Preliminary assessment of route optimisation for fuel minimisation and safety of navigation by the use of cooperatively collected data at sea

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Abstract. The growing pressure of the international regulations on GHG emissions from ships is pushing towards the adoption of a variety of operational energy efficiency measures. The fusion of measurement techniques, smart telecommunication technologies and numerical modelling approaches has a great potential for the implementation of services for the shipping industry. Among these, there are weather routing systems for improving both energy efficiency and navigational safety. PROFUMO Demonstrator is an ESA ARTES Integrated Applications Promotion (IAP) Programme project. Its main goal is to implement a pre-operational system for fleet management and weather routing services, based on the cooperative collection of meteo-marine data from ships, to improve weather forecasts. Atmospheric information from GNSS signals (namely Galileo and GPS) are also utilised to improve numerical weather predictions and enable detailed route optimisation services at the Mediterranean scale. The architecture of the system and some first implementation results will be described, in particular on the integration of meteo-marine forecasting with ship modelling and route optimisation, with some sensitivity analyses for the optimisation process, under different approaches on modelling wind and waves added resistances for computing the ship powering performance. In perspective we imagine the use of in-service measured data to dynamically improve the ship modelling components of the system.

Keywords. e-navigation, weather routing, energy efficiency, space technologies

1. Introduction

The need for the mitigation of environmental impacts, together with the issue of fuel consumption reduction, are the main drivers of the recent steady growth in the adoption of energy efficiency measures in the international shipping [1][2]. In this context, the best results are expected from the optimal integration of different measures selected , among a broad variety of possible approaches, depending on the business model to be fitted, going from retrofitting up to operational optimisation of fleet management and single vessel routing [3][4]. The recent developments and relevant innovations regarding these latter approaches can be more properly placed in the context of the e-navigation paradigm [5][6] and in the technological framework of Integrated Bridge Systems (IBS) [7]. Under such paradigms, energy efficiency and pollution reduction instances can be better managed together with safety of navigation by exploiting a wide set of emerging technologies. A growing relevance comes for numerical modelling of the numerous interacting components [8] of the mission-ship-environment system and for their integration with the technological infrastructure supporting the functions of data collection, data processing and data telecommunication [9].

A key role in this framework is played by space technologies for Earth observation, positioning and communication. This explains the motivation of developing the PROFUMO Demontration project (Preliminary assessment of Route Optimisation for FUel Minimisation and safety of navigatiOn) within the ESA ARTES Integrated Applications Promotion (IAP) Programme of the European Space Agency (ESA). PROFUMO Demonstration comes out from two previous projects, all three of them coordinated by VITROCISET Belgium S.p.r.l. [10] (hereafter VTCB). The first has been COSMEMOS, a proof-of-concept project, developed within the European FP7 programme in the context of the scientific application of the European Galileo satellite navigation system, then followed by PROFUMO Feasibility, the feasibility phase of the present demonstration project, developed in the same ESA programme.

The whole chain of projects is aimed at the implementation of an innovative decision support system for the Mediterranean maritime community, firmly based on space technologies. The system has been designed to deliver innovative weather routing and nowcasting services oriented to fuel consumption and pollution emissions reduction, but also strongly concerned with safety of navigation issues. A relevant point is the near-real-time exploitation of data from sensors present on board of cooperating ships of the service users, that in this way participate to the improvement of the service. Such cooperatively collected data are used in the system to improve meteo-marine forecast, through data assimilation algorithms, and to improve situational awareness. Space technologies play a relevant role in the system, both in guaranteeing data transmission resources to and from the service users, via cost optimised channels, and by providing a host of environmental data. This include also data from Global Navigation Satellite Systems (GNSS) as. GPS and Galileo, planned to be utilised, through innovative processing algorithms, to improve meteo-marine forecasts by data assimilation procedures, involving also conventional in-situ data.

In this paper a high level description of the whole system architecture is given, then in specific paragraphs details of the main numerical modelling components are presented with a main focus on the route optimisation service development. Finally, the first results of sensitivity analysis for the optimisation algorithm are described, evaluating the role of some specific ship performance modelling features.

