Planning for efficiency

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Zaccone and Figari present a methodology for ship voyage planning based on 3D dynamic programming.

Who should read this paper?

Ocean field researchers and operators should read to have an exhaustive overview of what ship voyage optimization is about; what are the state of the art methodologies and how they can be integrated into an optimization framework; and the benefits brought by such an approach in simulation trials. Ship operators may be interested in understanding the theoretical basis of voyage optimization and its benefits on ship operation as well. The existing commercial applications of ship routing are not well documented and tested in public domain scientific literature; this paper could help to fill this gap.

Why is it important?

Ship voyage optimization is an open research topic: very few exhaustive scientific papers have been published. The paper aims to give an overview of the voyage optimization problem, presenting its various aspects and their respective theoretical principles. The approach presented merges different marine engineering, mathematical, and computational tasks into a voyage optimization application.

The case study highlights the benefits brought by a voyage optimization tool, both in terms of fuel saving and compliance with the most recent IMO and EU pollutant emission rules. Comfort, operability and safety issues are tackled as well. A low computational time and hardware demand is a consequence of a smart software design of the proposed tool, making it affordable for a wide range of small vessels ranging from professional fishing to yachts.

The presented technology has been recently implemented into a web application framework, which is currently under extensive testing. A pilot project is scheduled to start soon; the presented technology will be tested in the real environment on ferry ships sailing in the Mediterranean Sea.

About the authors

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ENERGY EFFICIENT SHIP VOYAGE PLANNING BY 3D DYNAMIC PROGRAMMING

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ABSTRACT

Energy efficiency is a crucial issue in ship management and operation. A proper fuel saving oriented routing strategy can be helpful in reducing running costs and pollutant emissions, as well as increasing the voyage safety and comfort. This paper presents a methodology for ship voyage planning based on 3D dynamic programming. It aims to select the optimum courses and related speed profile for a ship voyage in accordance to a minimum fuel consumption strategy, on the basis of the ship response to wave and wind conditions inferred from weather forecast maps. The ship voyage is parametrized as a multi-stage decision process where the fuel optimization is carried out in a discretized space-time domain and the optimal solution, in relation to the arrival time requirements and motion related constraints, is found by a dynamic programming algorithm which has been developed and implemented by the authors. Simulation trials for a merchant ship sailing different typical routes in the Mediterranean Sea, in a wide range of weather conditions and using high quality weather forecast maps, are presented and discussed. With respect to previous authors' publications, the presented methodology shows the high potential benefit of detailed weather forecast maps as well as the innovative use of a minimum distance algorithm.

KEYWORDS

Voyage optimization; Weather routing; Ship propulsion; Ship simulation; Dynamic programming

INTRODUCTION

On a global scale, the United Nations has set goals towards year 2030 dealing with energy efficiency and cleaner fossil-fuel management for a more eco-friendly environment. This new scenario also involves international shipping through International Maritime Organization (IMO) actions, one of which is MARPOL Annex VI; in fact, the latest IMO regulations seek to significantly reduce the carbon emissions of the maritime sector. The introduction of technical measures, namely the energy efficiency design index (EEDI) and the energy efficiency operational indicator (EEOI), are part of this strategy.

The European Union put forward the new EU MRV regulation concerning monitoring, reporting and verification of carbon dioxide emissions from maritime transport to enter into force in 2018. The aim of the new rules is to move toward lower carbon emission shipping through improving shipping efficiency.

Ship energy efficiency has long been an area of focused research: Figari and Soares [2009] suggested new control strategies to reduce fuel consumption; Geertsma et al. [2017] presented an up-to-date review and discussion of the most used design and control approaches to propulsion systems; Coraddu et al. [2014A] addressed the EEOI improvement by real data statistics and numerical simulations; Altosole et al. [2015] discussed heat recovery to improve ship efficiency. Most of the research efforts were addressed to improve ship efficiency from a technical point of view, regardless of the real ship operational profile.

Ship propulsion systems simulation is a critical issue when tackling ship energy efficiency: the authors achieved significant experience in relation to ship propulsion modelling and simulation in steady state and dynamic conditions [Altosole et al., 2012A; 2012B; 2014; Coraddu et al., 2012], and diesel and natural gas four stroke engines modelling [Altosole et al., 2017]. Vrijdag and Stapersma [2017] presented a detailed discussion about the linearization of ship propulsion dynamic models. Baldi et al. [2015] addressed the simulation of large two-stroke diesel engines for ship propulsion.

Maritime voyages are significantly influenced by the environmental conditions encountered along the route. In the recent years, the ever-increasing availability of reliable weather forecast data has significantly improved the safety of ship voyages, allowing operators to select convenient routes to avoid rough weather and to better estimate ship times of arrival, as well as the associated costs. Moreover, increased attention is paid nowadays to seakeeping abilities of ships, thus increasing the ship safety also in rough weather conditions.

On the other hand, medium intensity weather conditions do not impair ship safety but affect fuel consumption and comfort on board.

The concurrent addressing of ship efficiency, ship routing, ship safety and comfort issues can be handled numerically, in real-time, providing a relevant decision support tool.

In this framework, optimization algorithms find their application, in order to provide a significant support to the decision making process; they allow integration of multiple aspects of a process and to optimally select with respect to the objective.

Ship and human safety, fuel consumption, energy efficiency, crew and passengers' comfort, voyage time, control of delays – these are all different aspects that contribute to formulate the overall objective (cost function) of the ship voyage. The "optimal voyage" is the one associated to the minimum value of the cost function, within the constraints of the problem.

In the last decades, ship voyage optimization has been addressed through different approaches. Walther et al. [2016] presented a detailed literature review, in which the different methodologies are classified according to the optimization algorithm used. According to Walther, the most used approaches are based on the calculus of variations (isopone method, dynamic programming), discrete optimization (isochrones method and Dijkstra algorithm variations), or evolutionary algorithms (mainly genetic algorithms variations). The first pioneer works, by James [1957], was based on the isochrones method; Zoppoli [1972] and later Papadakis and Perakis [1990] used dynamic programming to voyage time minimization, almost neglecting the ship response modelling.

Traditionally, the interaction between the ship and the upcoming weather state is modelled via involuntary and voluntary speed reductions. This approach, which is based on the Beaufort Wind Force Scale, is used also in recent works [Shao et al., 2012; Lu et al., 2015], despite its excessive level of approximation. Chen [2013] suggested a more detailed modelling of the ship response as a key point in ship voyage optimization; the aim is to better fit different ship types, shapes and dimensions, which in principle behave differently in weather and speed conditions. State of the art approaches targeting different aspects of ship response in a seaway, in terms of ship motions and propulsion, are proposed by several authors. Marie and Courteille [2009] presented a two objectives optimization approach using the FRONTIER implementation of MOGA genetic algorithm: the optimization is performed with respect to fuel consumption and sailing time, and ship added resistance is taken into account in order to evaluate the fuel consumption on the route. Maki et al. [2011] published a multi objective genetic approach to container ship vessels voyage optimization, taking into account the total energy spent during the voyage, and parametric rolling, and adding penalty function constraints to vertical motions. A modified isochrones method has been presented in Lin et al. [2013] and Fang and Lin [2015], minimizing a weighted summation of fuel consumption and arrival time. An original approach based on a quasi-Newton local search method is presented by Safaei et al. [2015]. Coraddu et al. [2014B] addressed the EEOI improvement by weather routing.

