routes considering wave resistance are shown in Table 4 for each case. This table shows that, during adverse weather conditions, several voyages reveal substantial differences between the minimum distance and the optimised route. For instance, case R9 results in an increase of almost 20 nm for the optimised route, this being the cost function (sailing time) reduced by 5.4 hours. This case illustrates that avoiding bad weather conditions (larger sailed distances) may reduce the sailing time. This fact has also been ascertained for different distances travelled.

Table 4. Route results using SIMROUTE: distances (in nautical miles) and sailing time (in hours)

Routes	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10

Date of departure (dd/mm/yy)	23/1/21	11/1/21	09/1/21	20/1/20	19/1/20	30/1/21	28/1/21	10/1/21	21/1/20	19/1/20
Minimum distance route time	5.206	1.293	1.214	8.137	11.641	30.06	19.10	23.25	37.08	30.04
Optimum route time	5.157	1.279	1.205	7.643	8.741	29.61	18.94	23.10	32.04	29.30
Minimum distance	96.869	24.774	24.774	121.20	121.20	578.12	379.44	445.71	583.30	577.93
Optimum distance	97.100	24.787	24.782	127.19	125.84	581.57	383.62	446.28	603.43	590.56



(a) (b) (c)

Figure 2. (top) minimum distance route (min, black) versus optimum route (opt, magenta), (middle) CO_2 emissions and (bottom) accumulated CO_2 emissions per time interval. (a) R9, (b) R5 and (c) R2. The colour bar represents the value of significant wave height (Hs) and the black arrows show wave propagation direction during the mid-term of the voyage.

Figure 2 shows the results for 3 routes with different travel lengths: long (600 nm, R9), medium (120 nm, R5) and short distances (24 nm, R2), respectively.

Figure 2 also compares the optimum route with the minimum distance, in terms of time and CO_2 emissions. The top and middle plots show how maximum emissions correspond with the highest significant waves. In the shorter route (R2), emissions reduction is around 3%, despite the time saving being below 1% (see the results summary in Table 5). Furthermore, the medium distance route (R5) shows the difference between the minimum distance and the optimum route to be 24.9% of time saved; this leads to 30.6% fuel saving and 34.75% emissions mitigation. The most outstanding case is for longest route (R9), in which emission reduction is more than 30%. Figure 3 shows sequential images of this latter route (i.e. Livorno – Alicante), together with wave conditions and the storm's spatial evolution. In this case, the optimal route suggests sailing southward to avoid energetic wave conditions. The results show time savings of 13.6%, which translated into a reduction of fuel consumption of 24.6% and subsequent emissions mitigation of 33.24%.

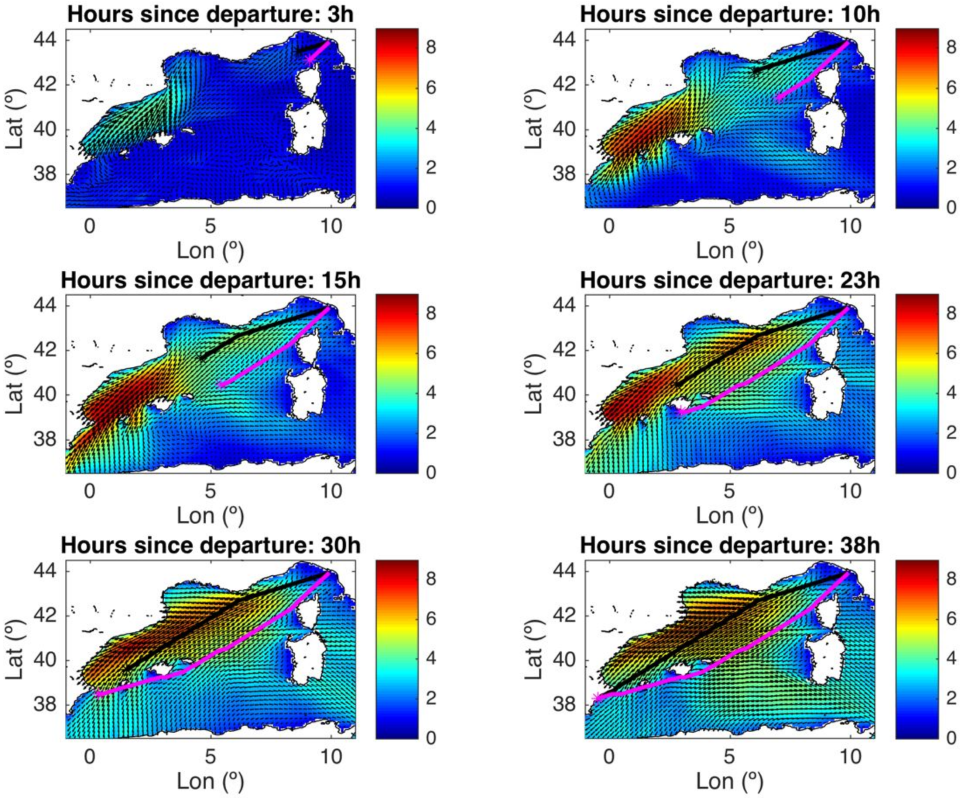


Figure 3. Temporal sequence of the snapshot of R9 (Livorno – Alicante). The optimal route is plotted in magenta and the minimum distance route is plotted in black. The colour bar represents the value of significant wave height and the black arrows stand for wave propagation.

