Weather routing,
multicriteria optimization

Joanna SZŁAPCZYŃSKA[1]

MULTICRITERIA WEATHER ROUTING: MOTOR DRIVEN VS HYBRID PROPULSION SHIP MODEL

Weather routing methods find the most suitable ocean's route for a vessel, taking into account changeable weather conditions and navigational constraints. In the multicriteria approach based on the evolutionary SPEA algorithm one is able to consider a few constrained criteria simultaneously. Previously the author has presented the SPEA-based weather routing solution for a ship with hybrid propulsion (motor and sails propulsions). In this paper the same approach is applied for a motor-only driven ship. The paper underlines the most significant differences in the application for hybrid and motor-only propulsions.

WIELOKRYTERIALNA NAWIGACJA METEOROLOGICZNA: PORÓWNANIE MODELI STATKU Z NAPĘDEM MECHANICZNYM ORAZ HYBRYDOWYM

Nawigacja meteorologiczna polega na poszukiwaniu oceanicznej trasy przejścia statku z uwzględnieniem ograniczeń nawigacyjnych oraz zmieniających się warunków meteorologicznych. Problem optymalizacji trasy w podejściu wielokryterialnym, bazującym na algorytmie ewolucyjnym SPEA, definiowany jest za pomocą zbioru równocześnie rozpatrywanych kryteriów. We wcześniejszych pracach autorka proponowała już podobne rozwiązanie dla statku z napędem hybrydowym (wyposażonym w silnik oraz dodatkowy pędnik wiatrowy – żagle). W niniejszym artykule opisywane jest analogiczne rozwiązanie dedykowane dla statku z napędem mechanicznym. Podkreślono tu również najważniejsze różnice pomiędzy aplikacją rozwiązania dla statku z napędem hybrydowym oraz mechanicznym.

1. INTRODUCTION

Weather routing methods and tools deal with a problem of finding the most suitable vessel route. During the route optimization process they take into account changeable weather conditions and navigational constraints. Such a problem is mostly considered for ocean-going ships where adverse weather conditions may impact both, often contradictory,

[1]Gdynia Maritime University, Department of Navigation, e-mail: asiasz@am.gdynia.pl

economic and security aspects of voyage. Most of recent scientific researches in weather routing focus on shortening the passage time or minimization of fuel consumption alone.

One of the first weather routing approaches was a minimum time route planning based on weather forecasted data. Proposed by R.W. James in 1957 [1] an isochrone method, where recursively defined time-fronts are geometrically determined, was in wide use through decades. In late seventies based on the original isochrone method the first computer-aided weather routing tools were developed. Numerous improvements to the method were proposed since early eighties, with [2], [3] among others. Nonetheless, even the improved method has been displaced with time by genetic algorithms. Evolutionary approach as a natural successor of genetic approach has become popular in the last two decades and has been successfully applied to anti-collision maneuver modeling [4]. Modern weather routing tools also utilize evolutionary algorithms instead of the deprecated isochrone time-fronts. However, due to multiobjective nature of weather routing it is recommended to introduce some state-of-the-art multiobjective methods to the process of route finding.

In this paper a revised and extended version of a multicriteria weather routing solution [5] is presented. The Multicriteria Evolutionary Weather Routing Algorithm (MEWRA) is here described and adjusted for a motor-driven ship.

The paper is organized as follows: section 2 presents a brief review of the multicriteria techniques utilized by MEWRA algorithm. Section 3 describes the multicriteria model underlying MEWRA's optimization process. In Section 4 MEWRA algorithmic elements, including these designed for a motor-driven ship, are presented. Finally, section 5 summarizes the material presented.

2. MULTICRITERIA OPTIMIZATION TECHNIQUES IN WEATHER ROUTING

In the multicriteria approach to weather routing proposed in [5] two appropriate optimization techniques are utilized, namely a multicriteria evolutionary algorithm SPEA and multicriteria ranking method Fuzzy TOPSIS. The former is responsible for finding a set of Pareto-optimal solutions, whereas the latter aims at selecting a single route out of the Pareto set. The route is always chosen based on a decision-maker (here eg. a captain) preferences according to the optimization criteria set.

The following subsections give a brief description of both multicriteria optimization mechanisms utilized by MEWRA algorithm.

2.1 SPEA algorithm

The Strength Pareto Evolutionary Algorithm (SPEA), proposed originally in 1999 by Zitzler *et al.* in [6], is a multiobjective evolutionary algorithm able to find multiple Pareto-optimal solutions in parallel. Figure 1 presents the general algorithm flow.

