SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Reprint Series **CMRE-PR-2019-043**

Multi-criteria weather routing optimization based on ship navigation resistance, risk and travel time

Tommaso Fabbri, Raul Vicen-Bueno, Aren Hunter

May 2019

Originally published in:

Proceedings of the 2018 International Conference on Computational Science and Computational Intelligence (CSCI'18), 13-15 December 2018, Las Vegas, Nevada, USA, pp. 135-140, doi: 10.1109/CSCI.2018.00034

About CMRE

The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

Multi-criteria weather routing optimization based on ship navigation resistance, risk and travel time

Tommaso Fabbri*, Raul Vicen-Bueno*, Aren Hunter†
* *NATO STO Centre for Maritime Research & Experimentation (CMRE)*
La Spezia, Italy
{tommaso.fabbri, raul.vicen}@cmre.nato.int
† *Defence Research and Development Canada (DRDC) - Atlantic Research Centre*
Nova Scotia, Canada
aren.hunter@drdc-rddc.gc.ca

***Abstract*—This paper presents the analysis of the weather routing scenario in a multi-criteria setup. The set of 3 conflicting criteria is: added navigation resistance (caused by wind and waves), navigation risk and travel time. To this aim the International Maritime Organization (IMO) safety guidelines are exploited for the design of navigation risk criterion as function of the METeorological and OCeanographic (METOC) and sailing conditions. This is directly integrated in the multi-criteria setup. The proposed methodology is tested in an operational scenario in the Mediterranean Sea showing the different alternatives to the decision-makers.**

***Index Terms*—Weather routing, Decision support, Maritime risk assessment, Maritime safety, Pareto front**

I. Introduction

In the last years, weather routing has gained attention within the naval operations aiming to reduce the Greenhouse Gas (GHG) emissions, increase the safety at sea and operational endurance [1]. As highlighted in [2] a proper operational planning and decision-making methodology can achieve $2-4\%$ reduction on the GHG emissions and savings in fuel consumption.

Through the weather routing systems, the route toward a destination is optimized as function of the METOC forecasts and the derived sailing conditions based on the vessel type and its current operation (surge, heading, loading conditions, etc.). Due to the nature of the problem, the weather routing problem is usually modelled through the multi-criteria optimization perspective in order to include conflicting criteria for a complete assessment of the available routes. Several approaches were developed to model the weather routing problem ranging from constrained graph problems [3], constrained nonlinear optimization problem [4] to a combination of both. In contrast to the existing systems [3], [5], in which the navigation safety criteria are used for the declaration of navigation constraints defining the areas where the navigation is allowed and not allowed, in our paper the focus is on the translation of the navigation risk into a new metric to be minimized within a multi-criteria optimization setup. This design choice is based on the fact that, navigation risk and safety of a route is usually determined by the vessel operator experience at the decision stage. For this reason, we consider a conservative and limiting approach to remove from the solution space the areas where the navigation may be too risky based on ad-hoc constraints. For the above mentioned considerations, the paper proposes a weather routing system, where the navigation safety represents a criterion to be minimized together with other additional criteria such as the travel time and the added resistance caused by the interaction of the ship with winds and/or waves. The proposed weather routing system is tested in the operational planning of the route from the port of Tunisi (TN) to the port of Genova (ITA) in the Mediterranean Sea.

The paper is organized as follows: the architecture of the proposed weather routing system is presented in Section II, including details about the proposed implementation. Section III presents the scenario and the results for the determination of the best trade-off route between the selected locations. Finally, the summary of the main findings and future work are given in Section IV.

II. Multi-criteria weather routing optimization framework

Weather routing systems are characterized by a common architecture composed of 4 main components, as depicted in Figure 1. The *Environmental layer* collects the data available from the Area of Interest (AOI) and selected time-frame. Through this component the future METOC conditions (forecasts) are provided. The *Ship properties* component describes the static and dynamic behavior of the selected ship in order to model navigation status. These data are used at the *Planning layer* to compute the set of possible routes between the selected start and end locations through the solution of an optimization problem. Finally, the solutions provided by the Planning layer are analyzed at the *Decision layer* to select the solution representing the best trade-off among the available solutions. In the following subsections, each component of this weather routing system is briefly detailed for completeness.