2. The PROFUMO Demonstration system

The Profumo system is designed on a virtuous circle of information among three subjects, all playing an active role: a fleet of cooperative customers' vessels (VF), in the project represented by Forship S.p.A. and Grimaldi Group S.p.A., a Service Center (SC), managed by VTCB, and a Processing and Evolution Center (PEC), managed by Consorzio LaMMA [11] (hereafter LaMMA), as schematically shown in Figure1.

Figure 1. Overall PROFUMO Demonstrator system architecture.

In the planned system, each cooperative vessel of VF actively enters the circuit by sending to the PEC, in near real time, the meteorological data acquired by its on board instruments. All the collected data follow in parallel two paths: a very fast synthesis process, to produce a map of the observed meteo-marine conditions, and a more complex analysis, essentially consisting of the data assimilation in local area models for numerical weather predictions (NWP), operated at PEC. Observed conditions maps are made available to the SC, and hence to all the users' ships of VF, in nearly real time. NWP runs are repeated two or four times a day on the HPC platform of the PEC, with updated data. The forecast can be sent by SC to any ship of VF and it is used by the PEC to search for the optimal route of each vessel that requests it through SC. Clearly both the positioning and the communication systems play a fundamental role for the system proper functioning. For the communication, SkyLink device, developed in the project by ESNAH [12], will be installed on board VF vessel. In practice SkyLink is a remotely programmable transmitter-receiver, capable to temporarily store data and send/receive them via different communication channels (e.g. GSM mobile, Global Satellite), automatically selected according to cost minimisation objectives.

3. PROFUMO Integrated Modelling: meteo-marine forecasts

The meteo-marine forecasting component of PROFUMO will be implemented by gradually upgrading a baseline models chain, similar to the one already operational at LaMMA. This approach allows to exploit the experience built at LaMMA in the course of several years of meteorological and marine modelling and forecasting operational services [11][13][14][15], in addition to studies on weather routing applications [16].

In its baseline structure, the atmospheric component is based on the mesoscale meteorological model WRF [17], with initialisation and boundary conditions [18] from the American global model (NOAA NCEP GFS) and from the European ECMWF center. Namely the version 3.9.1 (August 2017) of the WRF-ARW core is the one adopted. The wave forecast component, driven by WRF wind data, is based on running the third generation spectral wave model Wavewatch III (WWIII), namely the 5.16 version [19]. The resulting wind-wave forecasting operational chain is run two times a day (initialisation at 00:00 and at 12:00 UC) over the whole Mediterranean Sea for the next five days at a resolution of about 12 km [11][13].

In this baseline structure surface currents forecasts are not included, however a component for these will be added soon, by exploiting both Copernicus data [20] and the marine hydrodynamics resources already operational at LaMMA but presently on a regional domain [14].

During the project, detailed studies will be performed with the goal of implementing and tuning a data assimilation scheme [18], capable of ingesting many kinds of real-time observed data inside the atmospheric component. These data will be both from conventional observing instruments, and from the cooperatively collected data introduced in the precedent paragraph. Once operational, such data assimilation component will be added to the baseline, in order to improve the short-term forecasting skills of the system.

Due to the strongly non-linear nature of the atmospheric and marine dynamics, meteo-marine numerical models exhibit a strong dependence on initial conditions, hence, also if a sound data assimilation system is present, limited predictability always affects meteo-marine numerical forecasts [18]. In order to cope with these limits and to dynamically estimate forecast reliability, an Ensemble Prediction System (EPS) [18] component will be implemented, as a further upgrading of the baseline system. EPS approaches have already been implemented in the contest of weather routing [21] [22], and some preliminary studies have already been performed also at LaMMA [16]. Their relevance lies in their potential of allowing rigorous estimates of the routing solutions reliability, a key feature in the complex decision-making process of the Officers Of Deck (OOD) onboard every ship at sea, especially in heavy weather conditions. Moreover, EPS systems offer the possibility of implementing probabilistic forecasts and stochastic route optimisation approaches.

