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WRM-RS: a metaheuristic algorithm for ship weather routing in the presence of obstacles

Stéphane Grandcolas¹

^{1*}Laboratoire d'Informatique et des Systèmes, Aix Marseille Université,
Université de Toulon, CNRS, LIS, Marseille, France.

Contributing authors: stephane.grandcolas@lis-lab.fr;

Abstract

In recent years ship weather routing has attracted a lot of interest. The primary objective is to reduce costs, but other criteria must also be considered, such as time, safety or carbon footprint. In addition, environmental factors such as wind and waves must be taken into account, especially as wind-assisted propulsion systems are being developed. Recently a metaheuristic algorithm called **WRM** (for Weather Routing Metaheuristic) has been proposed [4]. **WRM** searches for routes within a given time window. Its objective is to minimize the total cost of the journey, determining both the trajectory of the vessel and its speed all along this trajectory. The algorithm converges continuously towards the most promising region, concentrating its effort around the best route discovered so far. This strategy can be defeated in case there are obstacles, as the choice of itinerary is made very early on during the search. In this paper we propose a new approach, called **WRM-RS**, in which different options are considered simultaneously. As the search progresses the least promising options are abandoned one after the other. We have performed experimentations on a journey in the Mediterranean Sea for which different itineraries are possible due to the presence of islands and straits. Results show gains of up to 3.49 percent on the power required compared to **WRM**.

Keywords: Ship weather routing, Route and speed optimization, Metaheuristic algorithms, Shipping emissions

1 Introduction

In recent years ship weather routing has attracted a lot of interest. One of the reasons for this is the need to limit greenhouse gas (GHG) emissions in the sea shipping sector,

which is experiencing extremely strong growth. GHG emissions are directly correlated with fuel consumption, and are therefore highly dependent on environmental factors such as wind, waves or sea currents, which have an impact on the progression of the ship. This is even more the case now that new technologies are being developed to take advantage of the wind, including wingsails, kite sails, wind assisted rotors, inflatable or rigid sails. Mason et al. showed, on a selection of fourteen routes that they have analysed, that annual carbon emissions can be reduced by an average of 10.8 percent using Flettner rotors, and that by combining wind propulsion with route optimization, they can be reduced by around 17.7 per cent [15]. Similarly Sun et al. have estimated at 15.2 percent fuel saving for a journey from China to the Middle East if the route is optimized taking weather conditions into account, and at 19.6 percent if wind-assisted rotors are also used [18].

Various criteria are likely to be considered when it comes to evaluating a route, such as time, cost, pollutant emissions, safety, etc. For the sake of efficiency, minimizing fuel consumption is often regarded as the unique objective, while the other criteria are considered as constraints. Furthermore, route optimization involves not only determining the course of the ship, but also adjusting its speed all along the journey. It has been shown that taking into account this parameter gives much better results, in particular if the aim is to optimize fuel consumption [23]. This and the fact that the domains of the variables are continuous make the problem difficult to solve. Numerous approaches can be found in the literature. The best-known ones are based on isochrones [6][13], or use Dijkstra's (and A*) algorithm [24][3][18][12], dynamic programming [16][9][26], or evolutionary algorithms [21][14][25][11][2]. A detailed survey can be found in [28].

In the presence of obstacles, such as islands or reefs, searching for good quality routes is harder. First, the route must bypass the obstacle. Static meshings, on which many approaches are based, are not well adapted to get around the obstacles. The path can be very winding, or involves crossing narrow straits. Furthermore, the number of potential paths to avoid the obstacles can be very important, which means it grows exponentially with the number of obstacles. Finally, approaches based on a continuous transformation of a given route in order to improve its reliability when there are obstacles on the way. Indeed, with this type of approach it is important to avoid falling into local optimality and converging too fast [2]. If there are obstacles, at some point choices have to be made that will never be reconsidered later. It should be noted that obstacles are not necessarily lands or reefs. They can also be areas where navigation is impossible or at least dangerous, due to strong winds or waves which will affect the safety and the cost of the voyage. Such obstacles can move, grow, strengthen or simply disappear over time.

