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Multicriteria Optimisation in Weather Routing

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ABSTRACT: The paper presents a new weather routing solution fully supporting multicriteria optimisation process of route finding. The solution incorporates two multicriteria optimisation methods, namely multicriteria evolutionary algorithm (SPEA) and multicriteria ranking method (Fuzzy TOPSIS). The paper focuses on presenting the proposed multicriteria evolutionary weather routing algorithm (MEWRA). Furthermore, it includes some experiment results together with a short description of the assumed ship model.

1 INTRODUCTION

In weather routing one is about to find the most suitable ocean's route for a vessel, taking into account changeable weather conditions and navigational constraints. One of the first approaches to the problem was a minimum time route planning based on a weather forecast called an isochrone method. The method was based on geometrically determined and recursively defined time fronts, so called isochrones. Originally proposed by R.W. James (James 1957), isochrone method was in wide use through decades. In late seventies based on the original isochrone method the first computer-aided weather routing tools were developed. However, along with computer implementation some problems arose, i.e. with so called "isochrone loops". Numerous improvements to the method were proposed since early eighties, with (Hagiwara 1989, Spaans 1986, Wiśniewski 1991) among others. Since then several different approaches to the optimisation problem was in use, with dynamic programming (Bijlsma 2004) or genetic and evolutionary algorithms (Wiśniewski et al. 2005) among others.

It is a prime goal of weather routing tools to find a route between given origin and destination ports that is the safest, the shortest and the least expensive possible. Unfortunately, these criteria are often conflicting, especially the ones expressing safety and economics. A single route, time-optimal, cost-optimal and safety-optimal at one time, hardly exists. Thus, an acceptable trade-off between the criteria is sought instead. A mathematical approach towards solving such a problem involves multicriteria (sometimes referred to as multiobjective) optimisation. Because the currently available solutions hardly apply such an approach, thus it is well-founded to propose a new multicriteria weather routing method, presented previously in (Szłapczyńska 2007).

This paper focuses on presenting a solution, implementing the multicriteria weather routing method, together with some examples of usage. The remainder of the paper is organized as follows: section 2 introduces definition of the optimisation. Section 3 provides description of a model of the researched ship. Further details on weather modelling, such as weather data sources, formats, etc., can be found in (Szłapczyńska, in press). Section 4 describes the MEWRA solution. In section 5 some examples of usage of the solution are provided. Finally, section 6 summarizes the material presented.

2 DEFINITION OF THE OPTIMISATION PROBLEM IN WEATHER ROUTING

The proposed multicriteria set of goal functions in the weather routing optimisation process, revised comparing to (Szłapczyńska 2007), is presented by equations 1 – 3:

$$f_{passage\_time}(t_r) = t_r \to \min \tag{1}$$

$$f_{fuel\_consumption}(q_{fc}) = q_{fc} \to \min \tag{2}$$

$$f_{voyage\_risks}(i_{risk}) = (i_{risk}) \to \min \tag{3}$$

$$i_{risk} = \frac{\sum_k (1 - i_{j\ safety})^2}{k} \tag{4}$$

where:

t_r – [h] passage time for given route and ship model,

q_{fc} – [g] total fuel consumption for given route and ship model,

i_{risk} – [/] risk coefficient for given route and the ship model,

k – [/] number of route's segments with $i_{j\ safety} < 1$,

$i_{j\ safety}$ – [/] fractional safety coefficient for (j-1)-th and j-th waypoints and given ship model; values of the coefficient ranges [0; 1], where 1 depicts completely safe section of route and 0 – unacceptably dangerous section.

The assumed set of constraints in the weather routing optimisation problem includes:

- landmasses (land, islands) on given route,
- predefined minimum acceptable level of fractional safety coefficient $i_{j\ safety}$ for given route,
- floating ice bergs expected on given route during assumed ship's passage,
- predefined maximum acceptable ice concentration on given route.

The next section provides a description of a ship model and the way of modelling the goal functions (1) – (3).