4. PROFUMO Integrated Modelling: ship performance

Regarding the modelling of ship seakeeping and powering performance, several approaches are available in the specialised literature. In recent studies performed at LaMMA a quite detailed approach has been investigated [16]. For powering, engine load and fuel consumption are evaluated through the dynamic balance between propeller(s) thrust and ships total resistance by applying standard algorithms [23]. For seakeeping it was based on strip theory and a detailed treatment of the interplay of ship response functions with directional spectra provided by WWIII model. The overall computational load of all these algorithms was quite large. In order to speed-up the ship performance computational phase of the planned PROFUMO system, an approach based on the off-line computation of Look-Up Tables (LUT) has been defined, both for ship seakeeping responses and for powering performance. In the first implementations, the computation of such LUTs is based on very simple approaches and the numerical tests performed serve for benchmarking, for improving the algorithmic structure and as a sensitivity analysis of the adopted route optimisation algorithm (described below).

In the first tests only fuel consumption minimisation has been considered, schematising the ship total resistance in terms of a decomposition in the three main components [24]:

$$R_{tot} = R_{hull} + R_{wind} + R_{aw} \qquad (1)$$

where R_{hull} is the calm-water resistance, tabulated and stored in LUTs as a functions of ship speed through water. R_{wind} is the wind added resistance, and it is evaluated as:

$$R_{wind} = 0.5\, \rho_{air}\, A_T U_r^2\, C_x(\theta_{rwi}) \qquad (2)$$

where ρ_{air} is air density, A_T is the ship frontal area, U_r is the modulus of the ship-relative total wind vector (i.e. due to both meteo and ship speed). The longitudinal wind resistance coefficient $C_x=C_x(\theta_{rwi})$ is function of the ship-relative wind angle θ_{rwi}, and it is stored as part of the LUTs, considering (if needed) different functional shapes, depending on the ship loading conditions (e.g. different containers arrangement and filling factor for a containership). R_{aw} is the added resistance in waves, and it is evaluated as:

$$R_{aw} = H_s^2 C_{aw}(U_{STW},\theta_{rwa}) \quad (3)$$

where H_s is the value of significant wave height. The coefficient $C_{aw}=C_{aw}(U_{STW},\theta_{rwa})$ embodies the interaction between the ship and the directional characteristics of the wave field. In the first implementation of the system a very simple structure is assumed, i.e. only the dependence on ship Speed Through Water U_{STW} and on the ship-relative wave average direction θ_{rwa} are accounted for. In further developments of the system, more detailed approaches to the pre-computing of C_{aw} will be adopted, allowing to account for the dependence on other parameters, e.g. $C_{aw}=C_{aw}(U_{STW},\theta_{rwa},\sigma_\theta,T_p,\sigma_T)$, where T_p is wave peak period, and σ_θ, σ_T are direction and period spectral spreading. Such further dependencies could be traced to the detailed wave spectral structure to account for spectral partitions [25] for wind sea, swells and multimodal wave spectra [26][27]. The estimation of C_{aw} LUTs will be performed, in the off-line phase, by detailed account of ship added resistance in waves response function and wave directional spectra [24] or by adopting simplified approaches e.g. as in [28][29]. In further developments a similar approach will be extended also to other seakeeping responses [24], to include them in the route optimisation process accounting for safety of navigation [30] and comfort onboard.

Once the total ship resistance is computed, the corresponding fuel consumption is determined, by picking the right value of the fuel consumption rate from the respective powering LUT. In such a LUT, fuel consumption rate values are stored, after off-line pre-computing [23], over the needed range of ship speed, and for several values of the engine load, i.e. of the values of the total resistance R_{tot}.

An interesting perspective offered by the availability of data measured during ship voyages, as planned in the PROFUMO system, is the possible integration of meteo-marine data with ship performance data, to implement “big-data processing” [9] algorithms finalised to check and/or tune the ship specific LUTs. This could allow to cope with some of the deficiencies of ship hydrodynamics computational approaches, by exploiting the availability of large datasets of in-service measured data [31]. This approach could be integrated with scale ship model basin experimental methods.