Given SPEA algorithm flow reflects the generic evolutionary algorithm. Its key elements are:

- initial population creation,
- fitness assignment,
- selection,
- applying problem-specific operators,

– checking for termination condition.

These elements are supplemented by additional steps concerning maintenance of a nondominated set *N*. Here, throughout the evolution process two populations are maintained, the basic population *P* and the secondary one – *N*. The main purpose of the latter is to sustain all nondominated individuals during the complete generation process. Individuals from the nondominated set *N* also participate in fitness assignment, thus selection procedure is able to utilize a multiset union of individuals from *P* + *N*.

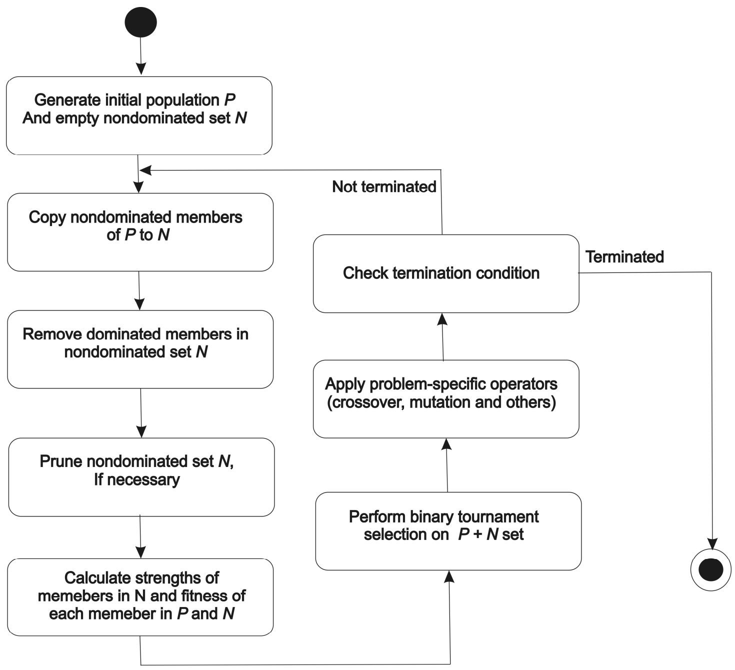

Fig. 1 SPEA algorithm flow

The nondominated set *N* is initialized as empty during the creation of initial population in *P*. Then, in each generation current nondominated individuals from *P* are added to the nondominated set *N*. However, adding new individuals to *N* may cause some of the old elements already in *N* becoming dominated. Thus, checking and removal of the dominated individuals from nondominated set *N* must be performed. In cases of exceeding the defined maximum size *N*, the nondominated set must be pruned in terms of clustering.

Fitness assignment in SPEA is organized in a twofold way. Firstly, for each individual from the secondary population *N* a fitness value, so-called "strength", is calculated. The strength of given individual from *N* is proportional to the number of individuals from basic population *P* that are covered by him (which means that are dominated or equal to). In the second step all individuals from population *P* are assigned a fitness value that is a sum of strengths of elements from *N* that cover given individual from *P*.

2.2 Fuzzy TOPSIS ranking method

Basic TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) [7] is a ranking multicriteria decision making method operating on crisp values. The method is based on a concept that the best alternative among the available alternative set is the closest to the best possible solution and the farthest from the worst possible solution simultaneously. The best possible solution, referred to as an ideal one, is defined as a set of the best attribute values, whereas the worst possible one, referred to as a negative-ideal solution, is a set of the worst attribute values. In order to compare the alternatives and build the output ranking, the Euclidean distances between each alternative and both the ideal and the negative-ideal solutions are calculated first, then the closeness coefficient is calculated to measure the two distances simultaneously. Final TOPSIS ranking is created by sorting the coefficient values assigned to the alternatives in descending order. The alternative with the highest ranking value is considered as the best one.

Based on the TOPSIS method, Fuzzy TOPSIS [8] provides support for fuzzy criteria and fuzzy weights both described by fuzzy sets with triangular membership functions. Fuzzy TOPSIS preserves the core algorithmic steps of TOPSIS, however amends it, when necessary, to suit requirements of fuzzy sets operations. The primary difference between these methods is introduction of a fuzzy decision matrix (instead of a crisp one in TOPSIS) subject to further Fuzzy TOPSIS computations. Prior to performing a search of the ideal and negative-ideal solutions a supporting matrix is defuzzified. Final crisp ranking of alternatives in Fuzzy TOPSIS is created identically as in the TOPSIS method.