Vettor and Guedes Soares [2016] presented a voyage optimization method based on the following steps: off-line computation of ship response amplitude operator (RAO) by strip theory, parametric directional wave spectrum, and propulsion model with engine-propeller matching. The following limits are included: slamming probability, green water probability, vertical acceleration at bridge, and roll motion. The Portuguese weather forecasting system is used. The optimization is carried out by using a Genetic Algorithm coupled to a modified version of the grid-based Dijkstra's algorithm, used for pre-optimization of the first generation. They applied the method also to a Mediterranean fishing vessel showing good storm avoidance features.

On the market there are several companies providing ship routing and efficiency services but with very different levels of complexity and thus fidelity. Due to the limited information available in the public domain, the state of the art of the commercial services is out of the scope of this paper.

In a precursor work [Zaccone et al., 2016], the authors presented a 3D dynamic programming algorithm applied to ship voyage optimization, based on ship propulsion modelling, aiming to select the minimum fuel consumption route at assigned time of arrival. With respect to previous work, this paper aims to present a ship voyage optimization method based on an improved modelling of the ship's behaviour in presence of waves and wind. An improved ship model has been developed for this application to compute both ship motions and propulsion behaviour taking into account sea and wind conditions provided by detailed weather forecast maps. Moreover, propulsion performance limits and distance from the coastline are now taken into account. The optimum is defined as the minimum fuel consumption within all boundary conditions.

The paper is organized as follows: problem description, ship model description, route parametrization and optimization, and results for a number of case studies in the Mediterranean Sea environment. All the results presented in the paper have been achieved by using self-developed software, making wide use of C++ object oriented programming.

PROBLEM DESCRIPTION

The selection of the optimal route combines in principle a number of objective functions as well as various constraints. A ship's voyage is characterized by a starting point, an arrival point, a constrained arrival time window, and eventually a number of fixed waypoints. Geographical constraints (shoreline, traffic separation schemes, areas restricted to navigation), as well as constraints related to ship motions all need to be considered. From the point of view of energy efficiency, the output of the voyage is the integral of fuel consumption rate and the related CO_2 emissions. Depending on the problem formulation, a trade-off between constraints and objectives can occur.

The presented methodology aims to minimize the total fuel consumption of the voyage, while ship motions and arrival time are managed through constraints: a single objective optimization methodology is thus used to minimize a cost function (the total fuel consumption). If v is a proper parametrization of the voyage, $m_f(v)$ the cost function, (i.e., the fuel consumption associated to the voyage), and $g_i(v)$ and $h_i(v)$ the equality and inequality constraints respectively, the problem to be solved has the following form:

$$\begin{cases} \underset{\boldsymbol{v}}{\operatorname{argmin}}\ m_f(\boldsymbol{v}) \\ g_i(\boldsymbol{v}) = 0,\ i = 1,2,\ldots,m \\ h_i(\boldsymbol{v}) \geq 0\ i = 1,2,\ldots,p \end{cases} \tag{1}$$

Where argmin denotes the parametrization corresponding to the minimum value of the cost function $m_f(v)$, while satisfying the constraints.

In the present application, the cost function is evaluated by a ship performance model, which takes into account the still water and weather-induced components of hydrodynamic resistance as a function of the ship speed and heading and local weather conditions. The model then estimates the propeller and ship engine working points in order to finally assess the fuel consumption. Weather-induced ship motions are estimated too. Weather conditions at each ship position and time instant are estimated by interpolation into weather forecasts.

A 3D dynamic programming (3DDP) algorithm is used to find the optimal ship route in relation to each time of arrival considered in the user-defined arrival time window, compatible with the other problem constraints. Dynamic programming (DP) is an optimization strategy that aims to solve a problem by subdividing it into more simple sub-problems, named steps or stages. It assesses the result as a consequence of a number of sequential decisions. Optimal solution is found based on Bellman's principle of optimality:

"An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision." [Bellman, 1954]

The structure of the method adapts well to any multi-stage decision process, and among those "best path search" type problems [Bellman, 1958; 1962], which can be reduced as a sequence of decisions, leading from the start point to the arrival point, with a return depending on the decisions themselves.

A number of constraints are taken into account in the optimization: in particular, ship motion-based constraints are imposed by using probability of slamming, deck wetness, bow accelerations [Journée and Meijers, 1980], lateral force estimator (LFE) [Perez, 2006], and maximum motion sickness incidence (MSI) [Piscopo and Scamardella, 2015]. Moreover, ship propulsion related constraints are considered in the model; in particular, maximum power, torque limits and shafts maximum rotation speed are constrained below proper threshold values. Finally, geographical constraints are included and in particular the minimum distance from the shoreline or any other user-defined obstacle is computed by a nearest neighbour algorithm based on kd-tree data structures [Bentley, 1975; Friedman et al., 1977; Bentley and Friedman, 1979]. The constraints allow to implicitly take into account both voluntary and involuntary speed reductions in presence of rough weather and taking into account ship responses to waves in terms of motions and resistance increases.

3DDP algorithm efficiently performs an exhaustive exploration of the domain of the solutions, defined by a space-time grid. In general, the result of the optimization is a sequence of points identified by longitude, latitude and intermediate time, which determine the ship's trajectory as well as the optimal speed of each route segment.

The availability of meteorological data is a key point of the work, so the model is developed to be compatible with the most common weather forecast data formats. In this work waves and wind data are considered and gridded in function of time and geographical coordinates. Once the forecast maps are provided, wave significant height, mean period, direction and wind speed components are obtained via space-time interpolation for any time instant and location and identified by latitude and longitude. Wave and wind forecast data are used to estimate ship motion and added resistance in waves, in order to assess the required engine power and fuel consumption via steady state ship propulsion simulation.

Several weather forecasting maps can be used. In the present work, detailed Mediterranean maps of wind and sea (in terms of two parameters spectrum for each grid centre of 10 km) from Wavewatch III model are used [Mentaschi et al., 2013A; 2013B; 2015].

In principle, the total amount of fuel burned by the ship along a given route segment can be computed by numerical integration, combining weather forecast maps and power performance prediction. Once the cost of each route segment is assessed, the optimal policy of the multi-stage process representing the ship voyage is computed by dynamic programming.

To this end, the main tasks are:

1. weather forecasting data availability and management;
2. ship propulsion performance and hydrodynamic response modelling;
3. optimization problem formulation and solution.

The first point is considered as input data while the presented work is centred on the second and third points, which will be described in the remainder of the paper.

SHIP MODEL

The numerical ship model estimates the fuel consumption in given geographical positions, weather conditions and ship speeds.

The computation is, in principle, made in five main steps:

1. weather condition characterization
2. hydrodynamic resistance calculation
3. ship motion and comfort assessment
4. propeller performance prediction
5. engine performance prediction and fuel consumption estimate

The flow chart of the method is shown in Figure 1. For any assigned speed, time and geographical coordinates, the weather conditions (wave and wind data) are estimated by interpolating into weather forecast data, then the hydrodynamic resistance as well as ship motion are computed. The propulsion model evaluates the propulsion system working conditions and their associated fuel consumption. The ship model is developed in C++ language, using Armadillo library [Sanderson and Curtin, 2016].