3 MODEL OF THE RESEARCHED SHIP

The researched ship model (Oleksiewicz, in press) is based on a B-470 bulk carrier. Its basic parameters are shown in Table 1. The model ship is equipped with a hybrid propulsion including Sultzer RTA 48T engine and a palisade of six textile sails (Figure 1). Each sail has 522m^2 sail surface area. The ship is equipped with a semi-adjustable B-Wageningen screw propeller.

Table 1. Basic parameters of the model

Parameter name	Value
Length	172 m
Width	22.8 m
Draught	9.5 m
Height	14.3 m
Service speed	15 kn
Displacement	30 288 t
Block coefficient (C_b)	0.786

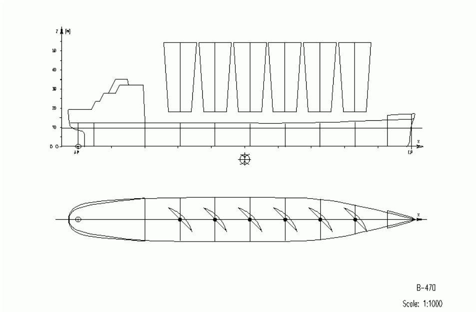

Figure 1. Sail model

3.1 *Modelling of passage time*

Ship speed forecast is a key element in passage time modelling. Speed characteristic of the model ship is based on algorithms presented in (Oleksiewicz, in press). Speed prognosis for the model ship is based on wind speed and wind angle forecasts. Then, speed reduction factor due to wave impact is applied to the prognosis. Detailed description on the model ship's speed modelling is given by (Szłapczyńska et al. 2007).

It is assumed that the ship model moves between two consecutive waypoints with constant velocity and propulsion type ("only motor engine" or "hybrid propulsion"). Thus the passage time for a route is given by:

$$t_r = \sum_{j=2..n} \frac{d_j}{v_j} \tag{5}$$

where:

t_r – [h] passage time for a route and given ship model,

n – [/] number of routes' waypoints,

v_j – [kn] speed of the ship model between (j–1)-th and j-th waypoints,

d_j – [Nm] distance between (j–1)-th and j-th waypoints.

3.2 *Modelling of fuel consumption*

Forecasted fuel consumption per hour for the ship model is calculated by:

$$FCPH = P * BSFC \tag{6}$$

where:

FCPH- [g/h] fuel consumption per hour,

P - [kW] engine power,

BSFC - [g/kWh] break specific fuel consumption.

Based on the model's engine (Sultzer RTA 48T) catalogue data the *BSFC* value is assumed to be

171 g/kWh. Values of engine power P belong to a discrete set, depending of current telegraph command, as presented in (Szłapczyńska et al. 2007).

Another aspect of fuel consumption is connected to starting the engine. Additional portion of fuel is required to every start of the engine, which might become significant when it is possible to turn the engine on and off during the voyage. Thus, the total fuel consumption of the model ship for a route is given by:

$$q_{fc} = \sum_{j=2..n}(t_j \; FCPH_j) + m \; FCPS \tag{7}$$

where:

q_{fc} – [g] total fuel consumption for given route and ship model,

t_j – [h] passage time between (j-1)-th and j-th waypoints,

$FCPH_j$ – [g/h] $FCPH$ valid between (j-1)-th and j-th waypoints,

m – [/] number of engine starts,

$FCPS$ – [g] fuel consumption per start.

3.3 *Modelling of the voyage risk*

It is assumed that the wind causes the prime safety threat during the voyage. Thus, the definition of the fractional safety coefficient $i_{j\ safety}$, utilized by (4) to calculate the risk of a voyage i_{risk}, is given by:

$$i_{j\ safety} = \frac{v_{w\ \max} - v_{w\ j}}{v_{w\ \max}} \tag{8}$$

$$v_{w\ \max} = v_{\max\ def} - \lambda \Delta v_{\max\ def} \tag{9}$$

where:

$v_{w\ max}$ – [kn] maximum allowable wind speed,

$v_{w\ j}$ – [kn] wind speed between (j-1)-th and j-th waypoints,

$v_{max\ def}$ – [kn] threshold wind speed, assumed as 35 kn,

λ – [/] shape coefficient (Figure 2), dependent of the ship propulsion type and wind heading angle,

$\Delta v_{max\ def}$ – [kn] possible threshold wind speed margin, assumed as 10 kn.

