Multi-objective Route Optimization for Onboard Decision Support System

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ABSTRACT: An onboard decision support system for the route selection is being developed. The intrinsic multi-objective nature of the problem is kept by adopting a widely tested and robust genetic algorithm allowing the optimization of conflicting objective such as the expected time of arrival (ETA), the fuel oil consumption (FOC) and the safety, resulting in a set of routes approximating the optimum in the Pareto meaning. The complete modelling of the ship responses in waves and engine performances for different sea-states, ship speeds and headings will also be described. Finally a test case will allow to assess the potentialities and lacks of the tool and to discuss about the further improvements of the system.

1 INTRODUCTION

One of the most crucial aspects in the ship management is the correct choice of the route. Once a ship has been built, consumptions, emissions and operability level do not only depend on the over all quality of the vessel. How it is managed in terms of cargo distribution and route selection can strongly affect the safety and the efficiency of the journey (IMO, 2009). A large amount of information regarding land distribution, dangerous or restricted areas and weather forecast in the operating area, ship's behavior in sub-ideal environment conditions in terms of sea-keeping responses and propulsion system have to be collected and jointly analyzed. Traditionally all this burden was entrusted to the masters' experience (Motte, 1985) cause to the impossibility to perform reliable weather forecast and to solve complicated optimization algorithms. Nowadays, besides acting as an emergency measure to keep or bring ships out of weather hazards (Mackie and Houghton, 1992), sophisticated routing software are increasingly recognized as an important contribution to safe, reliable and economic ship operation, that will become more and more an irreplaceable aid to the human experience for more awareness decisions.

Although commercial marine weather services already exist (Ocean Prediction Center website), they are still not considered completely reliable by the ships' masters, as revealed by a series of interview (Prpić-Oršić et al., 2015). The most common claim is that weather routing software would push the vessel into too heavy storms, compromising the safety. This might be due to a too strong emphasis to the economical factor when (often) the optimization method is not intrinsically multi-objective, typically Dijkstra's algorithm (Cormen et al., 2001) is adopted (Chen, 2011) or to a poor modelling of the ship behaviour in real sea conditions, which neglects important factors (Guedes Soares, 1995; Orlandi & Bruzzone, 2012) or dangerous situations (IMO, 1995, Krata & Szłapczynska, 2012). Nevertheless there is room and need for a deeper investigation in this field in order to create more reliable software to be tailored on the requirements of the ship where they are equipped.

Since the accurate prediction of voyage duration is one of the main tasks in ship navigation (Guedes Soares et al., 1998), the first generation of weather routing methods were thought only to optimize time, as for instance James (1957), Zoppoli (1972), Spaans (1986). The more recent concerns on energy efficiency and reduction of emissions (IMO, 2009; Prpić-Oršić et al., 2015) and the increasingly competitiveness in maritime trades pressured researches into multi-objective optimization. The Dijkstra's algorithm was successfully applied in the Indian Sea (Padhy et al., 2008), but it requires summarizing the objectives in a single goal function. More recently (Skoglund, 2012) the same algorithm has been slightly modified to account for multi-objectives, simply saving the Pareto-optimal results encountered during the iteration process. It showed noteworthy improvement in reducing the fuel consumption with respect to the original one. The increasing computational capabilities allowed to develop more sophisticated methods like the GIS grid based multi-objective methodology (Pacheco and Guedes Soares, 2007) and the more and more frequent employment of evolutionary programming and genetic algorithms: Hinnenthal & Saetra (2005), Szłapczynska & Smierzchalski (2007), Marie and Courteille (2009) and Maki et al. (2011). The importance of accounting for uncertainties for a conscious evaluation of the hazards is stressed in Papatzanakis et al. (2012).