Relatively few researchers have focused on the problem of avoiding obstacles. Indeed, many approaches are based on a meshing of the sea surface, and crossings that are not feasible due to land masses or reefs can be discarded when creating the meshing. Methods using evolutionary algorithms are more concerned. Fagerholt et al. [8] formulate the problem as a shortest path problem in the presence of polygonal obstacles, and describe an efficient algorithm that generates the arcs of a graph only when needed. Szlapczynska et al. [19] proposed an adaptation of the isochrone method with

area partitioning, suggested by Hagiwara [7], which ensures that the routes would not cross land. The method is used in their evolutionary approach for the creation of the initial population. Tsou et al. [21] experimented a genetic algorithm whose objective is to optimize the distance covered, the time spent in threatening areas (less time is better), and the time spent in mild conditions (more time is better). The initial population is selected from all the possible itineraries that bypass the obstacles, and the authors present a procedure that generates them efficiently. Kuhlemann et al. [11] have implemented a genetic algorithm that minimizes fuel consumption, that takes into account the wind and the waves. They describe a procedure for generating the initial population that takes obstacles into account. It consists, starting with the direct route, in dividing the segments that constitute the route by inserting and moving new waypoints, until none of the segments intersects land. By choosing the first points at random, different routes are generated that avoid all the obstacles. Vlachos [22] proposed an approach based on simulated annealing. The idea is to transform a given route, by making slight displacements of the waypoints. However, there is no guarantee that accepting to degrade the route will enable to discover other possibilities to bypass the obstacles. Kosmas et al. [10] described another approach based on continuous transformations of an initial route. The method aims at optimizing the time of voyage and the voyage comfort, taking wind and waves into account. To overcome the problem that in some cases, transformations of the initial route cannot lead to the optimal one, the authors consider all potential initial itineraries, and then decide for the one that seems the most promising. Grifoll et al. [5] have compared the optimized routes produced by the software SYMROUTE with the shortest routes on different examples in which the presence of islands forces choices to be made. It appears that in many cases longer distance routes may be covered in less time.

Recently, a metaheuristic algorithm, called **WRM**¹, has been proposed [4]. **WRM** optimizes at the same time ship's speed and course. It proceeds by solving a series of *simplified versions* of the problem. Each time a simple search procedure is applied to discover better routes. At the beginning, the procedure explores the search space without any restrictions. Thereafter, the exploration is limited to an area surrounding the best route discovered so far, which becomes more and more restricted as the search progresses, thus intensifying the search in the most promising region. The approach neither rely on a predefined mesh of the space nor on time discretization. Constraints on sailing conditions or on safety can easily be taken into account, as well as additional costs resulting, for example, from navigation in Emission Control Areas (ECA). However, in the presence of obstacles as islands, as the search converges continuously, some regions with high potential can be missed. To address this problem we propose to maintain simultaneously several possibilities that show a good potential. The alternatives are represented by a selection of routes, which are expected to show a certain diversity. We have called this new approach **WRM-RS**.

The paper is organized as follows: in section 2 we present the weather routing problem we are interested in and the method **WRM**. Then, in section 3, we introduce the notion of diversified sets of routes and in section 4 we describe **WRM-RS** approach.

¹for Weather Routing Metaheuristic

section 5 we show the results obtained with WRM-RS on a specific instance and we evaluate its performances. Finally we conclude, in section 6.