5. PROFUMO Integrated Modelling: route optimisation

The route optimisation algorithms DIJK3, utilised in all the implementations of the first versions of PROFUMO Demo system has been developed in recent years by the project partner Aleph s.r.l. [32]. It implements a new kind of approach to the vessel routing problem. Avoiding the discretisation of the research domain into a graph, the algorithm explores the domain and produces solutions for every given point from a single origin (port of departure) or destination (port of arrival). It has been designed to resolve general minimum cost path searching problem in continuous domain and in nonstationary condition by Aleph. It has been integrated in PROFUMO for the first time, within a complete meteo-marine forecasting and route optimisation chain.

A relevant peculiarity of DIJK3 is that it allows to implement customised cost functions in a very straightforward and general way. Based on this, different approaches to the combined effect of wind and waves on total resistance, as those described in the precedent paragraph, can be adopted and simply integrated within the route optimisation algorithm.

6. Sensitivity analysis of route optimisation to ship modelling details

The first computational tests of the system have been performed by considering a dataset corresponding to a ro-ro ship about 167 m length, already studied in [16]. Data for the calm water resistance and regarding the ship propulsion system (bare hull, propeller, and engines) [32] are those adopted in that study. For the definition of the values of the coefficients for wind resistance $C_x(\theta_{rwi})$ and for added resistance in waves $C_{aw}(U_{STW},\theta_{rwa})$ a very simplified approach has been adopted.

In Figure 2, left panel, the three different alternatives selected and adapted from literature for C_x are shown: **Cos**ine-like similar to [34], small **Cont**ainership [35], **Pass**enger ship [36].

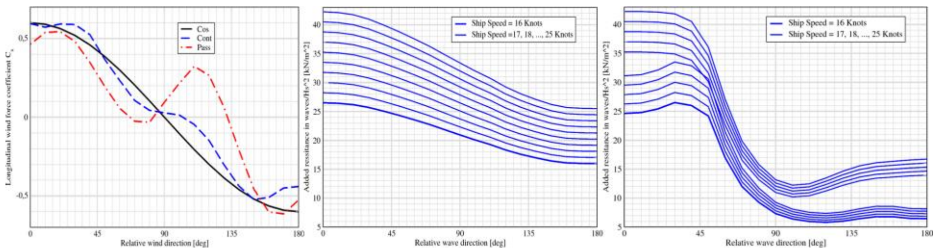

Figure 2. Adopted alternatives for the ship wind resistance coefficient C_x (left panel: *Cos*, *Cont*, *Pass*), and for the added resistance coefficient C_{aw} (center: *Smooth*; right: *Choppy*) for the *High* variant (speed:16-25 knots, 1 knot steps). Sign convention: C_x, C_{aw}, R_{wind}, R_{aw} are positive when opposed to ship motion.

The central and right panels of Figure 2 show the adopted dependencies for C_{aw} as a function of the relative average wave direction and ship speed. Two variants for the angular dependency have been defined. The *Smooth* one (central panel) is considered to correspond to the interaction of the ship with a seaway characterised by a wide wave directional spreading (as in the case of wind sea), that tends to strongly smooth the details of the directional structure of the R_{aw} response function, that can be considered as “dressed” by the wide spectral form. The *Choppy* one (right panel) has structure details to be directly traced to the directional structure of the “bare” R_{aw} response function, due to a very narrow wave spectral peak (as in the case of a swell). A linear dependence on ship speed is assumed for C_{aw} in the range of ship speeds from *16* to *25* Knots (*1* Knot steps). To account for the wide variability of literature data [37], the values of C_{aw} have been tuned in two different variants: R_{aw} *High* in Figure 2, and a scaled down (by a factor of about 0.6) R_{aw} *Low*. The powering part of the ship numerical model LUTs summarises the fuel consumption performance as determined from main ship data and Wartsila technical manuals [32]. The engines system is composed of four Wartsila 12V46-B diesel engines, delivering *11700 kW* each at *100%* load (*514 RPM*).