A. Environmental layer

The Environmental layer is the system component in charge of managing the access to the data available for the given AOI with data coming from field measurements (e.g. satellites, sensor buoys, etc.) and from METOC forecast providers. The availability of these data allows users and routing systems to

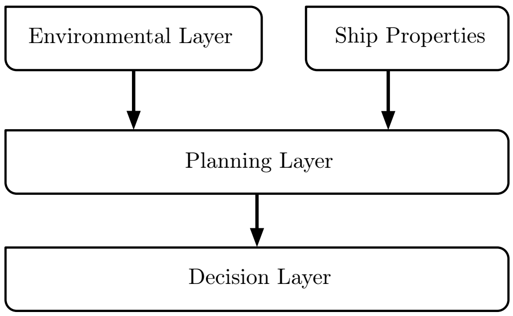


Fig. 1: Architecture of the proposed ship weather routing system.

estimate the evolution of the environment in the selected AOI, both in time and space. Considering the particular application of weather routing, the selected variables/parameters are the ones that have direct impact on the navigation safety of a ship [6], [7]. These parameters are the ones able to fully specify the sea waves (H_S [m]), wave period (T [s]), wave length (λ [m]) and wave direction (α ° respect to North direction). They also include the mean wind direction (ϕ ° respect to North direction) and wind intensity/speed (U_{10} [$\mathrm{m\,s^{-1}}$] measured at $10\ \mathrm{m}$ above the sea-surface). Finally, the bathymetry or depth profile over the AOI is required to identify the areas where the navigation is allowed and where the maneuverability is limited (due to the shallow water [8]).

B. Ship properties

The Ship properties is the system component providing the inputs to the navigation model to estimate the navigation behavior of the selected ship. It consists of a set of static and dynamic parameters. The static parameters are the ones characterizing the shape of the ship and its hull, such as length (m), draft (m) or beam (m). The dynamic parameters are current surge U (kn), heading ψ (° respect to the North direction) and sea waves conditions. All this determines the *sailing conditions*. As an example, the wave period experienced by the ship, known as wave encounter period, T_e, is determined as function of the encounter angle χ, the vessel surge U and the wave celerity $c = \lambda/T$ as reported in Equation (1) [9].

$$T_e = \frac{\lambda}{c + U\cos(\chi)} \tag{1}$$

Due to the adverse METOC conditions and/or the current course, the ship may face dangerous situations [6] that must be modelled in the definition of a weather routing tool. In this implementation, the Ship properties component collects the following parameters: ship length (m), draft (m), beam (m), metacenter height (m), maximum surge (kn).

C. Planning layer

The Planning layer represents the computational core of the weather routing system. At this level the waypoints characterizing a route are computed based on the METOC forecasts and the derived sailing conditions. To this aim, in this paper the weather routing problem is addressed and solved as a multi-criteria path finding problem through the Martins labelling algorithm [10].

At this level, the graph spatial grid $\mathcal{G}(N, A)$ with $N = \{1, \ldots, n\}$ the finite set of location nodes, and $A \subseteq N \times N$ the finite set of linking edges is computed based on the specified departure and arrival geographical locations [11]. Starting from the nominal route [12] from origin to destination, a perpendicular to the route multistage grid is defined. The start and the end locations represent one node each and along the route new nodes are added to each stage. The graph spatial grid is composed by a finite number of stages where each node of one stage is connected to all the nodes in the next. Finally, the resulting graph spatial grid is then *cleaned* of the edges and nodes where the navigation is not allowed (e.g. depth too low, edge crossing land, etc.). In contrast to existing systems [3], [5] in which the navigation safety criteria are used for the definition of navigation constraints to limit the areas where the navigation is allowed and not allowed (by removing the edges involved), in this paper all the available waterways are kept in the graph spatial grid, and the safety/risk criteria are included as discussed below.