An advanced onboard decision support system for the selection of the preferable route is being prepared. The guideline that drives the development is a strong attention to the needs of the master, in order to be able to provide, together with the indication of the routes that better fits the requirements, all the necessary information for an aware final decision. The first vital requirement is a reliable and detailed modelling of the ship behaviour in seaways. Both the motions induced by rough weather and the combined effect of waves and wind in the propulsion performances are considered. To deal with all the complex interacting sub-systems of the weather routing optimization, a class will be dedicated to each component. To design the code with this framework since the beginning is fundamental since it will allow separately treating each problem (such as sea-keeping, propulsion system, weather, etc.), to easily replace methods and algorithms if needed and to tailor the code to the specific requirements in the real implementation.

The main objective of this paper is to describe the detailed assessment of the sea-keeping responses and the propulsion system performances for many conditions of sea-states, ship speeds and headings. Section 2 is dedicated to this issue. In section 3 a brief description of the code, which adopt a multi-objective optimization algorithm for the search of the Pareto-optimal solutions is given. Finally an example will show the results of a run of the code in a specific case.

2 SHIP PERFORMANCE

When the optimal routes have to be identified, first of all it is essential to be able to describe all the significant aspects of the ship in a seaway, which allows to compute the objectives. Under adverse weather conditions, the ship behaviour differs significantly from the one in still water with increased periodic motions (mainly heave, pitch and roll) and a component of added resistance due to waves, wind and, possibly, currents and other factors. These aspects, besides compromising the safety, comfort and work ability on board, due to slamming, green water, vertical and lateral accelerations and other dangerous effects, have a great influence on the propulsive system with an increased request of power in sub-optimal regimes, eventually being too demanding and out of the specific load diagram.

Since waves are commonly recognized as the major cause of degraded ship performances, only the sea-state has been considered so far, but the influence of other not negligible factors such as wind and currents will be taken into account in the future.

Ship modelling consists in the assessment of the sea-keeping responses and the propulsion performances in every possible weather condition (sea-state) and speed of advance. There are two ways to achieve this requirement: either to consider the specific sea-states described by means of the actual wave spectra (possibly directional) and apply them to the response amplitude operators (RAOs), or to compute off-line the ship responses for a set of more or less accurately pre-defined sea-states with a standard spectrum taken as a model for any encountered wave condition. The latter is widely adopted method cause it allows to describe the sea-states through few integral parameters simplifying the calculation and reducing the computational time. However it must be considered that different spectral shapes may have an effect on the short-term wave-induced ship responses, especially in case of multi-modal spectra (Guedes Soares, 1990; Orlandi and Bruzzone 2012). As a first approach, the first method has been chosen, but the good performances of the code in terms of computational time (see section 4) encourage to study more sophisticated ship models. In order to have a more reliable description of the ship performances they have been computed for many different sea-states (H_S from 0m to 15m with a step of 1m and T_P from 0s to 20s with a step of 2s), headings (from 0° to 180° with a step of 30°) and ship speed (from 0kn to 20kn with a step of 1kn) and saved in tables which are imported when an object of the “Ship” class is instantiated.

The hydrodynamic calculations are carried out off-line with a computer code based on the strip theory (Salvesen et al., 1979), which provides the transfer functions of the motions and the added resistance.

2.1 *Sea-keeping responses*

Starting from the RAOs and the given wave spectrum, being the real or a standard one in a parametric form, several sea-keeping performances can be computed and their relevance depends on the type of ship and the mission of the trip many standards have been proposed in the literature (Nordforsk, 1987; Dubrovski, 2000). For a containership, important factors may be the structural load due to bottom or flare slamming or damage to the cargo due for instance to green water or lateral accelerations; the operability of a passenger ship, instead, will be more influenced by comfort criteria governed by the vertical acceleration such as the motion sickness incidence (MSI); in the case offshore supply vessels, navy vessels or any other ship that must guarantee the possibility to work on the deck, attention has to be paid on the motion induced interruptions (MII).