A wide set of simulations came out by composing one of the three C_x (*Cos*, *Cont*, *Pass*), with one of the possible C_{aw} *High* or *Low*, *Smooth* or *Choppy*. A relevant meteo-marine case study has been selected and several voyages have been simulated going from Gibraltar to Port Said (*GiSa*) and vice-versa (*SaGi*). Moreover, the Estimated Time of Arrival (ETA) has been varied for a total of 19 delays, in steps of *1 hour*, to evaluate the fuel savings potential in relation with time windows. Two constant ship speed conditions have been considered: *19* Knots and *24* Knots. Differences in ship speed induce different fuel consumption due to the different values of resistance components, but also due to a gradually differing sequence of the encountered meteo marine conditions.

The meteo-marine conditions in the selected case study are shown in Figure 3, through significant wave height maps from LaMMA. A wide area of heavy waves, oriented in zonal direction towards East, is present over great part of the central and east Mediterranean Sea. In this case, the exchange *GiSa*-*SaGi* allows to analyze the differences between "head heavy weather" and "following heavy weather".

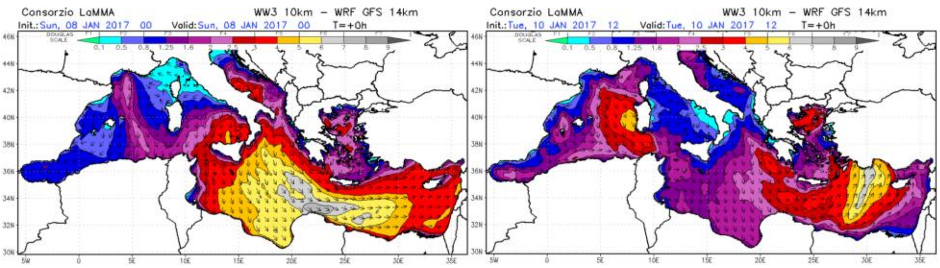

Figure 3. Significant wave height pattern for the selected case study.

The solution with zero meteorological wind and no waves is the geometrically shortest one, of about *3486* km (*1882* NM). At the two considered speeds of *19* and *24* Knots, it requires about *99* hours and *33* hours of voyage, and *248* tonnes and *325* tonnes of fuel, respectively. These data can be considered as baseline values to be compared with the results of all the studied variants in heavy weather.

An example of the results obtained is in Figure 5, where total fuel consumption data for minimum fuel optimised routes are plotted versus the 19 ETA variants (in steps of 1 hour w.r.t. 2017/01/11 at 04:00 UTC). The variants in Figure 5 are characterised by: ship speed *24* Knots and R_{aw} *High*. In the left panel the *GiSa* and in the right the *SaGi* voyages data are plotted. In each plot, both the *Smooth* and the *Choppy* results are shown. The *Smooth* data are the upper curves and the *Choppy* are the lower curves for both *SaGi* and *GiSa*. This feature marks the main difference emerged from the study: the *Choppy* C_{aw} shape generates lower fuel consumption (it is strongly anisotropic and gives markedly less resistance for beam and following waves). As expected, far less differences emerged from the different variants of wind resistance coefficient C_x (black, blue, red). These latter differences, together with the overall total fuel consumption, increase in passing from *GiSa* to *SaGi* voyages, in accordance with the fact that in SaGi voyages head heavy weather is encountered. The dependency on the ETA delay suggests interesting potential fuel savings, if ETA time windows are available, but mainly in the *Smooth* version.

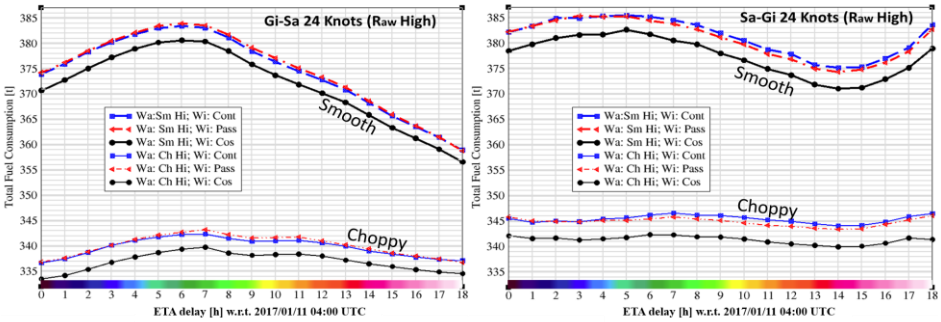

Figure 5. Total fuel consumption data for minimum fuel optimised routes versus ETA, at 24 knots.