Weather Conditions

Two weather actions are considered: waves

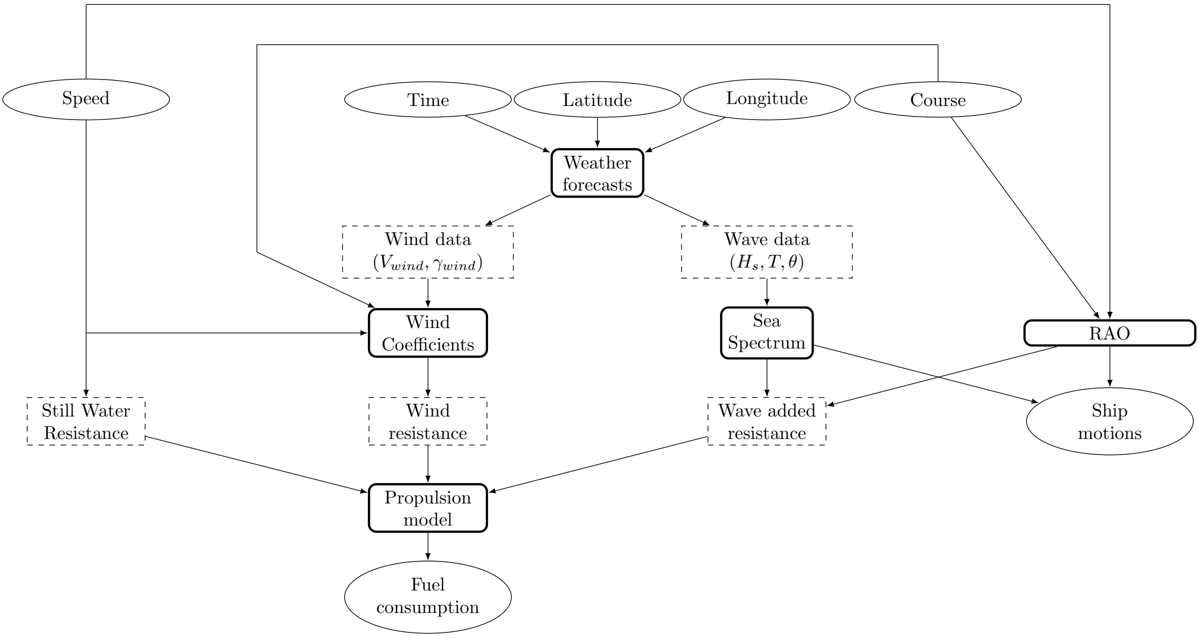

Figure 1: Ship model flow chart.

and wind. Wind data is provided in terms of wind speed components u, v as a function of geographical coordinates and time. Wave significant parameters are provided as well in function of the same variables, in particular significant wave height $H_{\frac{1}{3}}$, wave period T_1 , and sea main direction θ_w. ITTC '84 JONSWAP spectral formulation is used:

$$S(\omega,\theta) = 155 \frac{H_{\frac{1}{3}}^2}{\omega^5 T_1^4} \exp\left(-\frac{944}{\omega^4 T_1^4}\right) (\gamma)^Y \frac{2}{\pi} \cos^2 (\theta - \theta_w) \qquad (2)$$

Where:

$$Y = \exp\left[-\left(\frac{0.191\omega T_1 - 1}{\sqrt{2}\sigma}\right)\right] \qquad (3)$$

The choice of the spectral formulation can significantly affect the results, as it directly influences the ship motions and resistance. In particular, real and parametric spectra may differ significantly in presence of crossing seas: these aspects are not addressed here as the presented work is mainly focused on investigating the potential of the optimization procedures in a voyage optimization framework.

The weather forecasts of the Mediterranean Sea, used in this paper, have been provided by the Department of Civil, Constructions and Environmental Engineering (DICCA) of the University of Genoa, and are based on Wavewatch III model [Mentaschi et al., 2013A; 2013B; 2015]. The weather forecasts, provided in GRIB2 format, have 10 km resolution and 120 hours depth.

Resistance Assessment

The hydrodynamic resistance of the ship, R_{tot}, is decomposed in accordance with the following equation:

$$R_{tot} = R_t + R_{aw} + R_{wind} \qquad (4)$$

where R_t is the still water hydrodynamic resistance, R_{aw} is the added resistance due to the rough sea effect, and R_{wind} is the resistance due to wind.

The still water resistance R_t is a function of ship speed, displacement and trim. Depending on the availability of such data, different approaches may be used, ranging from towing tank tests to CFD calculation or semi-empirical formulations. Regardless of the method used, still water resistance is evaluated offline and stored into a multidimensional array, which feeds the optimization process. For the presented case study, the still water resistance is calculated in accordance with the method proposed by Holtrop and Mennen [1982] and re-analysed by Holtrop [1984].

The added wave resistance R_{aw} is estimated according to the following expression [Lewis, 1989]:

$$R_{aw}(V) = \int_0^{\infty} \int_0^{2\pi} \Phi_{aw}\,(\omega, \theta, V) S_{\zeta}(\omega, \theta) d\omega d\theta \tag{5}$$

where ω is the wave circular frequency, $S\zeta$ is the directional wave energy spectral density, Φ_{aw} expresses the longitudinal drift forces per squared wave amplitude and wave circular frequency, and is the encounter angle. The strip theory seakeeping open source code PDSTRIP [Soding and Bertram, 2006] has been used to evaluate Φ_{aw}.

The resistance due to wind R_{wind} is expressed through a function of the relative wind speed V_r:

$$LFE_P = \ddot{\eta}_2 - \ddot{\eta}_4(z_P - z_g) + \ddot{\eta}_6(x_P - x_g) - g\eta_4 \tag{6}$$

where ρ_{air} is the air density, A_F is the ship's above water front projection area, and c_X is the wind resistance coefficient, depending on the encounter angle, γ_w computed in accordance to the method proposed by Blendermann [1994].

The effects of rough weather are thus modelled in terms of resistance increase, rather than speed reductions: the resistance increase is actually the cause of the involuntary speed reduction, or when possible, the power output increase needed to achieve the required speed.

Ship Motion Effects

Ship motions spectra have been computed as suggested by Lewis [1989]. The energy spectrum $S_{\eta i}$ of absolute i^th^ motion η_i is evaluated in accordance with the following equation:

$$S_{\eta i}(\omega, \theta, V) = |H_{\eta i}(\omega, \theta, V)|^2 S_{\zeta}(\omega, \theta) \tag{7}$$

where $H_{\eta i}$ is the complex response amplitude operator (RAO) of i^{th} motion η_i and S_{ζ} is the directional wave energy spectral density. Open source, strip theory code PDSTRIP [Soding and Bertram, 2006] has been used to evaluate ship motions absolute RAOs.

Lateral force estimator (LFE) is used to estimate lateral accelerations [Perez, 2006]. The LFE represents apparent lateral acceleration, or lateral force per unit of mass. In particular, the lateral force estimator at the point P is given by the following equation:

$$LFE_P = \ddot{\eta}_2 - \ddot{\eta}_4\,(z_P - z_g) + \ddot{\eta}_{66}$$

$$(x_P - x_g) - g\eta \tag{8}$$

Where $\ddot{\eta}_i$ represents the acceleration of the i^{th} motion and subscripts 2, 4, 6 represent the sway, roll and yaw motions respectively.