In order to compute the optimal path between the source and destination locations, it is necessary to associate to each edge a cost. In this implementation we are concerned with the multi-criteria path finding problem, therefore each edge is characterized by a set of 3 costs defining the cost for sailing through the selected edge. The 3 criteria used in this setup are the following:

- **Travel time**: Computation of travel time for traversing the edge based on the current sailing conditions [13].
- **Added ship resistance**: Estimate of the added resistance caused by waves and winds. This criterion enables the user to investigate the relation between the fuel consumption and the various sea states and directions that the ship may encounter during the voyage [14].
- **Navigation risk**: Estimate of the navigation risk based on the sailing conditions as function of the METOC conditions and ship properties and configuration. This is executed based on the guidelines for navigators defined in [6], [7] for the detection of dangerous and risky conditions, such as *surf-riding/broaching-to*, *successive high-wave attack*, etc.

D. Decision layer

The Decision layer represents the component of the weather routing system where the decision maker interacts with the system to shape the trajectory that represents the best trade-off among the available candidate routes. To this aim, the Pareto front is analysed and visualized through the Hyper Radial Visualization (HRV) [15]. The analysis that we propose is to group the Pareto solutions based on the navigation risk: this design choice allows a better understanding/comparing process of the available solutions as discussed in the following Section III.

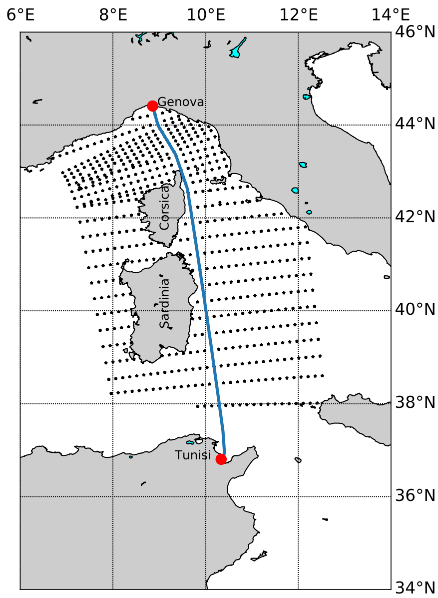


Fig. 2: Nominal route between Tunisi (TN) and Genova (ITA) provided by the web-service `searoutes.com` [12] surrounded by the multistage graph spatial grid with nodes plotted as black markers.

III. Scenario and results

The proposed methodology is tested in the scenario of planning the route from Tunisi (TN) to Genova (ITA). The limits of the AOI and the selected Estimated Time of Departure (ETD) are:

- AOI Longitude range: from $6.0°$ E to $14.0°$ E.
- AOI Latitude range: from $34.0°$ N to $46.0°$ N.
- ETD 12^{nd} June 2018 $06{:}00$ UTC.

The nominal route (provided by `searoute.com` [12]) is used for the generation of the multistage graph spatial grid as depicted in Figure 2. The route is plotted in blue colour and the nodes composing the graph spatial grid as black markers. In this simulation scenario, the graph spatial grid is composed by a set of 390 nodes and 6325 edges. The nominal route represents the shortest waterway connecting the starting location with the selected destination.

Recalling the architecture of the proposed weather routing system, the Environmental layer provides the METOC data within the AOI. In this setup, the METOC data are provided by DICCA-MeteOcean [16], [17]. The forecasts are generated through the Wavewatch III model [18]. The forecasts are provided with a 10 km spatial resolution and 1 h temporal resolution. The forecast covers a temporal window of 120 h and they are computed daily at 00:00 UTC. The bathymetry/depth profiles are provided by the EMODNet Network [19] to identify the available routes and the areas where the navigation is not possible. In this operational setup, the scenario considers a ship with the properties specified in Table I.

TABLE I: Ship general properties.