2 WRM approach for ship weather routing

In the field of ship weather routing, various issues have been addressed [17]. It all depends on the criteria to be optimized and on the constraints to be taken into account. The problem of arriving at a given destination before a given date at minimum cost seems the most common, and many approaches have been proposed, some very recently [12]. WRM aims to find routes of minimum cost within a given time period, while respecting constraints on navigation conditions [4]. The cost is the amount of energy required for the vessel to make the journey. The functions *duration* and *cost* are parameters of the program. They provide the duration and the energy needed for crossing from a point to another following a direct route at constant given engine power level given constant weather conditions, such as wind and waves. In WRM a ship weather routing problem is defined by:

- *chart*: specifies the areas where the ship can navigate,
- *departure, arrival*: departure point, arrival point,
- t_{dep}, t_{arr} : period during which the journey is planned,
- p_{min}, p_{max} : engine minimum and maximum power levels,
- *duration, cost*: vessel-specific functions,
- \mathcal{F} : weather forecast covering the area and the period in which the journey is to take place.

A route r is a triple $\langle t, (u_1, \dots, u_{n-1}, u_n), (w_1, \dots, w_{n-1}) \rangle$ where t is a date, the date at which the voyage starts, u_1, \dots, u_n are waypoints, and w_1, \dots, w_{n-1} are engine power levels. The route is composed of a series of *legs*. Each leg connects two successive points of the route following the direct route. On each leg we suppose that the power level of the engine is constant, denoted w_i for the leg (u_i, u_{i+1}) . The weather forecast \mathcal{F} gives the values of different environmental factors (wind, waves) at different moments on a latitude-longitude grid. Using the functions *duration* and *cost*, and the weather forecast \mathcal{F} it is possible to calculate the dates at which the vessel will pass through each point of the route and the cost corresponding to each leg, and then to calculate the final arrival date t' . The route r is *valid* given the problem P if, (1) u_1 is *departure* and u_n is *arrival*, (2) for each leg (u_i, u_{i+1}) the power level w_i satisfies $p_{min} \leq w_i \leq p_{max}$, and (3) $t \geq t_{dep}$ and $t' \leq t_{arr}$. In the rest of the paper we will only consider valid routes. The total cost of the route is the sum of the costs of its legs. The problem is to find a valid route whose cost is minimal.

Note that, even under constant and uniform sailing conditions and no obstacle on the way, the optimal route is not necessarily the direct route. It all depends on the ability of the vessel to progress according to weather conditions (that is on the functions *duration* and *cost*). For example, it can be advantageous, with a strong headwind, to deviate a little from the direct route, or to perform a series of zig-zag maneuvers as would make a sailing boat, assuming the vessel can do it. This is all the more true as new techniques are being developed to take advantage of the wind

to help the progression. It can also be the case if the direct route crosses difficult or dangerous sailing conditions, such as a large swell at a certain angle with the risk of a heavy rolling phenomena. For these reasons, and also because weather forecasts change with time, simply positioning the potential waypoints with respect to the grid of the prediction model, so that each cell is traversed along a direct route, is not sufficient.

The basic idea behind **WRM** is to generate and solve a series of *simplified versions* of the problem. A simplified version of the problem is defined by a graph and by a set of potential engine power levels. The vertices of the graph represent potential waypoints, one of them corresponding to the departure port, another to the final destination. Solving a simplified version of the problem consists in propagating *dated costs* through the graph using the potential engine power levels, where a dated cost (t, c) attached to a vertex p indicates that a route which reaches p at the date t for a cost c has been discovered. So complete routes can be reconstructed from the dated costs attached to the destination vertex. The function `searchAGoodRoute` performs this task, and just returns the less costly route that reaches the final destination (see [4] for a full description). The simplified versions of the problem are generated randomly, and solved each time using specific parameters, as the size of the graph, the number of power levels that are considered, the number of dated costs attached to each vertex, etc. The objective is to intensify the search in an area that is gradually being narrowed around the best route discovered so far. This is done by marking the search space, so as to limit the area in which the waypoints are placed, and to reduce the ranges in which the engine power levels are selected.