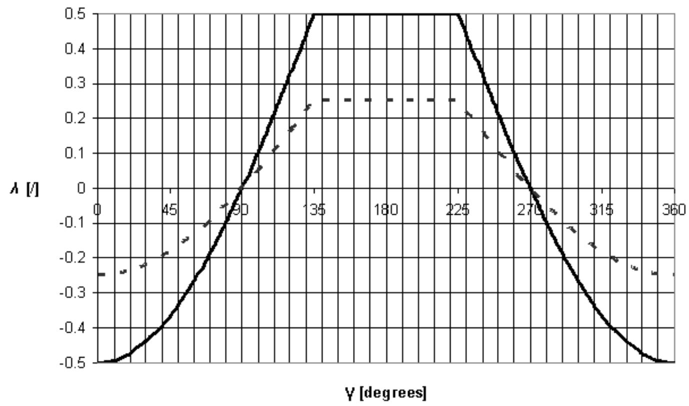

Figure 2. λ shape coefficient (solid line - hybrid propulsion; dotted line - only motor engine) as a function of wind heading angle γ

The main purpose of the λ shape coefficient is to differentiate the maximum allowable wind speed $v_{w\ max}$ dependent of the wind heading angle. The coefficient discriminates (by greater λ values) mainly the following winds.

The $i_{j\ safety} = 0$ depicts a totally dangerous route sector (with $v_{w\ j} \geq v_{w\ max}$). In contrary, $i_{j\ safety} = 1$ depicts a completely safe route sector (with $v_{w\ j} = 0$).

4 WEATHER ROUTING WITH MULTICRITERIA OPTIMISATION

The proposed weather routing algorithm is based on the optimisation criteria set (1) - (3), defined in section 2. The solution utilizes two basic multicriteria mechanisms, namely multicriteria evolutionary algorithm – Strength Pareto Evolutionary Algorithm (SPEA) and multicriteria ranking method – Fuzzy TOPSIS.

4.1 *Multicriteria evolutionary weather routing algorithm (MEWRA)*

The SPEA framework in the proposed algorithm is responsible for iterative process of population development. The result of SPEA is a Pareto-optimal set of solutions. The multicriteria ranking method (Fuzzy TOPSIS) is responsible for sorting the resulting Pareto-optimal solutions according to the given preferences of the decision-maker. The preferences are represented by linguistic values with fuzzy weights assigned to the decision criteria. The main algorithm's flow is illustrated in Figure 3.

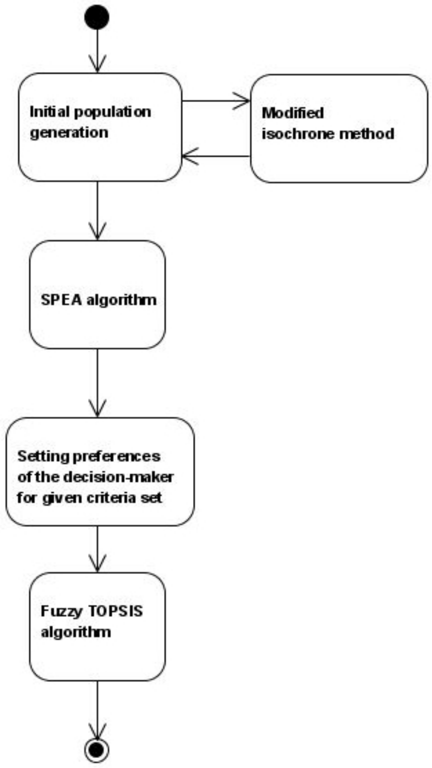

Figure 3. Multicriteria evolutionary weather routing algorithm

4.2 *Chromosome structure*

An individual in the evolutionary approach, also referred to as a solution, represents a route. The route includes an array of waypoints constituting ship's trajectory, where the first one is equal to the position of the origin port and the last one – to the destination port. A single entry of the waypoints array includes:

- geographical coordinates (longitude, latitude) of the waypoint,
- motor engine relative settings valid from the previous to the given waypoint, ranging [0;1],
- propulsion type (there are two different propulsion modes distinguished for the assumed ship model: "motor only" and "motor & sails"),
- time of reaching given waypoint,
- velocity of the ship, assumed constant on a sector between two waypoints, valid from the previous to the given waypoint,
- uncertainty index for given waypoint (value representing uncertainty of the waypoint's data).

Only the first three elements of the waypoint entry are in direct control of the evolutionary mechanisms: the coordinates, motor settings and propulsion type. All the other values can be calculated as functions of the former and are stored in the chromosome in order to improve on efficiency of the algorithm.

4.3 *Initial population*

The first step towards evolutionary computation is always building an initial population. In the considered weather routing case, a preliminary set of basic routes is generated at first. For given pair of origin and destination ports the set includes the following routes:

- an orthodrome,
- a loxodrome,
- a time-optimized isochrone route (Spaans 1986, Hagiwara 1989,Wiśniewski 1991), referenced further as IZO_REF_TIME,
- a route given by fuel-optimization applied to the time-optimized isochrone route, referenced further as IZO_REF_FUEL.

The isochrone routes (IZO_REF_TIME & IZO_REF_FUEL) are generated with time step 2h.

The initial population is generated by creating random mutations of the basic routes. Also pure basic routes are included in the initial population.

4.4 *Specialized operators*

There are several specialized "genetic" operators required by the evolutionary framework, each customized to the established chromosome structure. The set of specialized operators in the multicriteria evolutionary weather routing algorithm includes:

- one-point crossover,
- non-uniform mutation,
- route smoothing by means of average weighting.

4.5 *Final ranking of routes*

When SPEA completes its computations, the available result set includes the Pareto-optimal set of individuals (routes) and a corresponding Pareto front. Unfortunately (or fortunately, but from the other perspective) the Pareto-optimal set is numerous. Thus it would be inconvenient for the user (e.g. a captain) to browse manually through the complete set of resulting routes in search of the most suitable one.

Yet another problem might be encountered: how to decide which route is the best within given multicriteria optimisation environment? To solve this problem decision-maker's (e.g. captain's) preferences to the given criteria set should be defined. Hence a tool for sorting the Pareto-optimal set is provided – Fuzzy TOPSIS method. The method creates a ranking of routes based on the decision-maker's preferences expressed by linguistic values with triangular fuzzy values assigned (Table 2). The decision-maker picks one linguistic variable per criterion. The variable should describe the most accurately the significance of the criterion and its impact on the decision. The first route in the final ranking will be the most suitable one from the Pareto-optimal set, with reference to the previously defined preferences to the criteria set.

Table 2. Linguistic values and corresponding triangular fuzzy values, utilized to express decision-maker's preferences to the criteria set

Linguistic value	Triangular fuzzy value
very important	(0.7; 1.0; 1.0)
important	(0.5; 0.7; 1.0)
quite important	(0.2; 0.5; 0.8)
less important	(0.0; 0.3; 0.5)
unimportant	(0.0; 0.0; 0.0)

5 EXAMPLES OF USAGE

This section presents two experiment results with the proposed multicriteria evolutionary weather routing algorithm. The experiments' origin and destination ports as well as the departure dates vary to present performance of the algorithm for various weather conditions. In both cases output of the algorithm is compared with the routes found by the time-optimised and fuel-optimised isochrone method respectively. Output routes of the multicriteria evolutionary weather routing algorithm (depicted as MEWRA) were selected by means of linguistic values assigned to the criteria set as given in Table 3.