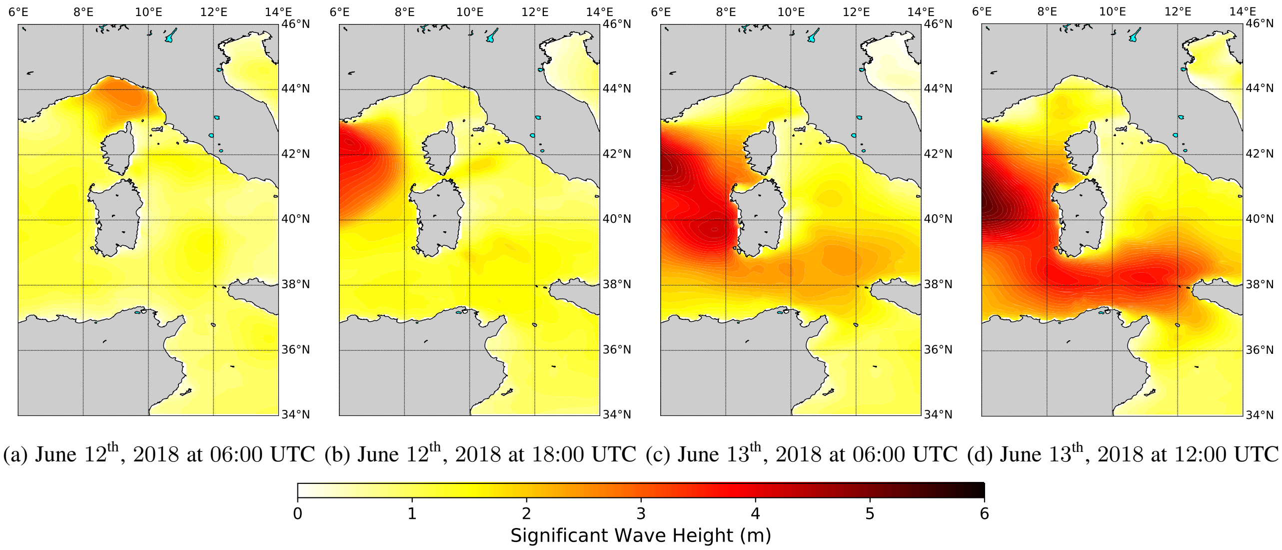
Ship static properties	Value
Length (m)	134.0
Beam (m)	16.0
Draught (m)	5.0
Max. Surge (kn)	20.0
Metacenter (m)	1.6

As highlighted in the METOC snapshots depicted in Figure 3, for the temporal window of 30 h from the ETD (nominal travel time to transit from Tunisi (TN) to Genova (ITA) in nominal navigation conditions), the AOI is crossed by a storm (high H_S, with $H_S > 3$ m). This presents dangerous navigation conditions within the AOI according to IMO [6].

Once run the proposed weather routing system, Figure 4 shows the set of Pareto efficient routes connecting the start and destination ports. Each candidate route represents a different trade-off among the criteria selected in the simulation scenario. The usage of the Martins algorithm [10] (at the Planning layer) allows the computation of the complete set of Pareto solutions and not a subset of the Pareto routes as done in other solving methods(e.g. genetic algorithms [20]). Furthermore, the design choice of including the navigation risk in the multi-criteria setup allows the estimation of the total risk associated to each Pareto optimal route.

Despite the availability of possible routes/solutions crossing the west side of Sardinia and Corsica, as highlighted by the presence of graph nodes in that area in Figure 2, no one route represents a good candidate in the Pareto sense. This is due to the approaching storm coming from the west Mediterranean sea (Figure 3). Figure 5 allows a deeper analysis of the set of Pareto solutions as a 4-dimensional plot, where each axis represents a different minimization criterion (x axis - travel time, y axis - navigation added resistance and z axis - navigation risk). To simplify the analysis, the navigation risk is also associated with a color map: the solutions in purple and blue colors are associated with the routes characterized by low risk; the solutions in lighter colors (green, yellow) are characterized by risk from medium to high. As can be observed, the solutions characterized by low travel-time are the ones characterized high navigation added resistance (therefore travel cost). The medium-high navigation risk routes are more concentrated in the group of the routes with low travel-time; instead the low risk routes span most of the Pareto frontier on the $x-y$ plane (travel time and navigation added resistance). The integration of the navigation risk in the multi-criteria setup allows to identify the routes characterized by the high navigation risk maneuvers. As matter of fact, the routes can be ranked/grouped in different parallel $x-y$ planes with different z navigation risk values, as depicted in Figure 5.