The corresponding optimised route shapes are shown in Figure 6, with corresponding plot panels positions: left *GiSa*, right *SaGi*, top *Smooth*, bottom *Choppy*. Only results for *Cos* C_x are shown. Optimised routes for different values of ETA are referred to different colors of the shown palette. The same palette is shown over the horizontal axis in Figure 5. A relevant difference emerging is that, with the more anisotropic *Choppy* wave resistance, a sort of "tacking" behaviour emerges in the optimised route shapes, characterised by several cusps of rapid ship heading variation. In the *SaGi Choppy* case (bottom, right panel), the last two ETA delay values imply route passing very near the Egyptian and Libyan coast. This can be traced to the fact that the strong anisotropy of *Choppy* resistance does not allow to conveniently cross the very heavy weather area visible in right panel of Figure 3, and obliges the solution to find lower sea states in coastal waters. This kind of solution could be filtered out in real applications of the system, as a consequence of constraints on the minimal distance from coast. Analogously, the greater fuel consumption due to the Smooth wave resistance imply the possibility of longer optimal routes for certain values of ETA delay. In such cases the exploitation of the wave shadowing effect of Crete Island becomes viable and some optimised routes pass north of it (R_{aw} *Smooth*, Figure 6).

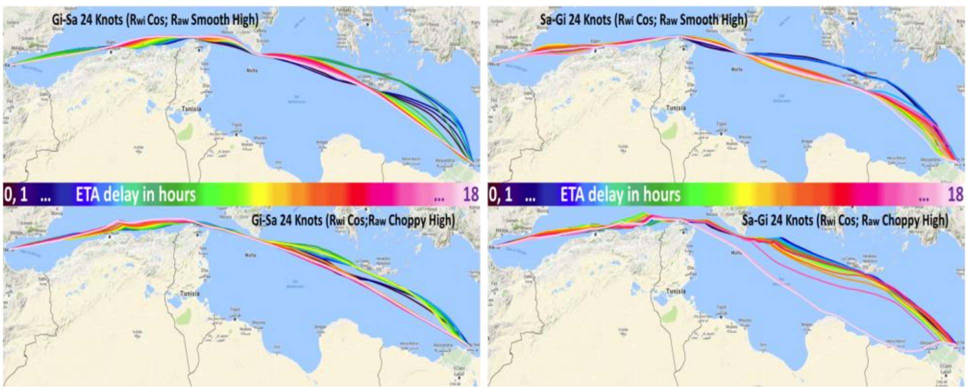

Figure 6. Minimum fuel optimised routes for *GiSa* (left) and *SaGi* (right) voyages at *24 Knots*.

A complete analysis of the huge amount of data is still not available and the work is still ongoing, but some general clues are given in next paragraph.

7. Conclusions

The general architecture of the PROFUMO Demonstrator system has been described, with a particular focus on the application of integrated modelling components for the route optimisation service.

The first numerical tests of this component consist in a sensitivity analysis of the route optimisation algorithm to different simple schematisations of the added resistance terms due to the encountered wind and waves in a relevant heavy weather case study. The huge amount of optimisation data generated by considering all the ship modelling and voyage alternatives can be summarised, in terms of % increments of fuel consumption and of optimal route length, w.r.t. the (shortest) calm weather solution, as follows: *i)* The most relevant term is (as expected) the added resistance in waves, it adds up to 16% for fuel. *ii)* The directional structure of such term emerged as very relevant in comparing the effects of a strongly anisotropic shape, peaked in head waves, with a much smoother one. The former producing lower fuel increments up to 3-5%, versus 10-16% of the latter. These two main points confirm the importance for weather routing of a sound treatment of the complex seakeeping problem for the ship-wave interaction. *iii)* Differences in wind resistance coefficient induced fuel increment variations from a fraction, up to few %. *iv)* Differences in optimal route length increments are usually of the order of 0.5%, but in some cases may arrive up to 2.5%. *v)* Variations in ETA may induce fuel increment variations from few % to 10%. *vi)* Head versus following heavy weather produces differences in fuel increments of 2-4%.