The code allows to adapt the optimization to the required strategy and to define appropriate limits for each effect. A risk coefficient is then computed, similarly to the concept adopted to define the seakeeping operability limit (see Nordforsk, 1987, fig. 3.3), through the following equation.

$$RISK_{coeff} = \left[\begin{array}{l} \max\left(\dfrac{Max\_Seakeeping\_eff_i}{Limit_i}\right) + \\ \max\left(\dfrac{Mean\_Seakeeping\_eff_i}{Limit_i}\right) \end{array} \right] \Big/ 2 \qquad (1)$$

The ratio aims to normalize all the seakeeping effects in a value in the range [0,1] depending on the distance from the respective limit, such as 1 correspond to the most extreme conditions that the ship can stand. All the effects are however stored and are available to the user in the set of optimal routes.

To run the test case (see section 4) three effects have been considered: the slamming probability, the green water and the vertical acceleration on the bridge.

A slamming event occurs when the keel emerges from the water, meaning that the relative motion is greater than the draft, and, later on, impacts on it with a speed higher than the critical value calculated as in equation 2, thus it implies the knowledge of the relative motions and velocity at bow:

$$V_{CR} = 0.093\sqrt{gL} \qquad (2)$$

The probability of keel emergency is calculated assuming the Rayleigh distribution of the peaks as:

$$P_{ke} = \exp\left(-\frac{D_{ke}^2}{2C_S^2 D_{r\zeta}}\right) \qquad (3)$$

where D_{ke} is the actual keel draft, which should take into account the trim, the sinkage and the ship's own wave and C_S is a coefficient to include the swell-up effect, here neglected. $D_{r\zeta}$ is the variance of the relative motion on the bow.

The probability to impact with a speed higher than the critical value is given by:

$$P_{\dot{r\zeta}_{CR}} = \exp\left(-\frac{V_{CR}^2}{2C_S^2 D_{\dot{r\zeta}}}\right) \qquad (4)$$

where the variance of the relative velocity on the bow is used.

From the previous considerations and assuming in first approximation the relative motion and velocity to be independent, the following equation yields:

$$P_{sl} = P_{ke} \cdot P_{\dot{r\zeta}_{CR}} = \exp\left(-\frac{D_{ke}^2}{2C_S^2 D_{r\zeta}} - \frac{\dot{r\zeta}_{CR}^2}{2C_S^2 D_{\dot{r\zeta}}}\right) \qquad (5)$$

For the green water effect, the freeboard exceedance is a necessary, but not sufficient condition. If the speed is not too low, in fact, most of the time the exceedance of the freeboard does not imply a green water event. Nevertheless for this study the probability of deck submergence is considered to be a good indication and it is computed with the equation:

$$P_{ke} = \exp\left(-\frac{F_e^2}{2C_S^2 D_{r\zeta}}\right) \qquad (6)$$

where F_e is the effective freeboard.

The criteria on the vertical acceleration, being a varying quantity, are given on the root mean square (rms) of the variance of the vertical acceleration on the bridge:

$$V\_acc_{rms} = \sqrt{D_{\ddot{r\zeta}}} \qquad (7)$$

2.2 *Propulsion system*

The calculation of the total resistance in irregular waves for each sea-state derives from a time-domain method proposed by Prpić-Oršić and Faltinsen (2012) where the instantaneous ship speed is calculated according to the method of Journee (1976) and Journee & Meijers (1980) by taking into account propeller in-and-out-of-water effect on ship propulsion and the effect of mass inertia. The still water resistance is calculated according to Holtrop & Mannen method (Holtrop & Mannen 1982, Holtrop 1984), an approximate procedure, which is widely used at the initial design stage of a ship. The method is based on regression analysis of random model experiments and full-scale data, available at the Netherlands Model Basin. The added resistance in waves is computed according to direct pressure integration procedure developed by Faltinsen et al. (1980).

For the main engine a two-stroke electronically controlled low speed marine engine with main particular listed in table 1 is used.