In order to identify the route representing the best trade-off solutions, the HRV [15] methodology is exploited. Figure 6 presents the Pareto solution set in a 3-dimension space: where the x axis is travel time; the y axis is the navigation



(a) June 12th, 2018 at 06:00 UTC (b) June 12th, 2018 at 18:00 UTC (c) June 13th, 2018 at 06:00 UTC (d) June 13th, 2018 at 12:00 UTC

Fig. 3: Evolution of the significant wave height (H_S) in the AOI during the temporal window of the selected scenario.

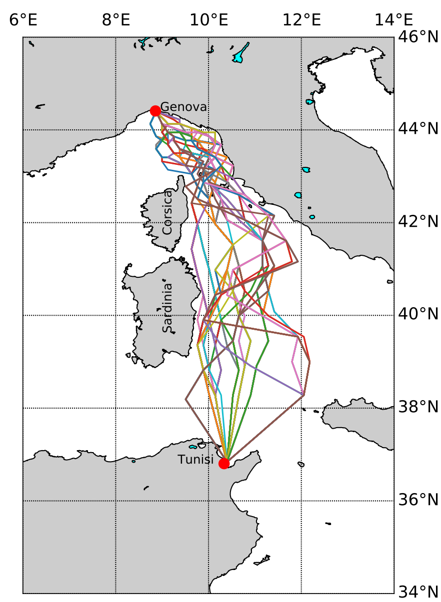


Fig. 4: Set of Pareto efficient routes generated through the weather routing process in the selected scenario.

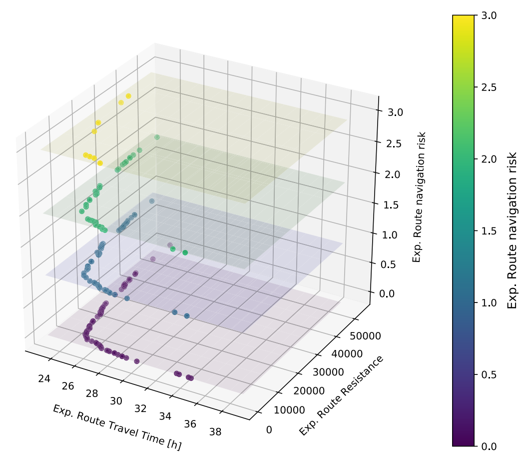


Fig. 5: Set of Pareto efficient solutions generated through the weather routing process in the selected scenario. Each axis represents a different criterion: x axis - travel time, y axis - navigation added resistance and z axis - navigation risk. The solutions are also grouped by color, with dark (purple, blue) and light (green, yellow) colors for low and high risk, respectively.

added resistance and the color domain identifies the routes by risk. In this representation the resulting objectives values are normalized so that the visualization is associated with the values in the range $[0, 1]$. The most desirable solution(s) from amongst the Pareto set is/are identified by evaluating the distance of each solution from the *Utopia point* (point $(0, 0, 0)$ the hypothetical point that corresponds to the minimum value of each individual criteria [21]). This allows the navigator to have a clear and intuitive reference-point during the decision-making process. The route representing the best trade-off (as the closest solution to the Utopia point) is depicted with red triangular marker in Figure 6.

Figure 7 presents the set of routes in the neighborhood of the best trade-off solutions by comparing them with the nominal route. The proposed routes by the weather-routing system are pushed to the western coastline of Italy in order to avoid the storm coming from the west Mediterranean sea and sailing in safe navigation conditions in the last part of the routes close to the destination (Genova - ITA).

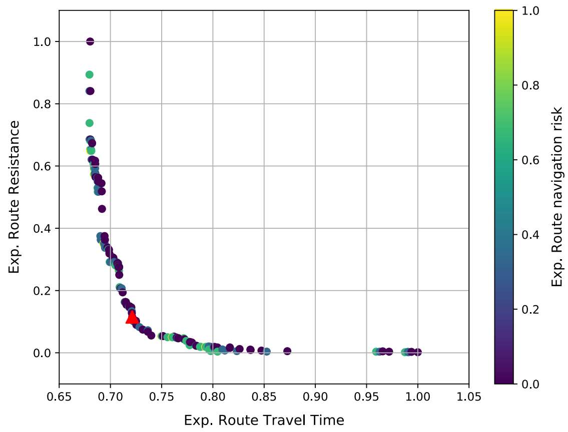


Fig. 6: Set of Pareto efficient solutions generated through the weather routing process in the selected scenario. The solutions are plotted in the 3-dimension space: x axis - travel time, y axis - navigation added resistance and the color domain to identify the routes by risk. The red triangular marker identifies the route representing the best trade-off solution.