Ship passengers' comfort evaluation has been the objective of research by various authors, who propose proper parameters depending mainly on vertical accelerations mean value and frequency. The most used parameters are the Motion Sickness Incidence (MSI), proposed by O'Hanlon and McCauley [1973], and the Vomiting Incidence by Lawther and M. J. Griffin [1986; 1988]. In this study, MSI has been used to estimate crew comfort. The MSI for a reference exposition time of two hours is given by the following equation [Cepowski, 2012; Piscopo and Scamardella, 2015], in dependence of the spectral moments of the absolute vertical motion η_{3P} at the point of interest:

$$MSI = 100\left[0.5 + \mathrm{erf}\,(\frac{\log_{10}\frac{a_v}{g} - \mu_{MSI}}{0.4})\right] \tag{9}$$

Where:

$$a_v = 0.798\sqrt{m_{4,\eta_{3P}}} \tag{10}$$

$$\mu_{MSI} = -0.819 + 2.32\left[\log_{10}\sqrt{\frac{m_{4,\eta_{3P}}}{m_{2,\eta_{3P}}}}\right]^2 \tag{11}$$

erf(x) is the error function, and $m_{n,\eta_{3P}}$ is the nth order moment of vertical motion at P.

Propulsion Simulation

The ship propulsion system is modelled in a deterministic way, assuming a steady state behaviour of its components. In particular, the propulsion performance is assessed by considering the equilibrium between the thrust required by the hull to sail at a constant speed and the one delivered by the propeller. The torque and revolution required by the propeller are thus computed and matched with the engine characteristics.

The propeller simulation is carried out by means of the propeller open water characteristics, reporting thrust and torque coefficients, K_T and K_Q respectively, versus the advance coefficient J. The interaction between hull and propeller is taken into account by the propulsive coefficients t, w, η_r. In the present application, the effects of the waves on propeller performance are neglected.

The engine fuel consumption is evaluated by using a quasi-static model based on specific fuel consumption maps and maximum torque, maximum power, maximum revolutions and compressor surge bounds.

Engine map bounds have a constraining effect on propulsion performance: feasible propulsion working conditions are bounded into a specific region of the power to rotation speed plane, as shown in Figure 2.

The feasibility or infeasibility of any combination of speed and weather conditions, as well as the associated cost in terms of fuel consumption, are thus a result of the propulsion simulation. In case of controllable pitch propellers, the search of a feasible working point includes also the proper propeller blade angle setting.

The mass of fuel burned at each stage, or route segment, is evaluated by numerical time-integration of the fuel mass flow rate. The cost of the voyage is obtained by integrating the whole voyage time, i.e., by summing each segment's contribution.

Constraints

Ship motion related issues are implemented in the optimization as constraints. In

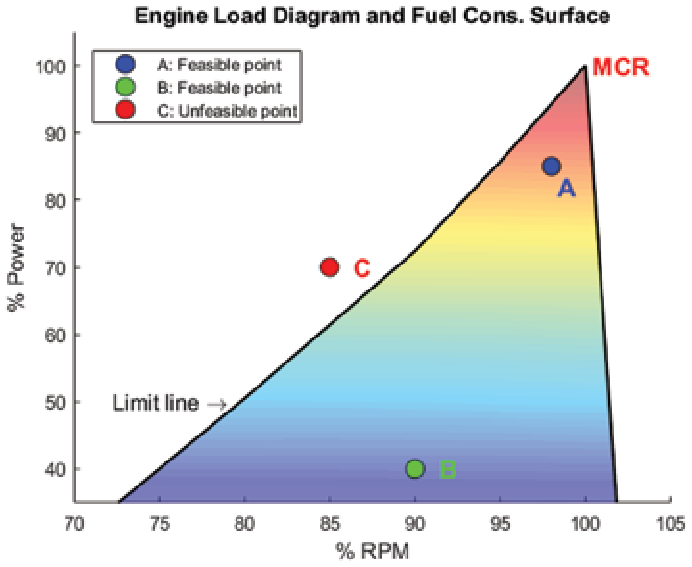

Figure 2: Feasible and unfeasible engine working conditions, plotted on top of a typical diesel engine performance map.

particular, slamming and deck wetness probabilities are checked [Journée 1976; Journée and Meijers, 1980] in accordance with the following inequalities:

$$P(\eta_{3r,0.9L} > T, \dot{\eta}_{3r,0.9L} > 0.093\sqrt{gL}) < 0.03$$

$$P(\eta_{3r,B} > f_b) < 0.07$$

$$P(\ddot{\eta}_{3,B} > 0.4g) < 0.07$$

Being $\eta_{3r,0.9L}$ and $\dot{\eta}_{3r,0.9L}$ the relative vertical motion amplitude and velocity at 90% of the ship length respectively, $\eta_{3r,B}$ the relative vertical motion amplitude at bow, $\ddot{\eta}_{3,B}$ the absolute vertical acceleration at bow, and L, T, f_b the ship length, draft and freeboard at the bow respectively. In addition, the following inequality constraints are imposed:

$$LFE < LFE_{max}$$

$$MSI < MSI_{max}$$

Where LFE_{max} = 0.7g [Perez, 2006], and MSI_{max} = 10%.

ROUTE PARAMETRIZATION

A parametric definition of the ship trajectory is needed in order to perform the optimization. In the proposed dynamic programming framework, the ship route is modelled as a finite set of waypoints and a corresponding set of times of arrival at the waypoints. Figure 3 presents a schematic representation of the so obtained 3D domain. The waypoints lay on the grid obtained by discretizing the segment linking the start point to the arrival point, and adding a set of waypoints in the orthogonal direction.

The waypoints grid is based on the great circle geometry in order to identify the shortest solution. In this case, the local route R_X is variable along the great circle segment, according to the following relationship:

$$\cos R_X = \frac{\sin\varphi_X \cos(m_{AX}) - \sin\varphi_A}{\cos\varphi_X \sin(m_{AX})} \qquad (12)$$

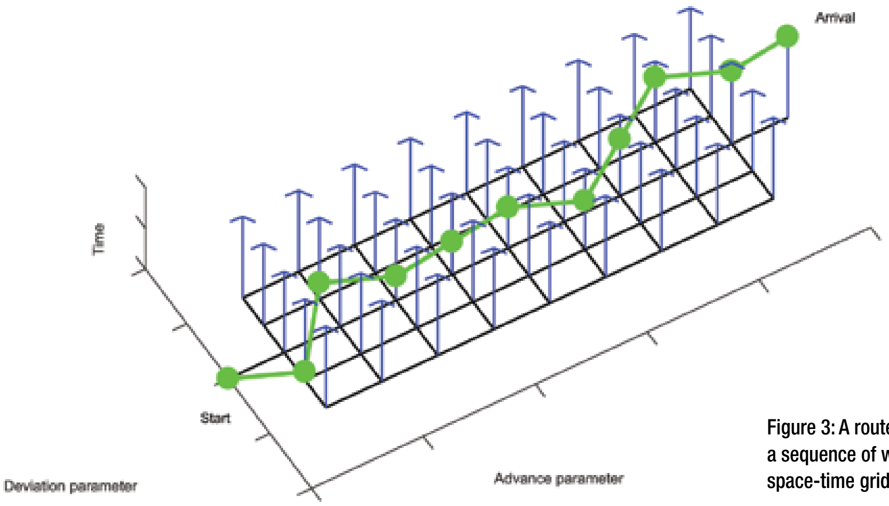

Figure 3: A route represented as a sequence of waypoints in a 3D space-time gridded domain.

where m_{AX} is the length of the great circle arc linking the start point A to point X, and φ_A, φ_B are the latitudes of points A and X respectively. The geographical coordinates of point X depend as well on the coordinates of the start point A and the end point B of the great circle segment.

Note that the present approach is oriented to provide a set of waypoints that the ship should follow, and does not include the effects of the rhumb-line approximation to great circle navigation, which effects may be significant in case of long distances between successive waypoints.

The route generation takes into account the shoreline shape, and in general the presence of user-defined static obstacles, in order to avoid groundings or prohibited passages.