Table 1. Characteristics of the main engine

Engine model	MAN B&W 9S50ME-C8-TII
MCR	14940kW at 127 rpm
SCR	12707kW at 120 rpm
Fuel	Heavy fuel oil

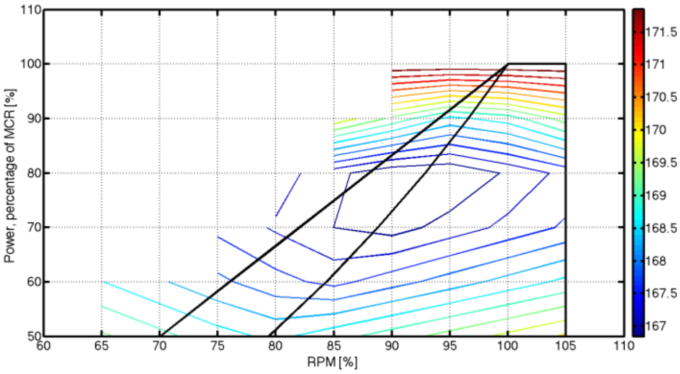

Figure 1. Main engine load diagram and SFOC contours.

The load diagram and the specific fuel oil consumption (SFOC) at an arbitrary load have been computer following the recommendation given by the constructor in the project guide (MAN B&W, 2010) and are shown in figure 1.

A B-series propeller is assumed and the open water propeller characteristics are obtained with the method of Oosterveld and van Oossanen (1975). The required brake power and the respective number of revolutions for all the considered conditions (in term of H_S, T_P, heading and ship speed) are then computed considering the thrust and the wake fractions computed with Holtrop method (1984).

From a simple comparison of the demand and the engine output, it is easy to obtain the fuel consumption per nautical mile for each condition, that is then used to compute the consumption for each track and, finally for the whole route.

3 SOFTWARE DESCRIPTION

Due to the intrinsic nature of the problem, the best route does not exist. Instead a compromise among conflicting objectives has always to be found and it usually depends on the type of ship and the decisions of the captain. In this perspective, the multi-objective optimization is aimed to produce a set of favourable route variants making the user aware of their values and lacks enabling a conscious decision-making process for the final ranking and selection. This concept is the base of the Pareto theory. A solution is Pareto-optimal if an improvement of one objective result in the impairment of another one. The Pareto frontier is the border between the feasible and unfeasible solutions and contains the closest routes to the ideal optimal (and in the general case unfeasible) one. Among them the best possible compromise to satisfy the request can be found.

3.1 *Code*

A C++ code that integrates the multi-objective optimization performed by a robust genetic algorithm SPEA2 (Strength Pareto Evolutionary Algorithm 2) proposed by Zitzler et al. (2002), has been developed. It takes care of the description of the sailing area, the weather condition as well as the modelling of the ship behaviour in the seaways, in terms of seakeeping responses and propulsive performances, and, ultimately, of the optimization of the route. The code consists in six classes: “Ship”, “Journey”, “Route”, “Domain”, “Land” and “Weather”; and five subclasses: “GeoPoint”, “Time”, “Seakeeping”, “Engine” and “Environment”. The architecture was designed to be flexible to future upgrades or modifications and to be completely controlled through simple input files.

3.2 *Genetic operators*

The initial population is made of random routes that are computed respecting the constrains. The ship performance is computed for many short tracks (30 miles in the case study in section 4) along the route, in order to ensure the weather condition to be stationary for each track.

The variation to produce the new generations is performed through three genetic operators: crossover, mutation and migration.

In the crossover two routes (parents) are randomly chosen from the selected set, as well as one of the waypoints (k^{th} waypoint). All the parameters (that is grid-point indices and ship speed) up to the k^{th} waypoint are copied from the first to the new route (offspring), while from the $(k+1)^{th}$ to the nWP^{th} are copied from the second parent.

In the mutation one individual is randomly chosen from the selected set as well as one of the waypoints, then the parameters relative to the detected waypoint are randomly varied ensuring the respect of the previously defined limitations. The mutation operator has usually a very low probability; nevertheless in this case it revealed a great capability of refining the routes in the proximity of the Pareto frontier, especially in an advanced stage of the optimization.

The migration simply consists in the generation of a new random route. This operator is often neglected in the genetic algorithms and can here be excluded.