Some of these considerations must be supported by further investigations, due to the idealised character of part of the adopted ship modelling. In particular, while interesting clues can be extracted regarding the effects, on optimal route solutions, of the different added resistance approximations, very prudent evaluations can be given from these results regarding a realistic fuel saving potential.

References

[1] IMO MARPOL Annex VI, Resolutions: MEPC.203(62) July 2011.

[2] DNV-GL, Maritime forecast to 2050, *Energy Transition Outlook 2017*.

[3] ABS, Ship energy efficiency measures advisory. *American Bureau of Shipping*, 2014.

[4] L. P. Perera, C. Guedes Soares, Weather routing and safe ship handling in the future of shipping. *Ocean Engineering*, Vol. 130, (2017), 684–695.

[5] E. Patraiko D., Introducing the e-Navigation Revolution. *Seaways, The International Journal of the Nautical Institute*, (2007).

[6] E. Vanem, e-maritime services for communication with class and for enhanced safety, security and environmental protection in shipping, *International Journal for Traffic and Transport Engineering*, 4(3), (2014), 234 – 252.

[7] IMO Resolution MSC.64(67), annex 1, Recommendation on performance standards for integrated bridge systems (IBS).

[8] F. Tillig, W. Mao, J. W. Ringsberg. Systems modelling for energy-efficient shipping . *Chalmers University of Technology, Department of Shipping and Marine Technology, Division of Marine Technology*. 2015 , Report No. 15:153 ISSN: 1652-9189.

[9] L. P. Perera, B. Mo, Handling big-data in ship performance and navigation monitoring, Maritime industry IoT developments 2017, *Supplement to The Naval Architect, The Royal Institution of Naval Architects*, (2017).

[10] VTCB, Vitrociset Belgium s.p.r.l.: www.vitrocisetbelgium.com.

[11] LaMMA meteo-marine models web pages: www.lamma.rete.toscana.it/mare/modelli/vento-emare.

[12] ESNAH Aeronautical Navigation Systems: http://www.esnah.com/esnah.

[13] A. Orlandi, Brandini C., Pasi F., Taddei S., Doronzo B., Brugnoni G., Rossini G., Benedetti R., Gozzini B., Ortolani, A., Vaccari F.P., Implementation of a meteo marine forecasting chain and comparison between modelled and observed data in the Ligurian and Tyrrhenian seas. *Volume sulle attività di ricerca scientifica e tecnologica del CNR nell'ambito del mare e delle sue risorse, CNR, Italy, Rome*, 2009.

[14] LaMMA Currents: http://www.lamma.rete.toscana.it/mare/modelli/correnti.

[15] B. Gozzini, F. Serafino, C. Lugni (3), A. Antonini, L. Costanza, A Orlandi, D. Arturi, G. Ludeno, A. Natale, F. Soldovieri, A. Ortolani, C. Brandini, An integrated sea monitoring system based on a X-band wave radar to support the removal activities of the Costa Concordia wreck, EGU General Assembly 2013, Vol. 15, (2013).

[16] A. Orlandi, F. Pasi, V. Capecchi, A. Coraddu, D. Villa, Powering and seakeeping forecasting for energy efficiency: assessment of the fuel savings potential for weather routing by in-service data and ensemble prediction, *IMAM 2015 Conference Proceedings, Towards Green Marine Technology and Transport – Guedes Soares, Dejhalla & Pavleti (Eds) © 2015 Taylor & Francis Group, London,* (2015).