3 Searching routes in the presence of obstacles

When there are obstacles on the way, as islands or forbidden areas, the strategy of **WRM** is compromised. Indeed **WRM** converges progressively towards the most promising area, which works well if the search space is continuous. Obstacles create a discontinuity, which forces the algorithm to abandon certain options that could have generated the best routes. For example if the vessel can pass to the south or to the north of an island with closed costs at a certain point during the search, as the perimeter of the marking decreases, one of the two options will no longer be considered since it does not correspond to the current best route. However it would be better to explore both alternatives as long as possible, until it becomes clear that one or the other is useless. This is the idea we have developed in **WRM-RS**. **WRM-RS** is based on **WRM**. The principle is to mark the search space using several routes, and not just from the best route discovered at this point. *Diversified sets of routes* will enable us to represent very different route options. For this purpose, the routes in the set are constrained to be at a minimum distance from each other. The distance between routes is defined using route decompositions.

Definition 1 (Route decomposition) *Given a problem P and a time step δ , the decomposition of the route r on the period $[t_{\text{dep}}, t_{\text{arr}}]$ with step δ is the sequence (p_0, p_1, \dots, p_k) of the positions of a ship following the route r at dates $t_{\text{dep}}, t_{\text{dep}} + \delta, t_{\text{dep}} + 2 \times \delta, \dots, t_{\text{dep}} + k \times \delta$, where k satisfies $t_{\text{dep}} + k \times \delta \leq t_{\text{arr}} < t_{\text{dep}} + (k + 1) \times \delta$.*

The function *duration* is all that is needed to calculate the decomposition. Furthermore the decompositions of two different routes have the same size, regardless of their departure dates.

Definition 2 (Distance) *Given a problem P and a time step δ , the distance between the routes r and r' is*

$$D_\delta(r, r') = \sqrt{\sum_{i=0,1,\dots,k} d(p_i, p'_i)^2}$$

where p_0, p_1, \dots, p_k and p'_0, p'_1, \dots, p'_k are the decompositions of the routes r and r' on the period $[t_{\text{dep}}, t_{\text{arr}}]$ with time step δ , and $d(u, v)$ is the orthodromic distance from point u to point v .

The distance D measures the similarity between the routes in terms of trajectory and of passage times. Whether or not a selection of routes is diversified depends on the distances between its routes. More precisely, the *diversification degree* of a set of routes is the smallest distance between two of its elements. The diversification degree is used in **WRM-RS** to maintain the diversity in the selection of routes used to mark the search space. An appropriate diversification degree is determined following an initial exploratory phase. This degree then serves as a lower bound for the diversification degree of the selection for the rest of the search.

Algorithm 1 : WRM-RS(P, n, π)

in : P : weather routing problem,

n : number of phases,

$\pi = (\pi_1, \dots, \pi_n)$: parameters for phases 1 to n ,

out: a set containing the best route discovered by the algorithm if one exists,

```

1  $\mathcal{R} := \text{search\_phase}(P, \emptyset, \pi_1, +\infty, 0)$ ,
2 remove routes from  $\mathcal{R}$  until only  $n - 1$  remain,
3  $d_{\min} := \text{MIN}_{r, r' \in \mathcal{R}} d(r, r')$ ,
4 for  $i := 2$  to  $n$  do
5     if  $|\mathcal{R}| > n - i + 1$  then remove the worse route from  $\mathcal{R}$ ,
6      $\mathcal{R} := \text{search\_phase}(P, \mathcal{R}, \pi_i, n - i + 1, d_{\min})$ ,
7 end for,
8 return  $\mathcal{R}$ ,
```

Given a weather routing problem P , the algorithm **WRM-RS** searches a good-quality route (algorithm 1). The process comprises n phases. The same processing is performed in each phase (function **search_phase**, algorithm 2). It consists in generating and solving simplified versions of the problem a number of times. The function **search_routes** is called each time. This is exactly the same function as the **searchAGoodRoute** function in [4], except that it returns all the routes that have been discovered, and not only the best one. Each phase is specifically parameterized. The

parameters specify the numbers of runs, the number of potential waypoints and the number of costs per point, the perimeter for marking the search space, etc. From one phase to the next, the search is more intensive and focused on the most promising regions. Throughout the process the set \mathcal{R} represents the selection of routes.