3. OPTIMIZATION MODEL

A proposed set of goal functions in the weather routing optimization process is presented below by equations 1 – 3:

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

$$f_{fuel\_consumption}(v_{fc}) = v_{fc} \rightarrow \min \tag{2}$$

$$f_{voyage\_risks}(i_{safety}) = (1 - i_{safety}) \rightarrow \min \tag{3}$$

where:

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

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

i_{safety} – [/] safety coefficient for given route and ship model. It is defined as a value ranging [0;1], describing a level to which the route is safe to be passed. “0” depicts totally impassable route and “1” absolutely safe route.

Exact formulas for goal functions (1) – (3) strongly depend on the assumed ship model. Thus, the explicit formulas for a ship model with hybrid-propulsion can be found in [5], while the ones for a motor-driven ship model are given in [9].

Set of constraints in the considered optimization problem includes the following elements:

- landmasses (land, islands) on given route,
- predefined minimum acceptable level of safety coefficient for given route,
- shallow waters on given route (defined as waters too shallow for given draught of ship model),
- floating ice bergs expected on given route during assumed ship's passage,
- tropical cyclones expected on given route during assumed ship's passage.

4. MULTICRITERIA WEATHER ROUTING ALGORITHM (MEWRA)

The Multicriteria Weather Routing Algorithm (MEWRA), presented in Figure 2, searches for an optimal route (according to goal functions (1) – (3)) for the assumed ship model. The input data for the algorithm are:

- geographical coordinates of route's origin & destination,
- weather forecasts (wind, wave and ice) for considered basin and time period of the voyage being planned.

The algorithm [5, 9] starts with a generation of initial population i.e. a diversified set of routes including the outermost elements of the searching space (Figure 3). The modified isochrone method [10] with extensions described in [11] is a source of single-criterion time-optimal and fuel-optimal routes. The routes are then a base for random generation of initial population. Also the original routes are included in the population.

In the next step SPEA algorithm iteratively proceeds the evolution on the initial population towards achieving Pareto-optimal set of routes. Once the evolution cannot improve on the Pareto set anymore the first optimization procedure is stopped. Then, from the set of Pareto-optimal routes (Figure 4) a single route must be selected, becoming a route recommendation.

Yet another problem might be encountered: how to decide which route should be recommended? 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. First the decision-maker has to set their preferences for given criteria set. In MEWRA these preferences are expressed by means of linguistic values (Table 1) with fuzzy sets assigned accordingly. The decision-maker selects a linguistic value of the predefined set to each of optimization criteria. Then the corresponding fuzzy sets build a weight vector for the ranking method. The last step of MEWRA – Fuzzy TOPSIS – is responsible to apply given weight vector to the decision matrix built of the goal function values of the Pareto-optimal routes. The route having the highest value of ranking automatically becomes then a route recommendation (Figure 5). Exemplary MEWRA results (Figures 3 – 5) have been obtained for hybrid propulsion ship model, Miami-Lisboa voyage on 2008-02-15 (departure time 12:00 pm) and decision-maker preferences given in Table 2.

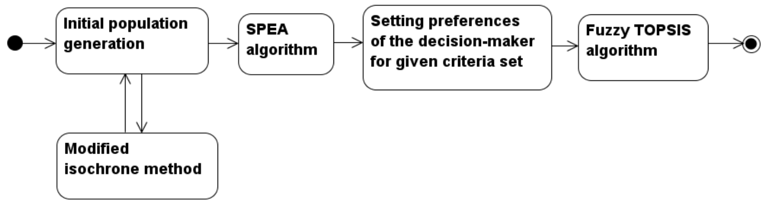

Fig. 2 Multicriteria Evolutionary Weather Routing Algorithm (MEWRA)

Tab. 1 Linguistic values and corresponding triangular fuzzy values, utilized to express decision-maker's preferences to the criteria set

Linguistic value	**Triangular fuzzy set**
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)