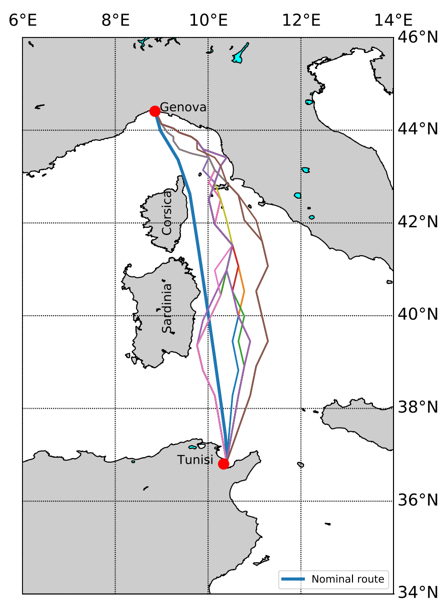


Fig. 7: Set of Pareto routes in the neighborhood of the best trade-off solution plotted with the nominal route provided through the web-service `searoutes.com` [12].

IV. Conclusion and Future Work

In this paper the weather routing problem has been modelled through a multi-criteria optimization setup characterized by a set of 3 conflicting criteria (travel time, ship navigation resistance and risk).

The proposed scenario demonstrates how the developed weather routing system is able to identify the waterways characterized by safer METOC conditions from a navigation point of view avoiding therefore dangerous navigation situations. Furthermore, the exploitation of the IMO guidelines [6] in the form of optimization criterion allows to estimate average risk associated to each route.

Future developments could be focused on the increase of the computational performance of the weather routing process by introducing novel spatial grid graph based on the partitioning the AOI in convex sections, characterized by uniform weather and risk conditions. This allows the reduction of the size of the spatial grid and therefore an improvement of the computing performance.

Acknowledgments

This work has been funded by the Defence Research and Development Canada (DRDC) under the project ”Mission Planning Aid - Decision Support and Risk Assessment” (MPA-DeSRA). The project has been developed in collaboration with the Environmental Knowledge and Operational Effectiveness / Maritime Intelligence Surveillance and Reconnaissance (EKOE/MISR) programme at the NATO STO Centre for Maritime Research and Experimentation (CMRE). The authors thank also the DICCA-MeteOcean Department [16] for providing the METOC forecast data for the scenario.

References

[1] L. P. Perera and C. G. Soares, “Weather routing and safe ship handling in the future of shipping,” *Ocean Engineering*, vol. 130, p. 684–695, 2017.

[2] E. H. Green, J. J. Winebrake, and J. Corbett, “Prevention of air pollution from ships - Opportunities for reducing greenhouse gas emissions from ships,” International Maritime Organization (IMO), Tech. Rep., 2008.

[3] G. Mannarini, N. Pinardi, G. Coppini, P. Oddo, and A. Iafrati, “Visir-i: small vessels, least-time nautical routes using wave forecasts,” *Geoscientific Model Development*, vol. 8, no. 9, p. 7911–7981, Sep 2015.

[4] T. Fabbri, R. Vicen-Bueno, R. Grasso, G. Pallotta, L. M. Millefiori, and L. Cazzanti, “Optimization of surveillance vessel network planning in maritime command and control systems by fusing METOC and AIS vessel traffic information,” in *OCEANS 2015 - Genova*, May 2015, pp. 1–7.

[5] D. Sidoti, G. V. Avvari, M. Mishra, L. Zhang, B. K. Nadella, J. E. Peak, J. A. Hansen, and K. R. Pattipati, “A multiobjective path-planning algorithm with time windows for asset routing in a dynamic weather-impacted environment,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 12, pp. 3256–3271, Dec 2017.

[6] IMO, “Revised guidance to the master for avoiding dangerous situations in adverse weather and sea conditions,” International Maritime Organization (IMO), Tech. Rep., 2007.