Table 3. Linguistic values assigned to the criteria set in the multicriteria evolutionary weather routing algorithm

Route description	Passage time	Fuel consumption	Voyage risk
MEWRA_TIME	very important	unimportant	unimportant
MEWRA_FUEL	unimportant	very important	unimportant
MEWRA-_COMPROMISE	important	less important	very important

5.1 *Lisbon – Miami, departure 2008-09-02 at 00:00*

The initial population generated for the Lisbon-Miami voyage is presented in Figure 4. The set of Pareto-optimal solutions (routes), obtained after 100 of generations during evolutionary optimisation, is then presented in Figure 5. The resulting MEWRA_TIME, MEWRA_FUEL and MEWRA_COMPROMISE routes are then presented by comparison to the isochrone routes in Figure 6-8 respectively. Basic performance parameters of the MEWRA and reference isochrone routes are collated in Table 4.

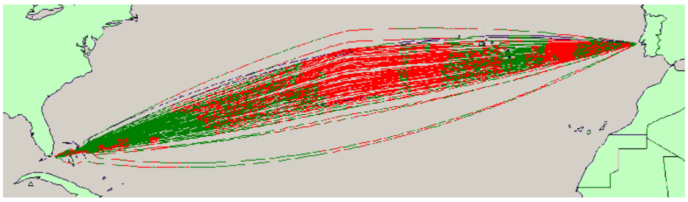

Figure 4. Initial population of routes for Lisbon-Miami voyage, departure 2008-09-02 00:00

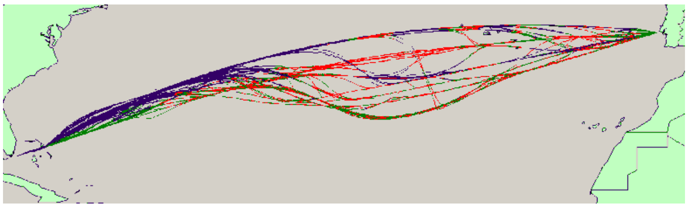

Figure 5. Set of Pareto-optimal routes for Lisbon-Miami voyage, departure 2008-09-02 00:00

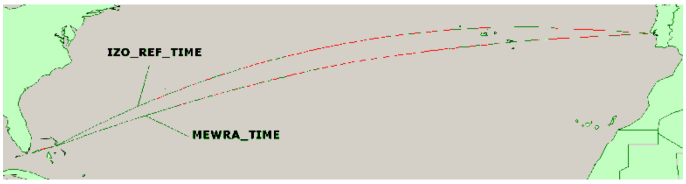

Figure 6. Output of the algorithm MEWRA_TIME compared to the time-optimal isochrone route for Lisbon-Miami voyage, departure 2008-09-02 00:00

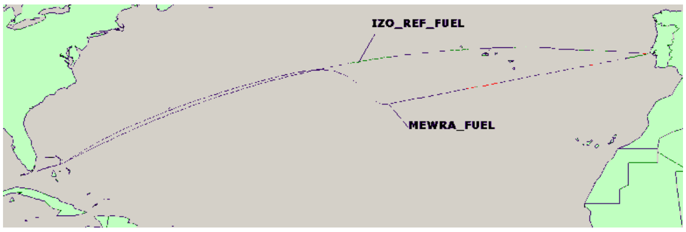

Figure 7. Output of the algorithm MEWRA_FUEL compared to the fuel-optimal isochrone route for Lisbon-Miami voyage, departure 2008-09-02 00:00

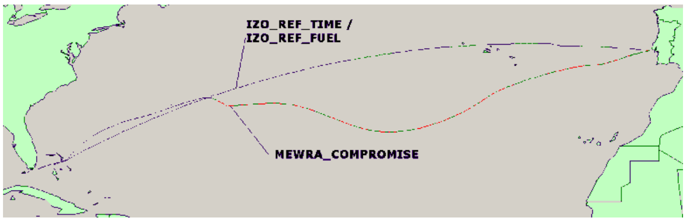

Figure 8. Output of the algorithm MEWRA_COMPROMISE compared to the time-optimal and fuel-optimal isochrone routes for Lisbon-Miami voyage, departure 2008-09-02 00:00