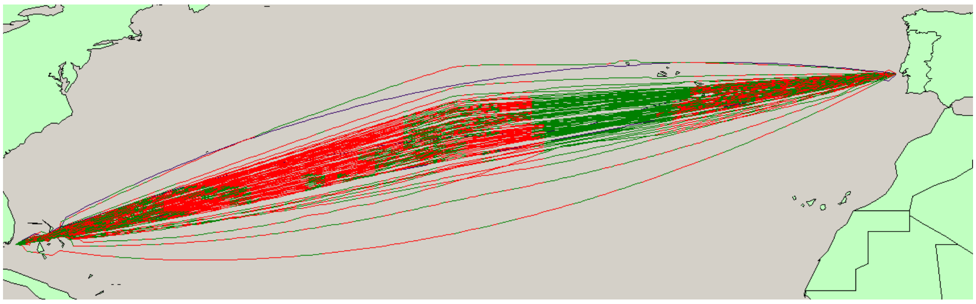

Fig. 3 Initial population generated by MEWRA for Miami-Lisboa voyage on 2008-02-15 (departure time 12:00 pm)

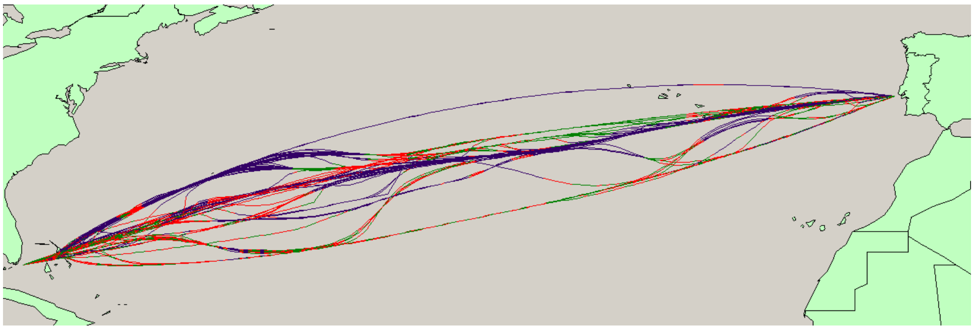

Fig. 4 Pareto-optimal set of routes generated by MEWRA for Miami-Lisboa voyage on 2008-02-15 (departure time 12:00 pm)

Tab. 2 Linguistic values assigned by a decision-maker to the criteria set

Criterion name	Linguistic value	Triangular fuzzy set
Passage time	important	(0.5; 0.7; 1.0)
Fuel consumption	quite important	(0.2; 0.5; 0.8)
Voyage risk	very important	(0.7; 1.0; 1.0)

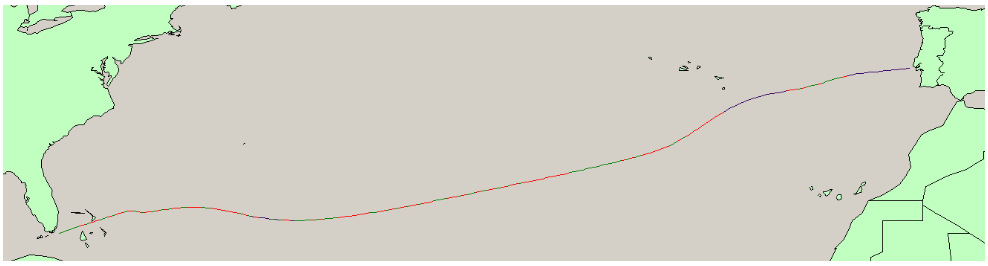

Fig. 5 Recommended route selected by MEWRA for Miami-Lisboa voyage on 2008-02-15 (departure time 12:00 pm) according to the preferences given in Table 2

4.1 Motor-driven MEWRA application

MEWRA application for the motor only propulsion has been constructed based on its hybrid-propulsion predecessor. The key differences between application versions for hybrid ([5]) and motor-driven ([9]) ship model are as follows.

1. The safety coefficient i_{safety} (utilized by goal function (3) and appropriate constraints) in case of the hybrid propulsion model is based on wind speed and heading only (assuming strict correlation between wind and wave conditions). In the motor-driven model the coefficient has been redefined as a percentage part of a route that is free from disturbances caused by dangerous waves. However, regions with severe wave threat are still bypassed by means of fulfilling a new constraint for restricted course sectors [9], presented in Figure 6.
2. Weather input forecasts for the motor-driven model has been enlarged by wave period and wave angle as given in 1. Also MEWRA's graphical user interface (GUI) has been changed accordingly to allow displaying the new data on the screen.
3. In the hybrid propulsion case there is a possibility to use one of the three propulsion modes, namely "motor only", "sails only" or "motor & sails". The "sails only" mode for a route segment requires the engine to be temporarily switched off, which in return may significantly decrease the fuel consumption. In the motor-driven case there is only one propulsion mode i.e. "motor only", which drastically limits possible fuel savings.
4. Speed characteristic obtained for the motor-driven ship model (Figure 7) is definitely less susceptible to wind heading than the characteristic of the hybrid

model [11]. On the other hand the motor-driven one is also dependent on wave forecasts, which causes some course sectors impassable due to restricted sector mentioned in 1.