[7] I. Thompson, “Fatigue damage variation within a class of naval ships,” *Ocean Engineering*, vol. 165, p. 123–130, 2018.

[8] M. Vantorre, K. Eloot, G. Delefortrie, E. Lataire, M. Candries, and J. Verwilligen, *Maneuvering in Shallow and Confined Water*. American Cancer Society, 2017, pp. 1–17.

[9] T. Perez, *Ship Motion Control: Course Keeping and Roll Stabilisation Using Rudder and Fins*, 1st ed. Springer Publishing Company, Incorporated, 2010.

[10] E. Q. V. Martins, “On a multicriteria shortest path problem,” *European Journal of Operational Research*, vol. 16, no. 2, p. 236–245, 1984.

[11] W. Shao, P. Zhou, and S. K. Thong, “Development of a novel forward dynamic programming method for weather routing,” *Journal of Marine Science and Technology*, vol. 17, no. 2, p. 239–251, Jun 2012.

[12] M. (MDS), “Searoutes.com,” https://www.searoutes.com, 2018, accessed: June-2018.

[13] J. Loeches, R. Vicen-Bueno, and L. Mentaschi, “METOC-driven Vessel Interdiction System (MVIS): Supporting decision making in Command and Control (C2) systems,” in *OCEANS 2015-Genova*. IEEE, 2015, p. 1–6.

[14] R. Lu, O. Turan, E. Boulougouris, C. Banks, and A. Incecik, "A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping," *Ocean Engineering*, vol. 110, p. 18–28, Dec 2015.
[15] P.-W. Chiu and C. L. Bloebaum, "Hyper-Radial Visualization (HRV) method with range-based preferences for multi-objective decision making," *Structural and Multidisciplinary Optimization*, vol. 40, no. 1, p. 97, Apr 2009.
[16] Dipartimento di Ingegneria Civile, Chimica e Ambientale (DICCA), "MeteOcean - DICCA," http://www.dicca.unige.it/meteocean/, 2018, accessed: June-2018.
[17] L. Mentaschi, G. Besio, F. Cassola, and A. Mazzino, "Developing and validating a forecast/hindcast system for the mediterranean sea," *Journal of Coastal Research*, vol. 2, no. 65, p. 1551–1556, 2013.
[18] National Weather Service - Environmental Modeling Center, "Wavewatch III Model," http://polar.ncep.noaa.gov/waves/wavewatch/, 2018, accessed: June-2018.
[19] EMODnet Bathymetry - The European Marine Observation And Data Network, "EMODnet - understading the topography of the European seas," http://www.emodnet-bathymetry.eu/, 2018, accessed: June-2018.
[20] L. Walther, A. Rizvanolli, M. Wendebourg, and C. Jahn, "Modeling and optimization algorithms in ship weather routing," *International Journal of e-Navigation and Maritime Economy*, vol. 4, p. 31–45, Jun 2016.
[21] K. Miettinen, *Nonlinear multiobjective optimization*. Kluwer Academic Publishers, Boston, 1999.

Document Data Sheet

Security Classification		Project No.
Document Serial No. CMRE-PR-2019-043	**Date of Issue** May 2019	**Total Pages** 6 pp.

Author(s)

Tommaso Fabbri, Raul Vicen-Bueno, Aren Hunter

Title

Multi-criteria weather routing optimization based on ship navigation resistance, risk and travel time

Abstract

This paper presents the analysis of the weather routing scenario in a multi-criteria setup. The set of 3 conflicting criteria is: added navigation resistance (caused by wind and waves), navigation risk and travel time. To this aim the International Maritime Organization (IMO) safety guidelines are exploited for the design of navigation risk criterion as function of the METeorological and OCeanographic (METOC) and sailing conditions. This is directly integrated in the multi-criteria setup. The proposed methodology is tested in an operational scenario in the Mediterranean Sea showing the different alternatives to the decision-makers.

Keywords

Weather routing, decision support, maritime risk assessment, maritime safety, Pareto front

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
STO CMRE
Unit 31318, Box 19, APO AE 09613-1318]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@cmre.nato.int