3.3 *Objectives*

Although with a different extent in consideration of the ship, any navigation requires to reach the destination in a pre-determined or as short as possible time, in safe conditions and, especially when a weather routing system is adopted, to save fuel that likely also imply lower emissions. For this reason the classical objective in route optimization are the fuel oil consumption (FOC), the estimated time of arrival (ETA) and the safety (SAFETY).

Instead of using the actual values of the objectives, the following objective functions were introduced for the last two targets:

$$FOC_{obj} = \left(1 - FOC_{\min} / FOC_{journey}\right)^2 \tag{8a}$$

$$ETA_{obj} = \left(1 - ETA_{\min} / ETA_{journey}\right)^2 \tag{8b}$$

$$SAFETY_{obj} = k \cdot \left(RISK_{coeff}\right)^2 \tag{8c}$$

$$k = \left(1 - ETA_{\min} / ETA_{journey}\right) \tag{8d}$$

where FOC_{min} is the minimum fuel oil consumption achieved in calm waters at the most efficient optimal engine load, ETA_{min} is the minimum possible duration of the journey if the shortest route is sailed at the design speed and k, given in equation 8d is a factor adopted to discard routes which are safe but practically useless for the optimization cause of the excessive duration.

These functions help to accelerate the propagation of the initial routes towards the optimal solutions, a skill that is especially important in case of rough sea or land avoidance when the respect of the constrain might slow down the creation and recombination of feasible individuals.

Furthermore the objective function relative to the safety reduces the impact of meaningless routes, which minimize the slamming probability, but imposing weird courses.

3.4 *Selection*

Once the stopping criterion is achieved, the post-processing starts. It consists in writing a series of files to allow the quick visualization of all the route parameters (time of departure, expected time of arrival, sea-states that the ship will encounter, sea-keeping responses, etc.) and the file for the plots. In this phase a ranking method is also applied. In this case the distance of each route from the utopia point in the objective space determines the rank.

4 EXAMPLE

A test case was run considering the S175 containership as a reference. The simulation is performed for a route between the port of Sines in Portugal and the entrance of the entrance of the Gulf of Saint Lawrence. The departure time is set at 9.00pm on January 31st, 2001 in order to include in the travel period the evolution of a storm occurred between February 4th and 5th, identified analysing the HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) hindcast database (Pilar et al., 2008). This database contains 44 years of wind and wave data in the North Atlantic in a grid of 2°x2° and every three hours.

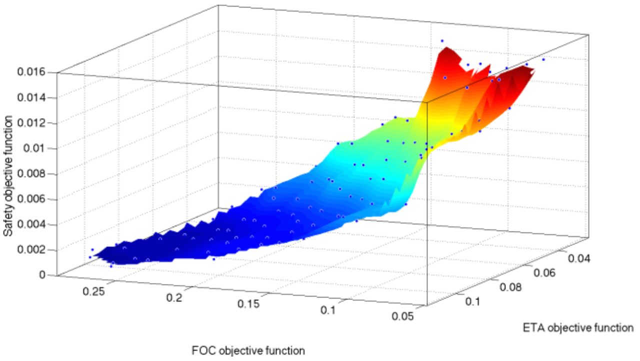

Figure 2. Resulting Pareto frontier after 1000 generations.