A brute force computation of the minimum distance from the obstacles can affect computation efficiency, especially if a high-resolution shoreline is used. In the presented application, an efficient nearest neighbour search algorithm has been implemented, based on kd-tree data structures [Bentley, 1975; Friedman et al., 1977; Bentley and Friedman, 1979]. Kd-trees are space partitioning data structures that organize data in a binary tree: the tree is built recursively by splitting data in half-spaces, cycling on the kth dimensions, and linking the median of each subspace to the medians of its child subspaces. Kd-tree structure allows computing nearest neighbour search in $O(\log n)$ [Friedman et al., 1977], taking advantage from the tree topology to reduce the number of visited nodes. In the presented case, a 2d-tree is used. Figure 3 shows some examples of half-cuts on a map of the western Mediterranean Sea.

DYNAMIC PROGRAMMING

The proposed formulation of the ship voyage optimization problem is solved by a 3D dynamic programming algorithm. Times of departure and arrival, together with geographical coordinates (latitude and longitude) of the start and arrival points, are assigned a-priori. A 3D space-time discrete domain is generated according to the previously described route parametrization algorithm. At each stage $f_i\ (X,t)$ represents the fuel burned to reach position X at time t starting from the beginning and by following an optimal policy. According to Bellman, the following functional relationship can be written:

$$f_i(X,t) = \min_{\xi,\tau} \left[m_{f\ (\xi,\tau)\rightarrow(X,t)} + f_{i-1}(\xi,\tau) \right],\quad i = 2,3,\dots,N \tag{13}$$

where $m_{f\ (\xi,\tau)\rightarrow(X,t)}$ is the fuel burned to travel from each position ξ on the grid at time τ to position X at time t.

The cost of each route segment, linking each couple of states and intermediate times at consecutive stages, is evaluated in the DP forward pass by running the ship propulsion and motions model integrating the fuel consumption along the segment. The ship model integration time step is tuned independently from the DP time step, in order to avoid aliasing effect of weather forecast maps in case of a loose DP grid. During the forward calculation, a number of pruning strategies are used in order to improve computation efficiency. The calculation finds the minimum cost associated with each admissible time of arrival. The optimal solution (i.e., route and speed profile) is finally extracted by backtracking.

The principal advantage of the proposed DP approach, if compared to heuristic global search algorithms (such as genetic algorithms), is that it is exhaustive i.e., it guarantees to achieve the optimal solution associated to the discretization of the problem. The pruning strategy adopted aims to minimize the number of evaluated segments, while maintaining the exhaustiveness of the algorithm. Time constraints, nodes visibility and distance from obstacles are checked before each cost evaluation. In addition, early recognition of suboptimal solutions is performed by lower bounding the cost of each segment, while a proper sorting of the start nodes of each segment helps to maximize the pruning effect.

CASE STUDY

Length b.p.	182 [m]
Beam	31 [m]
Draft	9 [m]
Displacement	41,577 [t]
Deadweight	40,846 [t]
Propeller	1 x FPP, 4 blades, 6 m diameter
Main engine	1x10 MW, 113 RPM 2 stroke diesel engine

Table 1: Main data of the case study ship.

Results related to an early version of the presented methodology has been published by the authors in the past. Different optimization modes have been compared in Zaccone et al. [2016], in particular, the speed and route optimization (voyage optimization) and the speed profile optimization (SO), considering a voyage through the Atlantic Ocean. The results presented here are obtained by an updated version of the developed code, mainly in terms of ship response modelling and computation efficiency. The results presented here refer to a cargo ship whose main data is summarized in Table 1 – four typical commercial Mediterranean routes are considered (in both directions): Genoa-Barcelona, Barcelona-Tangiers, Marseille-Tunis, and Tangiers-Suez. The main data of the considered routes are

	Genoa-Barcelona	Barcelona-Tangiers	Marseille-Tunis	Tangiers-Suez
Coord. (1)	44°12’N, 8°48’E	41°06’N, 2°24’E	43°12’N, 5°06’E	36°N, 5°06’O
Coord. (2)	41°06’N, 2°24’E	36°N, 5°06’O	37°18’N, 10°30’E	32°00’N, 2°00’E
G.C.dist. [nm]	342	502.06	448.4	1906.3
Num. of steps	8	12	12	21
ETA [h]	36	44	44	182

Table 2: Main data of the case study voyages.

summarized in Table 2, which also reports the number of longitudinal segments in which each route is subdivided.

The optimization of the voyages described above has been carried out on nine different weather conditions associated with their respective weather forecast maps. The dates considered as case studies, in yyyy-mm-dd format, are: 2015-10-01, 2016-01-07, 2016-01-14, 2016-02-10, 2016-02-16, 2016-02-29, 2016-03-03, 2016-05-01, and 2016-11-08. The forecasted sea and wind states at 12:00 p.m. are shown in Figures 5 and 6 respectively, as an example. All the routes present significantly variable weather conditions in the considered days, in terms of sea and wind severity and direction. A number of 72 optimization runs have been carried out for different routes and weather conditions.

The aim of the test case was to assess the influence of the different weather conditions on the optimal routing solution, as well as on the fuel consumed by the propulsion system during the voyage. Minimum distance, constant speed routes have been also simulated as a comparison term. Unfortunately, the test case does not represent the actual trade of the ship, so real field data are not available for comparison.

RESULTS

The output of the decision tool is the best routing (waypoint sequence) and the associated ship speed for each route segment (optimum speed profile), for a fixed arrival time (estimated time of arrival, ETA).

Prior to analyzing these results, it is convenient to analyze the relationship between ETA and fuel consumption, a relationship available by running multiple optimization with different ETA. Figure 7 shows, as an example for the Genoa-Barcelona trip, the fuel used along the best route for a selected ETA and for each of the nine considered weather forecasts (colours in Figure 7). The steepness of the curves is representative of the rate of fuel consumption decrease per hour of delay. By slightly relaxing the constraint put on the ETA, the results show a trade-off between fuel consumption and voyage time, i.e., any anticipation on the ETA results in an additional cost in terms of consumed fuel.

The predictions highlight a very high fuel consumption sensitivity to weather forecast, roughly doubling the consumption from the best to the worst forecast scenario. Also the

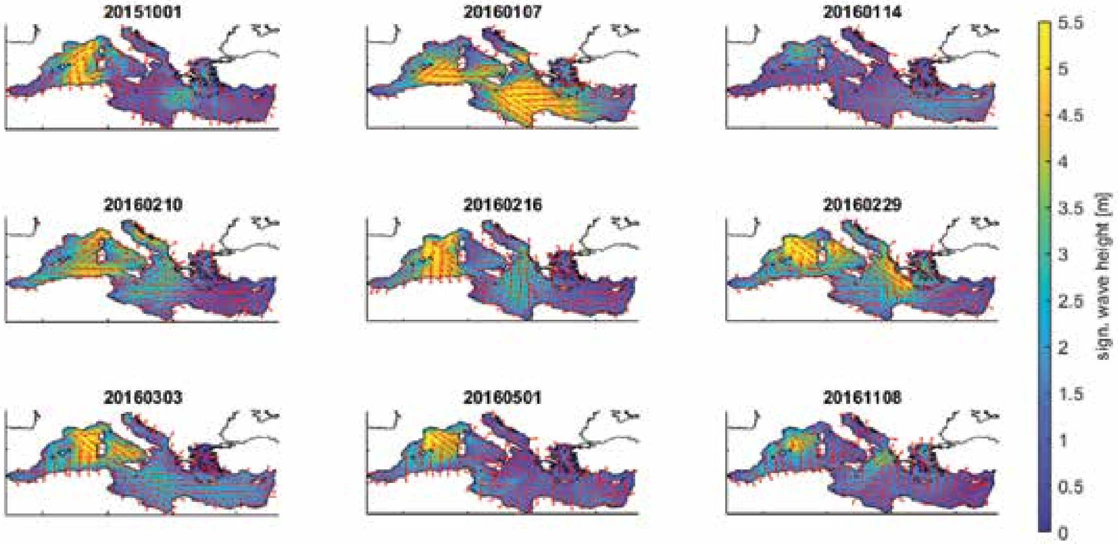

Figure 5: Significant wave height and direction forecasts at 12:00 p.m.