Table 4. Comparison of basic performance parameters of the reference isochrone routes and output of the algorithm (MEWRA routes) for Lisbon-Miami voyage, departure 2008-09-02 00:00

Route description	Passage time [h]	Fuel cons. [t]	Voyage risk [/]	Avg speed[kn]
IZO_REF_TIME	234.29	308.81	0.149	15.37
IZO_REF_FUEL	531.56	48.36	0.124	6.77
MEWRA_TIME	233.30	307.50	0.132	15.49
MEWRA_FUEL	373.54	8.45	0.094	10.24
MEWRA-_COMPROMISE	288.91	225.79	0.058	13.51

During the period of 2008-09-01 and 2008-09-15 the Tropical Weather Outlook of National Hurricane Centre reported activities of three tropical storms and cyclones in Atlantic region, namely Hanna, Ike and Josephine. However, the considered routes were threatened directly with Josephine only. The outlook of wind speed forecast (NOAA Wave Watch III) on 2008-09-10 is presented in Figure 9. The remnant low of Josephine continued moving to the west for the next several days.

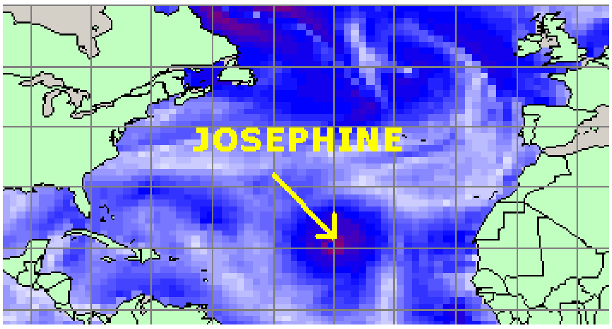

Figure 9. Wind speed forecast (NOAA Wave Watch III) on 2008-09-10 for the Northern Atlantic region with indicated position of tropical depression Josephine

As depicted by the Figure 5, all the Pareto-optimal routes bypass Josephine. The MEWRA_TIME route compared to the time-optimal isochrone route (IZO_REF_TIME) is shorter almost 1h, requires over 1.3t less fuel and is safer (lesser voyage risk factor) the same time. The similar tendencies can be found for the MEWRA_FUEL and IZO_REF_FUEL pair of routes. But this time passage time saving in almost 30%, fuel saving exceeds 80% and voyage risk is reduced by almost 25%. The MEWRA_FUEL route owes its supremacy the utilization of favourable winds with possibility to turn off the engine. Another aspect of the supremacy is that the IZO_REF_FUEL route is not a fully fuel-optimized one (it is a fuel-optimized time-optimal isochrone route). Due to that it is better to compare MEWRA_FUEL with IZO_REF_TIME. In such case fuel reduction exceeds 97% and voyage risk reduction is almost 37%, but for the cost of increasing passage time by almost 60%. On the other hand, the MEWRA_COMPROMISE route allows reduction of the risk factor by 60% (mostly due to bypassing the remnant of Josephine by means of “34 knot wind radius rule”) comparing with IZO_REF_TIME. The route allows over 26% fuel saving for cost of increasing passage time by less than 24%.

5.2 *Halifax – Plymouth, departure 2008-02-15 at 12:00*

The initial population generated for the Halifax – Plymouth voyage, is presented in Figure 10. The set of Pareto-optimal routes, obtained after 100 of generations, is then presented in Figure 11. The resulting MEWRA_TIME, MEWRA_FUEL and MEWRA_COMPROMISE routes are presented by Figures 12-14 respectively. Basic performance parameters of the MEWRA and reference isochrone routes are collated in Table 5.