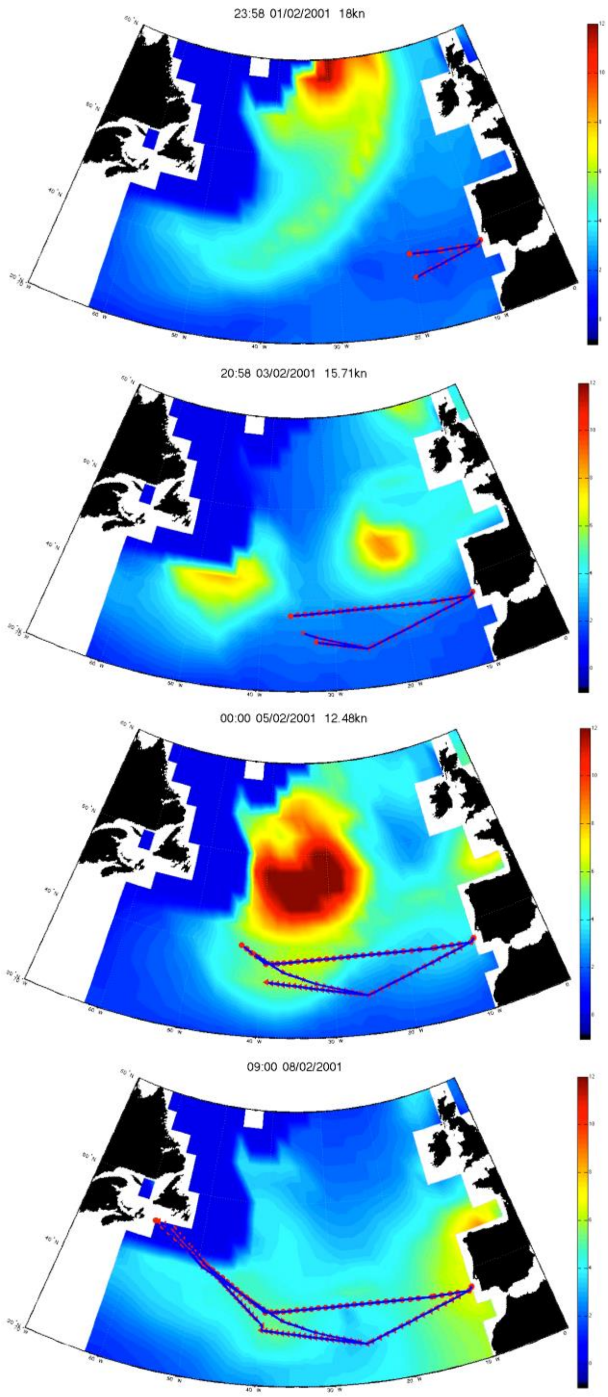

Figure 3. Paths of three of the Pareto frontier routes: smallest FOC (red stars), shortest time (red dots) and safest (red triangles).