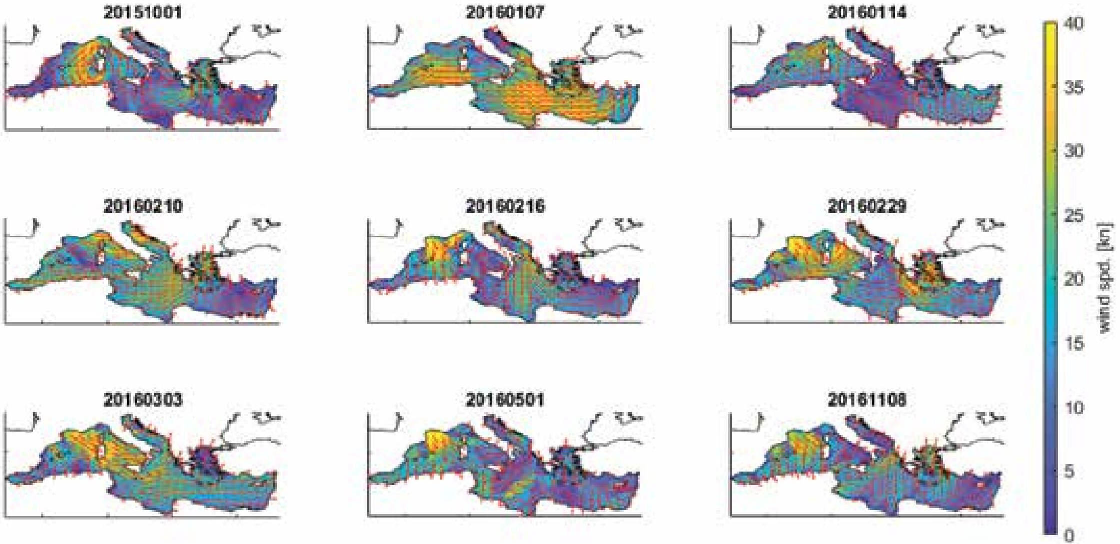

Figure 6: Wind speed (in knots) and direction forecasts at 12:00 p.m.

derivative of the curve is dependent on the weather. In addition, routes passing through more significant fetched waters, such as the Genoa-Barcelona (which crosses the Gulf of Lion, well-known for its severe sea conditions during storms), take greater benefit from optimization if compared to the ones sailing closer to the coast, such as the Barcelona-Tangiers.

Figure 8 presents the average fuel consumption obtained by optimizing the considered routes, compared to average of the minimum length constant speed reference solutions. The same result is reported in percentage form in Figure 9.

Note that the average fuel consumption reduction achieved reaches 7% in some cases.

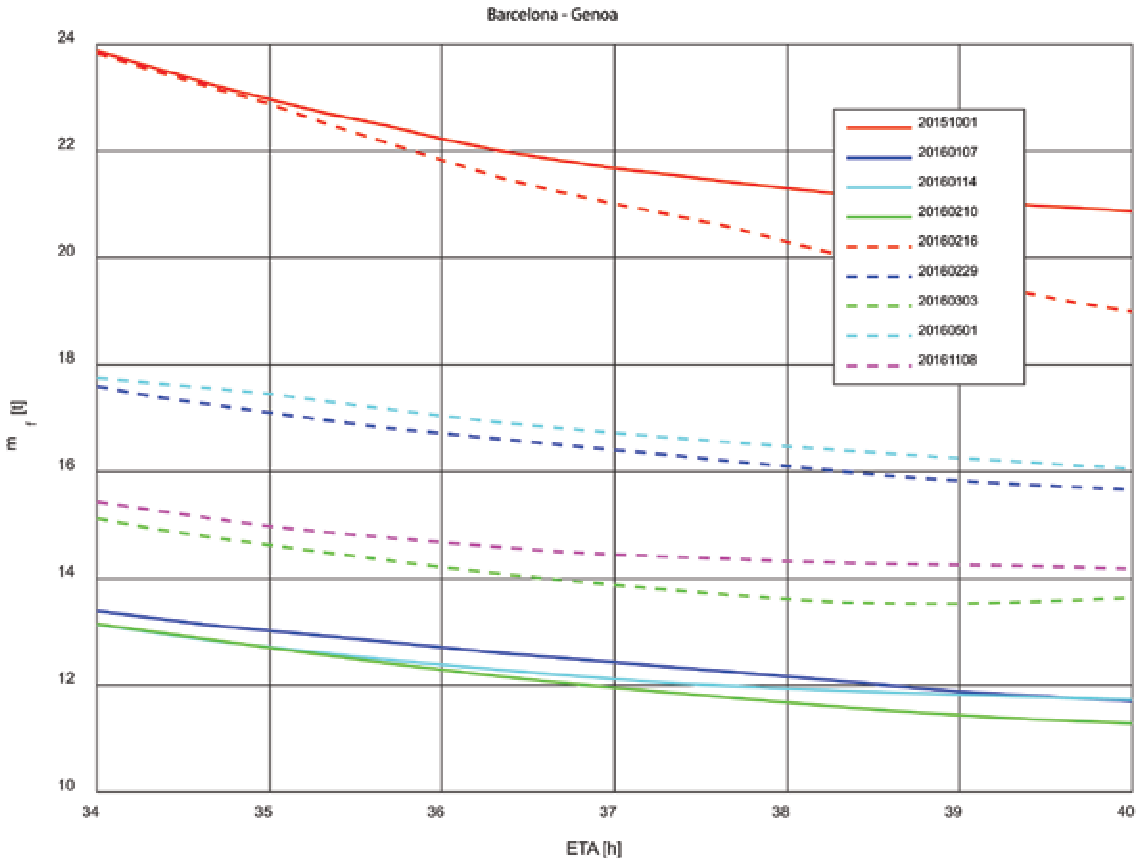

Figure 7: (Barcelona-Genoa) fuel consumption vs. estimated time of arrival trade-off curves.