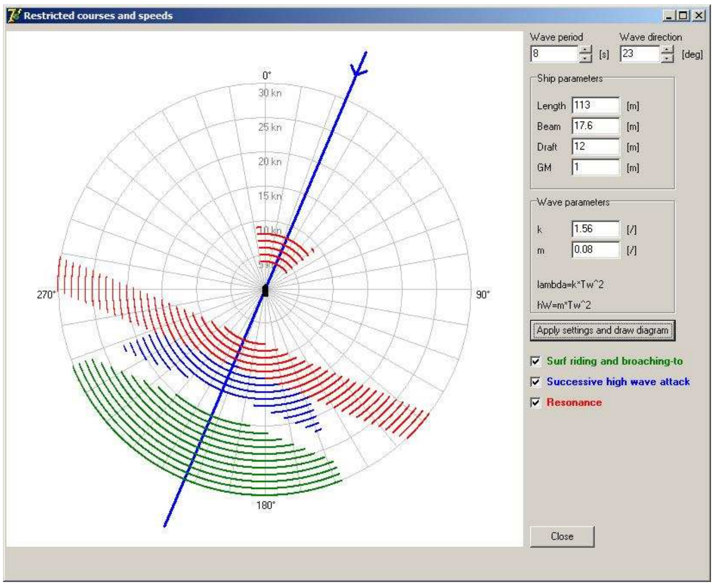

Fig. 6 Restricted course sectors for given wave period and direction caused by avoiding (1) surf riding and broaching to (green area), (2) successive high wave attack (blue area) & (3) resonance (red area)

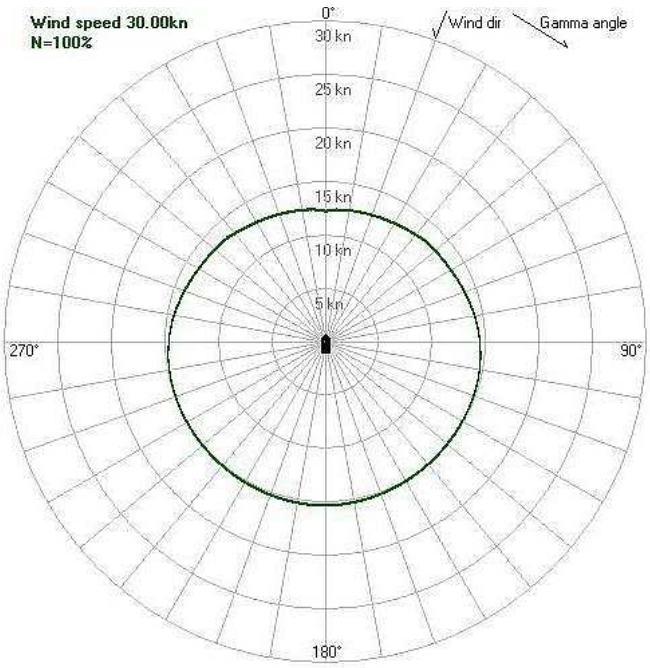

Fig. 7 Motor-driven ship speed characteristic applied for MEWRA

5. SUMMARY

The paper presents a description of multicriteria weather routing algorithm (MEWRA), presented earlier for hybrid propulsion ship model, here customized for a motor-driven ship. The MEWRA's route optimisation algorithm is based on Strength Pareto Evolutionary Algorithm (SPEA) and Fuzzy TOPSIS ranking method. The paper is primarily focused on how the multicriteria problem of route finding is defined and how the two optimisation methods (SPEA and Fuzzy TOPSIS) are utilized to solve the problem. Also, the most significant differences in MEWRA application for hybrid and motor-only propulsions have been underlined. Final test results of the MEWRA motor-only application will be presented as soon as the development phase is completed.

6. REFERENCES

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