The results shown in Table 5, reveal substantial variability in the percentage of CO_2 reduction as a function of the distance sailed or the maximum significant wave height faced by the vessel over the route. Nevertheless, in all cases, there is significant emissions mitigation, including for very short routes, proving that the results for short routes should not be neglected, particularly during adverse weather conditions.

Table 5. Summary of the additional fuel consumed and increase in emissions for the different route scenarios.

	Case	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**
	Max (Hs) (in m)	3.58	3.08	2.12	7.38	7.37	4.48	2.73	4.08	4.80	4.13
	Time saving (%)	0.94	1.1	0.8	6.1	24.9	1.5	0.8	0.6	13.6	2.5
	AFC (T)	0.37	0.10	0.07	3.60	15.40	3.73	1.93	1.09	34.43	7.33
AE_p	CO_2 (in T)	1.70	0.44	0.29	17.20	64.95	17.22	9.26	4.95	156.05	35.08
	SO_2 (in kg)	5.25	1.37	0.90	53.19	200.95	53.25	28.75	15.31	482.55	108.48
	NO_x(in kg)	32.5	8.63	5.79	308.5	1188.3	329.7	182.5	94.5	2905.2	671.5
	PM (in kg)	0.91	0.24	0.16	9.25	34.95	9.27	5.00	2.66	83.95	18.87
	Fuel saving (%)	2.13	2.4	1.87	11.4	30.6	3.86	3.25	1.45	24.6	7.6
	Emissions mitigation (%)	3.25	3.62	2.96	15.84	34.75	6.13	5.61	2.26	33.24	12.53

In order to investigate the CO_2 reduction pattern by the optimum route, Figure 4 shows the (a) maximum significant wave height faced and (b) distances sailed, as a function of the percentage difference in CO_2 emissions between optimum and minimum distance routes. These figures also include a linear regression, estimated through the minimum least squares' technique.

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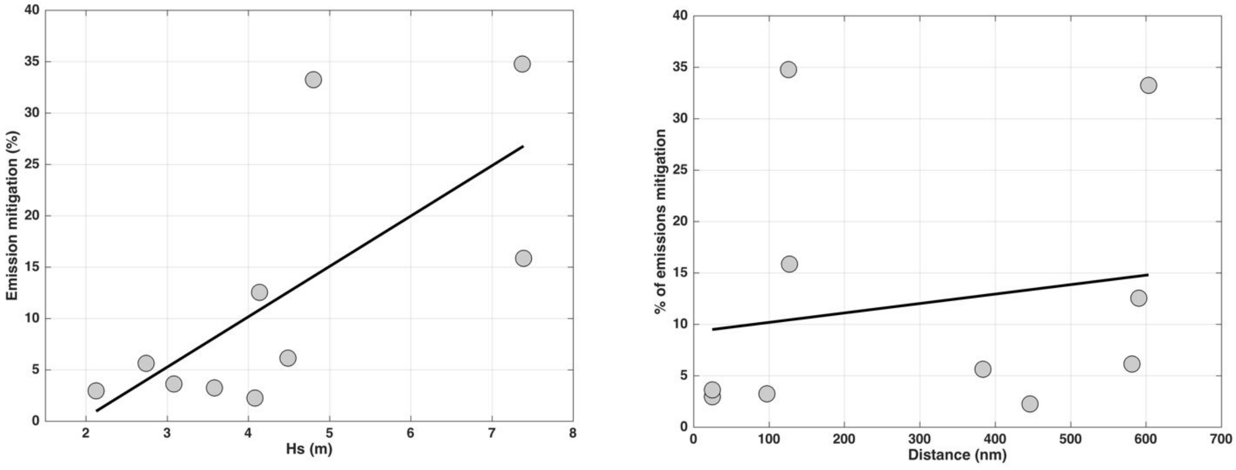

(a) (b)

Figure 4. (a) Wave maximum significant height and (b) distance covered as a function of the percentage difference in CO_2 emissions between optimum and minimum distance routes

The model shown in Figure 4a reveals a significant linear correlation (R=0.7 with p-value < 0.05), manifesting an increment in CO_2 emission differences between the optimum and minimum distance route, as the wave height increases (slope equal to 4.9026·and interception of -9.4574 in %). A different pattern is obtained for the percentage differences in CO_2 as a function of the distance sailed (Figure 4b). In this case, the correlation is not significant (R=0.18 with p-value > 0.05). However, absolute CO_2 differences increase as the distance increases, as we observed in Table 5.