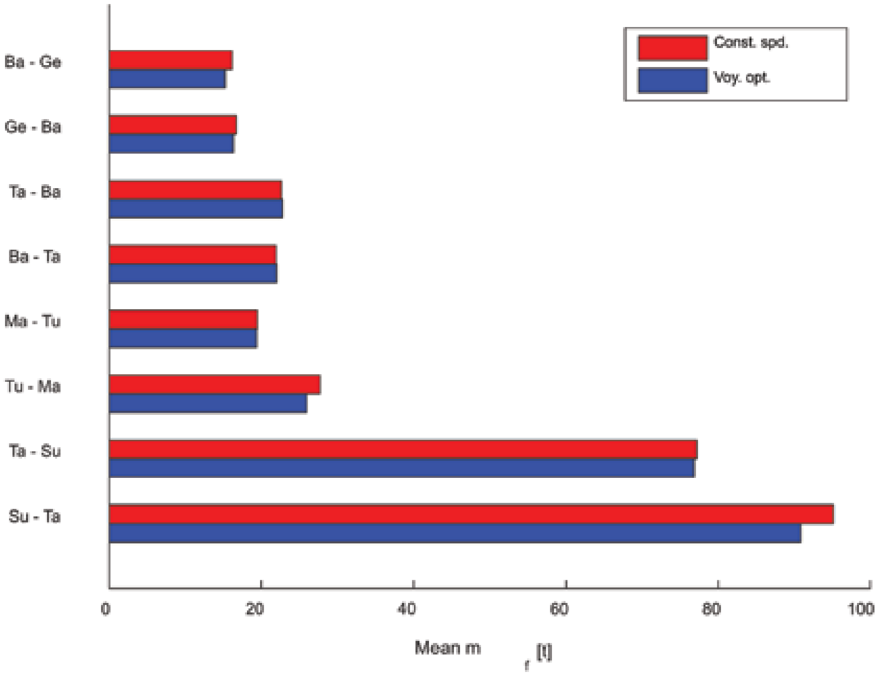

Figure 8: A comparison between the average fuel consumption values achieved by optimized versus constant speed solutions.

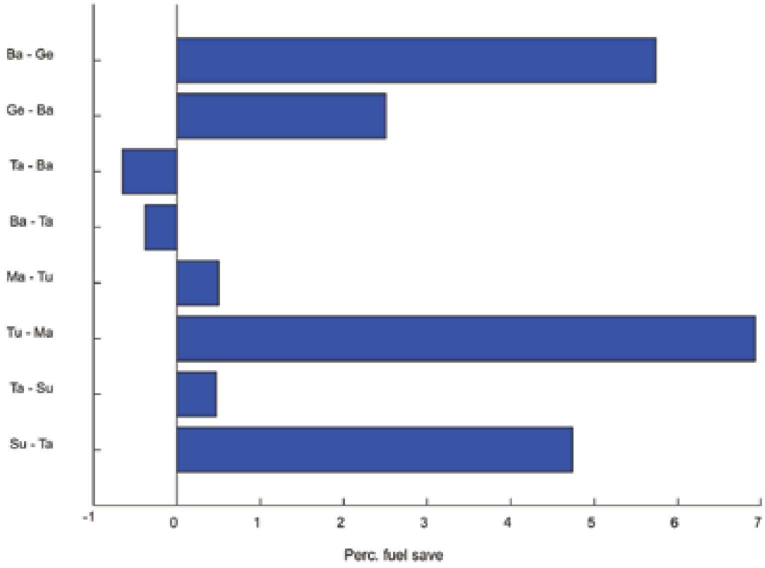

Figure 9: Percentage difference between the average fuel consumption values in optimized versus constant speed solutions.

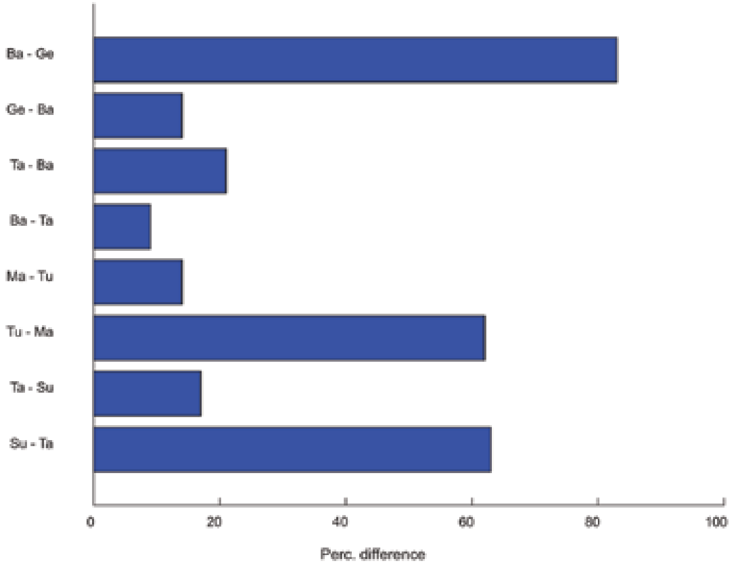

Figure 10: Percentage variation between minimum and maximum fuel consumption in optimized solutions in the considered days.

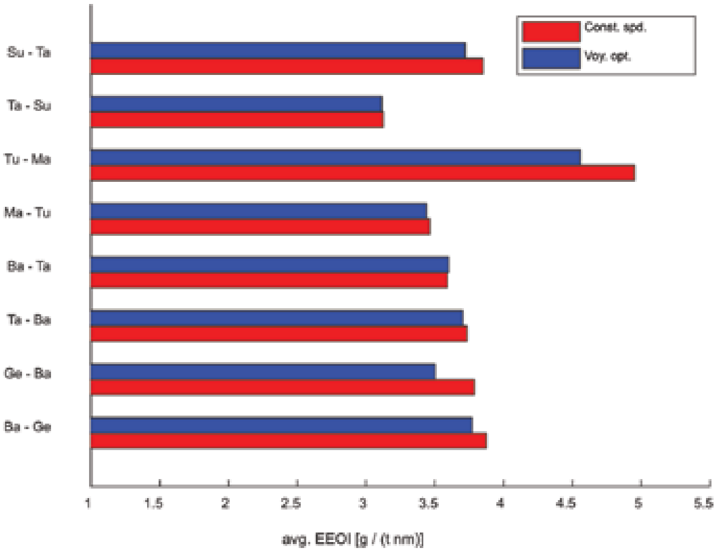

Figure 11: A comparison between the average energy efficiency operational indicator achieved by optimized versus constant speed solutions.

Note also that in some cases route optimization seems to perform worse than the reference route. This issue occurs in cases when weather conditions are calm, i.e., optimization is not necessary, and is due to the slightly different time discretization used in the two cases in order to keep low computation times in optimization (which order of magnitude is tenth of seconds).

Figure 10 shows the difference between maximum and minimum fuel consumption achieved by optimization for each route. Finally, Figure 11 presents a comparison between the average EEOI corresponding to the optimized routes, compared to average of the minimum length constant speed reference solutions.

Results presented in Figures 8, 9, 10, and 11 suggest that Barcelona-Genoa, Genoa-Barcelona, Tunis-Marseille, and Suez-Tangiers voyages are characterized by significantly severe weather in the considered days associated to a considerable spread of fuel consumption and higher benefit of the VO results in terms of energy efficiency gains.

The output of the optimization is presented in Figures 12, 13, and 14 where the effects of the optimization along the routes have been investigated.

Figures 12 and 13 present the trajectories and speed profiles of the optimal solutions in the Barcelona-Genoa and Tunis-Marseille cases respectively. Note that significant deviations are made in order to avoid rough weather, as well as noticeable speed variations. Note also that both optimal trajectories and speed profiles are different in the considered days, as they depend on the weather conditions encountered. On the contrary, Figure 14 presents the same results in the Tangiers-Barcelona case: the ship does not encounter significant weather conditions, thus the trajectory is straight and speed profile is regular in all the considered days. As one could expect, the most significant variations in terms of route and speed profile changes – fuel consumption values spreading and fuel save – are associated to the same voyages, i.e., the voyages affected by the most severe weather conditions.