[17] W. C. Skamarock, J. B. Klemp, A time-split non-hydrostatic atmospheric model for weather research and forecasting applications, *Journal of Computational Physics,* 227, 3465-3485, (2008).

[18] E. Kalnay, Atmospheric Modeling, Data Assimilation and Predictability, Cambridge University Press, pp. 341, 2003.

[19] WAVEWATCH III R Development Group (WW3DG), User manual and system documentation of WAVEWATCH III R version 5.16., *Tech. Note 329, NOAA/NWS/NCEP/MMAB, College Park, MD, USA*, 2016.

[20] Copernicus Marine: http://marine.copernicus.eu.

[21] M. Hoffschildt, J-R. Bidlot, B. Hansen, P.A.E.M. Janssen, Potential benefit of ensemble forecasts for ship routing. *ECMWF Research Department Technical Memorandum No. 287, ECMWF, Shinfield Park, Reading, RG6-9AX, UK*, 1999.

[22] P. C. Chu, S. E. Miller, J. A. Hansen, Fuel-saving ship route using the Navy's ensemble meteorological and oceanic forecasts, *Journal of Defense Modeling and Simulation: Applications, Methodology, Technology 2015*, Vol. 12(1), (2015), 41–56.

[23] J. S. Carlton, Marine propellers and propulsion, *Elsevier, ISBN: 978-0-7506-8150-6*, 2007.

[24] E. V. Lewis, Principles of naval architecture: volume III. SNAME Editions, 1990.

[25] B. E.-M. Tracy, J. L. Devaliere, T. Hanson, T. Nicolini, H. L. Tolman, 2007. Wind sea and swell delineation for numerical wave modeling, *Proc. 10th Int. Workshop on Wave Hindcasting and Forecasting,* (2007), 12.

[26] A. Orlandi, D. Bruzzone, Numerical weather and wave prediction models for weather routing, operation planning and ship design: The relevance of multimodal wave spectra. *Sustainable Maritime Transportation and Exploitation of Sea Resources Rizzuto & Guedes Soares (eds), 2012 Taylor& Francis Group, London*, (2011).

[27] E. Spentza, G. Besio, A. Mazzino, T. Gaggero, D. Villa, A ship weather-routing tool for route evaluation and selection: influence of the wave spectrum, *IMAM 2017 Conference, Towards Green Marine Technology and Transport 2017 Taylor & Francis Group, London*, (2017).

[28] T. Cepowski, Design guidelines for predicting wave resistance of ro-ro ferries at the initial designing stage, *Scientific Journals Maritime University of Szczecin,* 22(94), (2010), 5–9.

[29] H. van den Boom, H. Huisman, F. Menne, New Guidelines for Speed/Power Trials Level playing field established for IMO EEDI, *SWZ Maritime,* No 134, (2013), 18-22.

[30] SHOPERA (Energy Efficient Safe SHip OPERAtion), FP7 Project: http://shopera.org.

[31] T. A. Dinham-Peren, I. D. Dand, The need for full scale measurements, *William Froude Conference: Advances in Theoretical and Applied Hydrodynamics – Past and Future, Portsmouth, UK,* (2010).

[32] Aleph s.r.l., Transport Engineering: http://www.alephprogetti.com.

[33] Wartsila, W 12V46 Diesel Engine Project Guide, *Wartsila Marine*, 2001.

[34] G. Hughes, Model experiments on the wind resistance of ships, *RINA, Vol. LXXII*, 1930.

[35] J. M. J. Journe, Review of the 1979 and 1980 full-scale experiment onboard containership M.V. Hollandia. *TU Delft, Report 1349*, 2003.

[36] T. Fujiwara, M. Ueno, Y. Ikeda, Cruising Performance of a Large Passenger Ship in Heavy Sea, *Proceedings of the Sixteenth (2006) International Offshore and Polar Engineering Conference San Francisco, California, USA, May 28-June 2*, 2006.

[37] V. Bertram, P. Couser, Computational methods for seakeeping and added resistance in waves, *13th International Conference on Computer and IT Applications in the Maritime Industries COMPIT'14*, 2014.