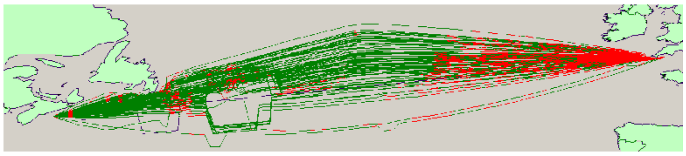

Figure 10. Initial population of routes for Halifax - Plymouth voyage, departure 2008-02-15 12:00

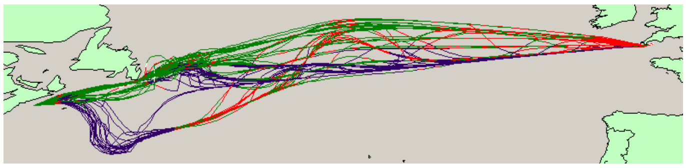

Figure 11. Set of Pareto-optimal for Halifax - Plymouth voyage, departure 2008-02-15 12:00

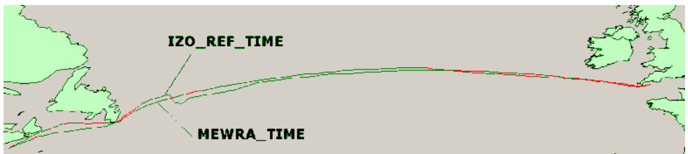

Figure 12. Output of the algorithm MEWRA_TIME compared to the time-optimal isochrone route for Halifax - Plymouth voyage, departure 2008-02-15 12:00

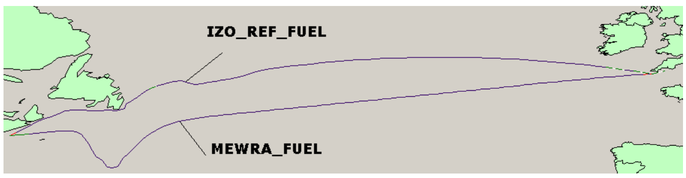

Figure 13. Output of the algorithm MEWRA_FUEL compared to the fuel-optimal isochrone route for Halifax - Plymouth voyage, departure 2008-02-15 12:00

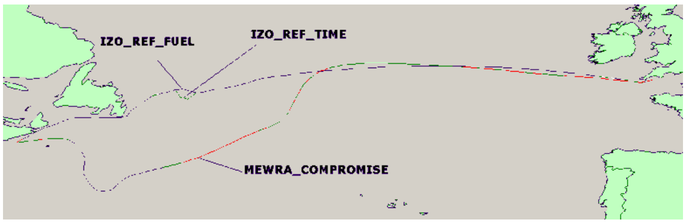

Figure 14. Output of the algorithm MEWRA_COMPROMISE compared to the time-optimal and fuel-optimal isochrone routes for Halifax - Plymouth voyage, departure 2008-02-15 12:00

Table 5. Comparison of basic performance parameters of the reference isochrone routes and output of the algorithm (MEWRA routes) for Halifax - Plymouth voyage, departure 2008-02-15 12:00

Route description	Passage time [h]	Fuel cons. [t]	Voyage risk [/]	Avg speed[kn]
IZO_REF_TIME	157.89	208.14	0.290	15.58
IZO_REF_FUEL	420.84	14.77	0.312	5.75
MEWRA_TIME	152.99	201.68	0.340	15.62
MEWRA_FUEL	259.66	1.23	0.245	10.25
MEWRA-_COMPROMISE	206.34	191.98	0.159	14.03

During the period of 2008-02-15 and 2008-02-28 neither tropical storms nor cyclones were reported by NHC. However, strong wind fields originating on US Atlantic coast, heading towards eastern coast of Greenland, were expected repeatedly during the period. A non-zero ice concentration was observed during the period at northern coast of New Funland. Also rare icebergs transported by Labrador Current were expected in the area.