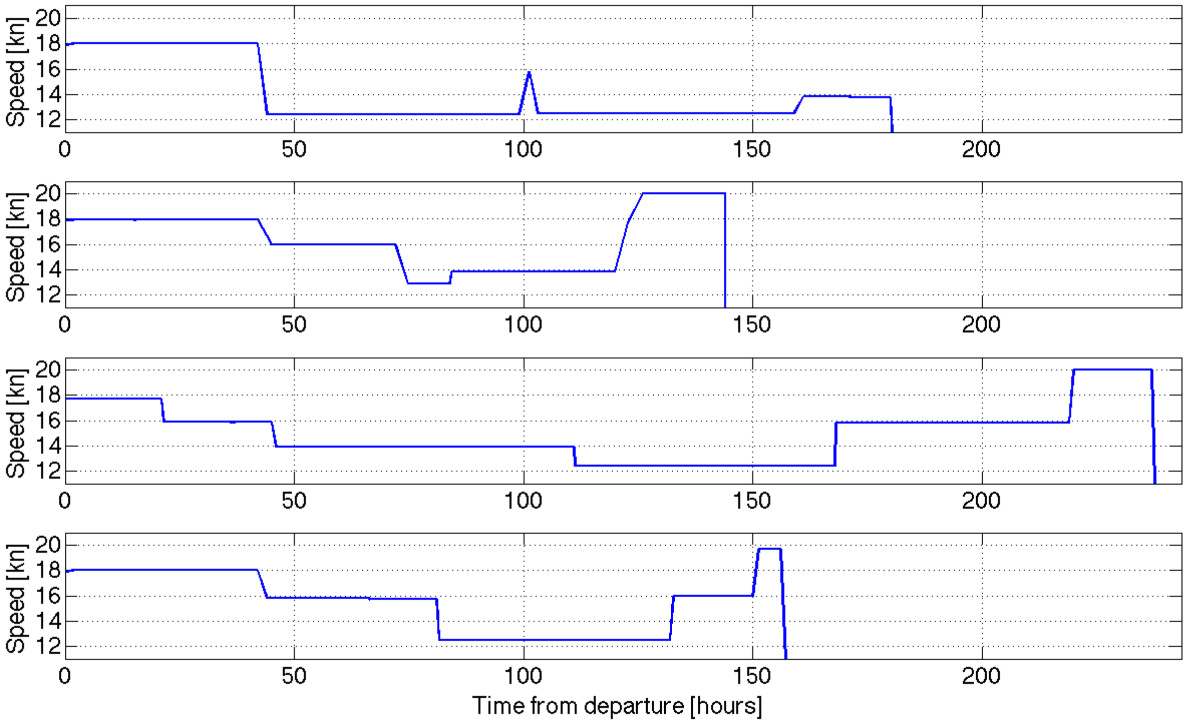

Figure 4. Speed profile of the routes depicted in figure 3: smallest FOC (first), shortest time (second) and safest (third), plus the first rank given in the selection process (fourth).

Relatively to the genetic algorithm, the dimension of the first generation is of 100 individuals, while in each generation the mating pool is of 15 individuals and 15 offspring are generated. The number of generation is 1000.

The run took around 15 minutes. Most of them are however dedicated to the initialization, in particular the reading of the bathymetry is quite demanding due to the large amount of data, but the computation of the first random generation is the most time-consuming routine, requiring almost 10 minutes cause to the presence of the heavy storm that imposes many tries to respect the constrains (runs in milder weather conditions, not shown here, are much faster).

In figure 2 the obtained Pareto frontier shows a good distribution of the results. In figure 3 the paths of the best routes among the selected ones in terms of minimum fuel oil consumption, shortest duration of the trip and smallest risk are shown, while the speed profiles are plotted in figure 4. A comparison of the 2 figures gives a clear view of the effect of the optimization of the different objectives. The fastest route takes 144 hours, it stays more north to reduce the distance and keeps an higher average speed 16.4kn, remaining out of the storm but close to the borders where waves can be quite heavy (the maximum encountered wave height is 5.5m). To save fuel the speed of advance is cut and maintained around 12.5kn for great part of the journey. Waves are still considerably high, but the fuel is reduced by 40% respect on the previous route but taking one and a half day more to reach the destination. The safest modulates the speed in order to reduce the ship motions but also circumnavigates the storm at a greater distance to avoid the tail.

The first rank route seems a good compromise. It takes 14 hours more than the fastest one, using 30% less fuel. It must be noted that even in this case rough weather condition are encountered, but always respecting the sea-keeping constrains. It is due to the presence of an heavy storm in the period of the passage. If more safety or comfort are required, once can set stricter constrains before the running or just chose another route in the rank. In the future a more flexible ranking method will be adopted.

5 CONCLUSIONS

The progresses in the development of an onboard decision support system have been described. Special attention was given to the modeling of the ship performance in terms of sea-keeping responses and propulsion system. Other important, but more critical sea-keeping effects must be included, in particular the roll motion in order to limit the occurrences of heavy beam sea. The optimization algorithm confirmed to be appropriate to deal with this problem, with a smooth distribution of the results in the Pareto frontier. The ranking method needs to be studied more accurately in order to be more flexible to the request of the decision-maker and to allow a re-selection if the first choice is not considered adequate.

The analyses of the computational time, deeper than the one discussed in section 4, indicates that the most critical part of the optimization is the construction of the first generation, while the calculation of the ship behavior is quite fast, in spite of the quite high resolution of the computation point along each route. This encourages to attempt an even more accurate modeling of the ship and the weather including comparison of the wave actual wave spectra and the RAOs in the code. This would allow to identify the possible dangerous situations due to the actual frequency distribution of the wave energy, especially in the cases of multi-modal spectra, and more in general to be more precise in the computation of the ship performances, thus in the optimization of the route.

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