The first phase is special (algorithm 1, line 1): the aim is to generate many routes with a lot of diversity. So the generation of the simplified versions of the problem is parameterized specifically: the number of potential waypoints is large, and their placement is free of any restriction (the perimeter for the marking is set to $+\infty$). Moreover, all the routes that are discovered are saved in \mathcal{R} , that is the size of \mathcal{R} is not limited and the minimum distance required between the routes of \mathcal{R} is zero. Then the less interesting routes are discarded (line 2). The objective is to obtain a diversified selection of $n-1$ high-quality routes. The process is similar to a hierarchical clustering algorithm. It consists in removing the more costly of the two closest routes in \mathcal{R} according to the distance D , as long as \mathcal{R} contains more than $n-1$ routes. Then d_{min} is set to the minimum distance separating two routes in \mathcal{R} (line 3). It will serve as lower bound for the diversification degree of the selection of routes for the rest of the process. In the following phases (lines 4-7), the selection of routes is made smaller and smaller. Initially, that is in phase 2, \mathcal{R} contains at most $n-1$ routes. In the last phase, \mathcal{R} is reduced to a unique route. Finally WRM-RS returns the set \mathcal{R} , which contains the best route discovered during the search.

Algorithm 2 : `search_phase`($P, \mathcal{R}, \pi, k, d$)

in : P : weather routing problem,
 \mathcal{R} : set of routes,
 π : parameters for generation and solving,
 k : upper bound for the size of \mathcal{R} ,
 d : minimum diversification degree of the selection of routes,

out: a selection of routes of size at most k and diversification degree at least d ,

```

1  for  $i := 1$  to  $nbRuns(\pi)$  do
2       $\mathcal{S} := mark\_search\_space(\mathcal{R}, \pi)$ ,
3       $C := search\_routes(P, \mathcal{S}, \pi)$ ,
4       $\mathcal{R} := update\_selection(\mathcal{R}, C, k, d)$ ,
5  end for,
6  return  $\mathcal{R}$ ,
```

The function `search_phase` (algorithm 2) generates and solves simplified versions of the problem a number of times. Each time, the search space is marked using the routes in \mathcal{R} and the *perimeter*, a parameter defined in π (line 2). This involves delimiting the regions of the map in which the potential waypoints will be set, as well as specifying time windows for the dates of passage of the vessel in these regions (or specifying ranges for the power level of the engine). Then the function `search_routes` generates a problem using this marking, solves it, and returns the routes that have

been discovered (line 3). The set \mathcal{R} is updated with these routes (line 4), so that it contains no more than k routes and its diversification degree is not smaller than d . The objective is to improve the quality of the routes of the selection while preserving their diversity. The process consists, for each route r in C starting with the best ones, to compare r with the route r' in \mathcal{R} which is the closest to r . If r is not better than r' then r is discarded. In the other case (1) r is inserted in \mathcal{R} , (2) the route r' is removed from \mathcal{R} if there are more than k routes in \mathcal{R} , and (3) each route r'' which is at a distance to r smaller than d is removed from \mathcal{R} . So there may be less than k routes in \mathcal{R} . The function `search_phase` returns the selection of routes obtained after $nbRuns(\pi)$ generations and solvings. This selection is given as input to the next phase, after removing the most costly route if necessary (algorithm 1, line 5).

4 Experimentations

We have implemented WRM-RS and we have performed experimentations. This section contains first a description of the implementation, then an illustration of the search process with an example, and finally an evaluation of the effectiveness of the approach on this example.