The Pareto-optimal routes (Figure 11) avoid the strong wind fields as well as the ice threat zone. The MEWRA_TIME route compared with the IZO_REF_TIME is shorter by almost 5h, requires over 6t less fuel for a cost of slightly higher voyage risk (less than 18%). On the other hand the MEWRA_FUEL route compared to IZO_REF_FUEL is significantly shorter (over 38%), allows enormous reduction of fuel consumption by over 91% and also improves route's safety (voyage risk reduced by over 21%). Again, when compared to IZO_REF_TIME, the MEWRA_FUEL achieves almost 99.5% of fuel reduction and 15% voyage risk reduction, but for the cost of almost 65% longer passage. On the other hand, the MEWRA_COMPROMISE route allows further minimization of the risk factor, with 45% reduction of the factor (due to bypassing strong wind fields on the south from New Funland) comparing with IZO_REF_TIME. The route allows 7% fuel saving with passage time increased by less than 31%.

6 CONCLUSION AND FUTURE WORK

The proposed multicriteria evolutionary weather routing algorithm (MEWRA) was presented here in application to the hybrid propulsion ship model. With MEWRA it was possible to obtain significant reductions of passage time, fuel consumption and risk factor, however (time in most cases) not all at the same. Based on the results presented in the previous section, the following tendencies can be observed:

– MEWRA_TIME routes, when compared with the time-optimal isochrone routes (IZO_REF_TIME), slightly shorten passage time (0.5% & 3.1%) and reduce fuel consumption (0.5% & 3.1%), but in one out of two cases may increase voyage risk (here: by 18%). The similar percentage values of passage time and fuel consumption reduction depict that the fuel savings are caused by the shortened passage only. The average service speed on MEWRA_TIME is 3.5% - 4.1% greater than the original service speed.
– MEWRA_FUEL routes, when compared with the fuel-optimized time-optimal isochrone routes (IZO_REF_FUEL), significantly shorten passage time (30% & 38%), reduce fuel consumption (80% & 91%) and decrease voyage risk (21% & 25%). The surprisingly good MEWRA passage time performance is caused here by the fact that the IZO_REF_FUEL route is suboptimal. Fuel consumption reductions are caused by the possibility of turning the engine off during the voyage. The average speed on MEWRA_FUEL routes is 30% - 35% lesser from the original service speed.
– MEWRA_FUEL routes, when compared with the time-optimal isochrone routes (IZO_REF_TIME), even more significantly reduce fuel consumption (97% & 99.5%) and decrease voyage risk (15% & 37%). The lengthened passage time (60% & 65%) is the cost of the savings in this case. Such a good MEWRA fuel consumption performance is caused, again as in previous comparison, by the very nature of the hybrid propulsion model. Allowing, during the voyage, the possibility of turning the engine off and finding the best possible wind conditions, one (at least theoretically) is able to achieve 100% fuel reduction. The question is, whether it is acceptable to drastically lengthen the passage to achieve such fuel savings.
– MEWRA_COMPROMISE routes try to establish a practical trade-off between the basic routes' parameters. The routes, when compared with the time-optimal isochrone routes (IZO_REF_TIME), significantly reduce voyage risk (45% & 60%) due to bypassing the main encountered security threats. The routes also reduce

fuel consumption (7% & 26%), but lengthen the passage time (24% & 31%). Actions taken to increase routes' safety are the major factors inducing longer passage. The average speed of MEWRA_COMPROMISE is only 6.4 % - 10% lesser from the original service speed.

To conclude, MEWRA is a new weather routing solution and, as proved by the experiment results, competitive towards other single-objected methods, such as e.g. the isochrone method. The solution expands functionality of typical weather routing tools by introducing the trade-off routes (MEWRA_COMPROMISE), yet preserving the possibility to search for single-objected routes (MERWA_TIME & MEWRA_FUEL). In addition to that, it is possible to define another set of result routes by assigning simple linguistic values (such as "important", "less important" or "unimportant") to each of the optimisation criterion.

It is worth mentioning that MEWRA execution time in the both presented cases (Lisbon – Miami & Halifax - Plymouth) was shorter than 20 min. The execution times seem to be acceptable, taking into account the future plans to improve MEWRA towards dynamic route update mechanisms. Other plans include expanding MEWRA to support a custom ship model with traditional motor engine.

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