Discussion

Emissions and fuel estimation techniques, applied to shipping routes, have been the objectives of many studies in recent years.[13,37,38] The emission results obtained in this contribution are based on a grid spacing mesh and, despite the assumptions and simplifications stated in the methodology section, the emission values are quantitatively similar to the state-of-the-art. For instance, the European Union report on Monitoring, Reporting and Verification for the year 2019,[39] suggests that the annual average of fuel consumption per distance, for the Ro-Pax case study vessel, is 163.24 kg per nm by the main engine and 3 auxiliary engines. The value obtained by the methodology presented in this contribution is 122 kg per nm for the main engine alone. Nevertheless, analysing auxiliary engine manufacturers' data shows that the fuel consumption of the three auxiliaries installed on-board (running at 85% load) would have a value slightly over 12 kg/nm per auxiliary engine. As the vessel's condition that was analysed is only a navigation service, it should be considered that only 1 auxiliary engine would be running; thus, giving a total consumption of 134 kg/nm, meaning a deviation of around 16%. This may, possibly, account for the consumption in port conditions and manoeuvring, which is not considered in this paper.

Weather Ship Routing is an optimisation problem based on a cost function that influences the subsequent emissions abatement analysis. Several parameters (such as type of vessel, propulsion machinery characteristics, type of fuel or the parametrization of wave effects on navigation) are involved in the optimum route and emissions assessment. Regarding the wave effects on navigation, we consider the increase in power required for maintaining a vessel's speed due to the speed reduction by wave effects. In this case, the parametrisation of wave effects on navigation is Bowditch methodology,[21] characterised by its intelligibility. The simplicity of this parametrisation could lead to oversizing the speed reduction due to wave effects. Sensibility tests have been carried out, analysing the impact of this formulation. For instance, additional computations have been carried out using Aertssen's and Khokhlov's contributions. These tests have shown an average 3% reduction on the values of emissions obtained through Bowditch methodology. A complex method of wave effects on navigation (for instance Kwon in 2008)[40] may provide more accuracy to the emissions assessments. Furthermore, the vessel speed included in the optimisation model may be modified, bearing in mind the strong dependence between vessel speed and fuel consumption. When speed is reduced to 10%, there is an additional 8% reduction in fuel consumption. Additionally, if changes are made on an average engine load, taking 75% instead of the 80% taken by default, 5% less fuel is consumed. The optimum engine load is determined by the manufacturer and should be kept as close to the optimum value as possible. The speed of the vessel could be modified, as long as the berthing time window permits it, as most container vessels do apply low steaming to their trips. Reducing speed is a straightforward method to reduce emissions, assuming ETA is not a constraint.[3] In any case, previous sensitivity exercises suggest a limited effect on the emissions assessment.

Emissions assessment results have shown small reductions of emissions in very short routes. Even though this mitigation might not seem decisive, the extrapolation of the results to long periods requires an analysis of the storm occurrence, jointly with the ship service frequencies. The required level of accuracy of the study will be enhanced for calculations for a whole year. This annual statistical study is considered to be future work, to examine the recurrence of the bad weather episodes from an annual saving cost perspective. On the other hand, results show very significant pollutant abatement for Short Sea Shipping routes up to 600 nm and attaining values of 30% reductions in emissions, which also suggests that further analysis of long-haul shipping activities is required.[34]

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Conclusions and Future Works

This paper highlights the importance of considering the optimal sailing route, to reduce ship pollution emissions. The use of a weather ship route optimisation system may significantly reduce emissions, even for short routes (of the order of 25 nautical miles). Based on 10 study cases in the Mediterranean Sea during the months of January 2020 and January 2021, ship emissions reduction increased linearly, as the distance sailed and the wave height faced during the route also increased. The emissions model is based on the power needed to overcome the speed decrement due to waves, in conjunction with STEAM2 methodology, to provide coherent values for comparison with other examples.

Further research should include a comparison with real routes (for instance, using an Automatic Identification System (AIS)) and the inclusion of emissions in the optimisation routing problem (i.e. multi-criteria optimisation). Additionally, further research into wave effects on navigation deserve special attention to increase the accuracy of weather ship routing and, consequently, pollution emission. The systematic use of ship routing optimisation by the world fleet appears to be essential and the benefits reverberate widely across society sectors, starting from an immediate improvement in air quality, thus mitigating the effects of climate change.

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For Peer Review

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For Peer Review

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