The obtained results, in particular the added resistance and thus the fuel consumption values, strongly depend on the response amplitude operators assumed, which calibration has not been carried out yet. This might affect the results in terms of absolute values, yet not acting on comparison operations on which the optimization process is based. Optimization is indeed the central aspect of the presented work, while model calibration is going to be performed in future research.

CONCLUSIONS

A ship voyage optimization method has been presented which aims to find the minimum fuel consumption voyage, subject to safety and comfort constraints, by using 3D dynamic programming. A parametric route model, based on great circle navigation, and taking into account shore geography, is used in order to give a dynamic programming formulation of the problem. The solution is found by an algorithm acting in accordance with Bellman's principle of optimality whose cost function i.e., the total mass of burned fuel, is evaluated

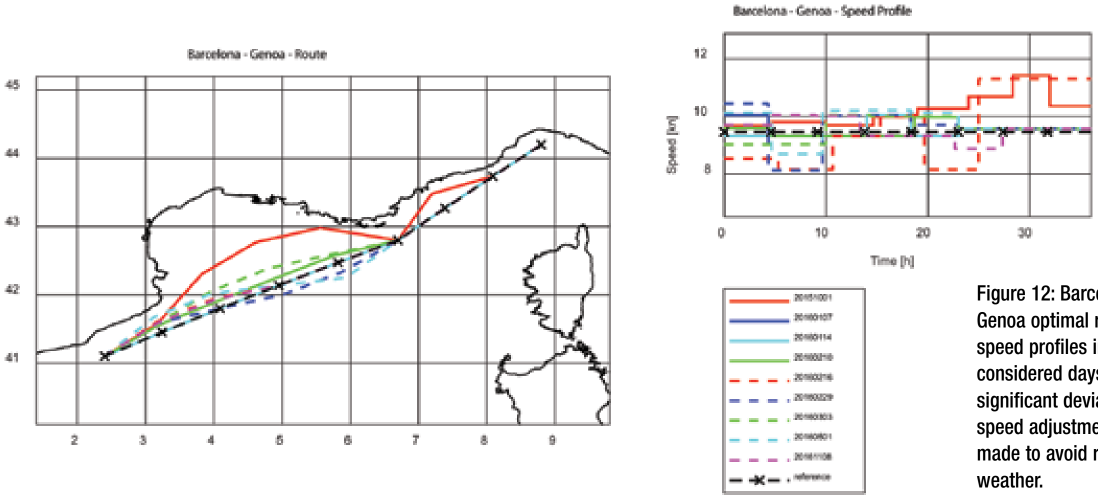

Figure 12: Barcelona-Genoa optimal routes and speed profiles in the considered days: significant deviations and speed adjustments are made to avoid rough weather.

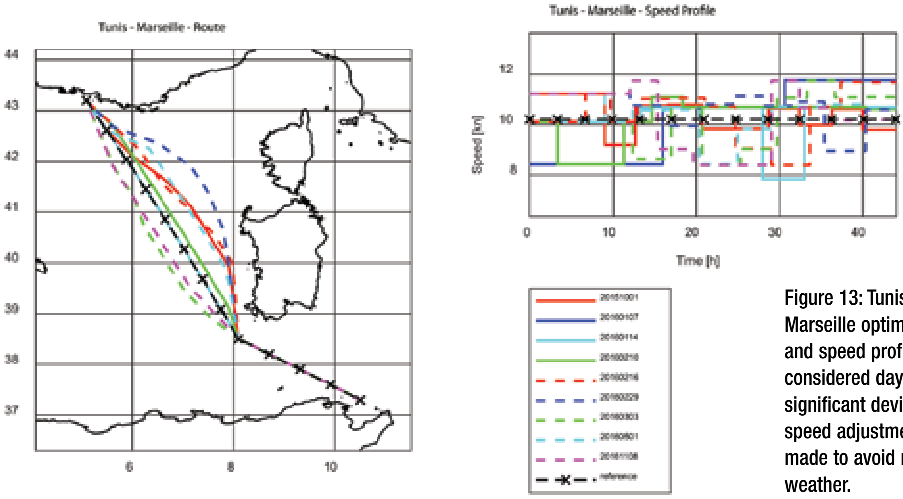

Figure 13: Tunis-Marseille optimal routes and speed profiles in the considered days: significant deviations and speed adjustments are made to avoid rough weather.

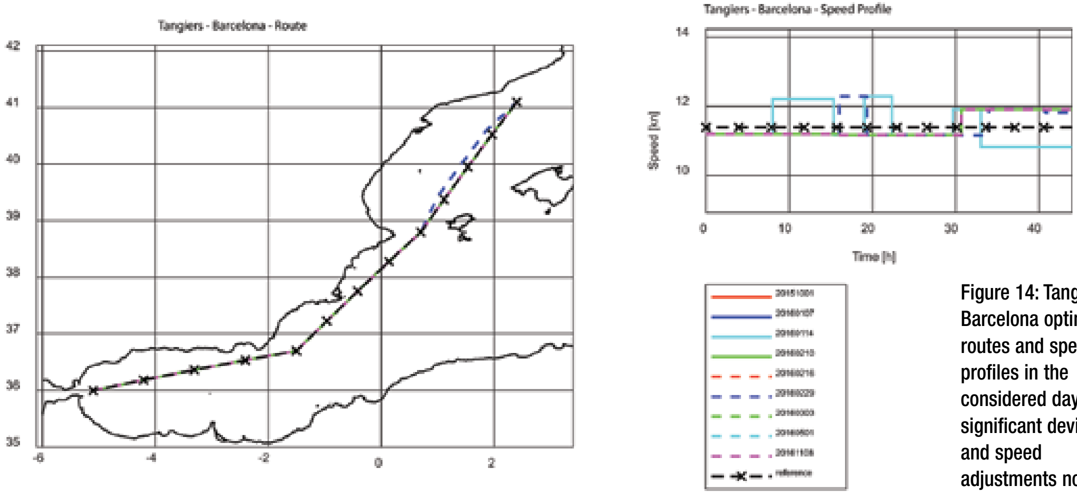

Figure 14: Tangiers-Barcelona optimal routes and speed profiles in the considered days: no significant deviations and speed adjustments noticed.

by means of a ship simulation model. The model computes the ship hydrodynamic resistance and the propeller and engine working points in relation to the weather conditions encountered, in order to estimate the engine fuel mass flow rate. In addition, it takes into account several indexes related to seakeeping abilities, in order to ensure safety and comfort of the voyage. In particular, slamming, deck wetness and high bow acceleration probabilities, as well as motion sickness incidence and lateral forces in the crew accommodations are constrained not to exceed threshold values. A solving algorithm has been devised and implemented by the authors in C++ language to solve the proposed task. The presented methodology has been numerically tested in a number of simulated scenarios for a merchant ship application, considering four typical commercial routes in the Mediterranean Sea. Computations have been carried out on nine different days, for which respective weather forecasting maps have been made available. In the considered voyages, the routing solutions presented significant variations in terms of trajectory and speed profiles depending on the conditions encountered: the optimal strategy to tackle the same voyage is significantly variable depending on the date of departure. The optimized voyages have been compared to the corresponding minimum distance, constant speed solutions at the same ETA, in order to appreciate the potential benefit of the presented solution: an estimated average fuel savings up to 7% has been computed. In addition, an average reduction of the IMO EEOI index up to 0.5 $\frac{g}{t \cdot mile}$ has been detected. The main drawback is due to deficiency in added resistance calibration, which however does not affect the validity of the model for purposes of comparison. Moreover, the simulation results are to be intended for demonstration purposes: more precise methods and experimental calibration should be mandatory in real applications.

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