4.1 Implementation

WRM-RS is based on WRM. In particular we have used the same model for estimating crossing times and costs. For full details see [4]. We considered the case of a small, highly maneuverable vessel with sails. The sails add a maximum of 1000 kW to the engine power, which is 7000 kW. So the wind has a strong effect on the progression of the ship. This makes it easier to assess the efficiency and relevance of the approach. It explains why optimized routes are so winding and why very different options can give very close results. Figure 1 shows the polars of ship speed for different wind speeds, as a function of the heading of the ship to the wind. The different curves correspond to different engine power levels (1000, 2000, 3000, 4000 and 6000 kW). We can see that the speed is higher between crosswind and three-quarter astern, as

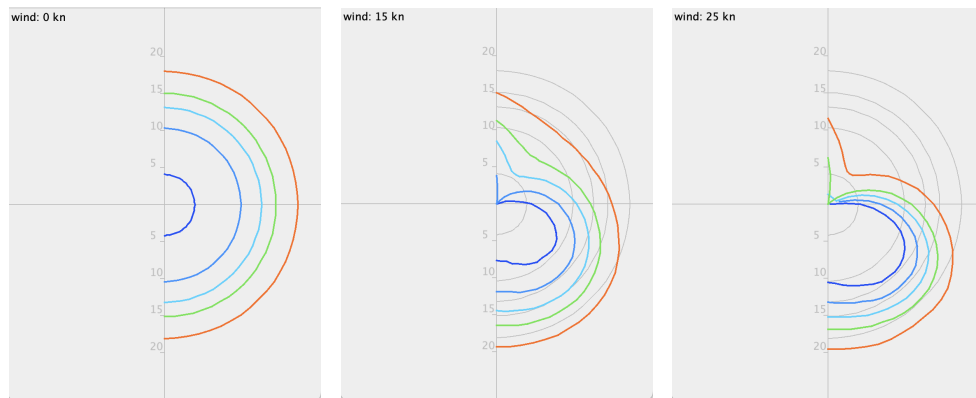


Fig. 1: Ship speed as a function of engine power and wind speed

the sails are much more efficient at these angles. It should be noted that these polars are purely theoretical, and there is no guarantee that they are valid in practice. They are used solely to test and evaluate our approach. Simplified versions of the problem are generated and solved in exactly the same way as in WRM. The costs represent the amount of energy needed (calculated using the function *cost*) and not the amount of fuel used, which depends on the engine.

<i>phase</i>	1	2	3	4	5	6
<i>number of runs</i>	12	26	17	17	17	10
<i>routes</i>	–	5	4	3	2	1
<i>waypoints</i>	3000	200	300	400	500	600
<i>perimeter</i>	–	40	20	10	5	2.5
<i>dated costs for each point</i>	40	48	60	72	72	72
<i>power levels per leg (mean values)</i>	7	6.8	8.9	12.4	15.0	19.5

Fig. 2: WRM-RS parameters

WRM-RS includes a total of six phases, each with its own specific parameters, listed in figure 2. The value of the perimeter in each phase depends on the length of the journey. We have reported the values corresponding to the example described below. We have also reported the average numbers of engine power levels used for the propagation on each leg. They depend on the range in which the power levels are taken and on their spacing, which decreases over time. The time step δ used for route decomposition is set at one hour.

4.2 Example: journey from Marseille to Beirut

We experimented on the journey from Marseille (43°3'N 5°3'E) to Beirut (33°51' N 35°12' E) in the period from February 12, 2022 at 7:00 am to February 17, 2022 at 1:00 pm. This means that the journey takes a maximum of 126 hours. We have chosen this example because it offers numerous possible options, as it is dotted with islands that can be bypassed on one side or the other. Moreover, within this time window, there are routes of very high quality that correspond to very different itineraries and dates.

We got weather data from NOAA² (GFS atmospheric and waves models), for a period of 16 days starting from February 7, 2022, with 3 hours intervals and a resolution of 0.25 degree. The program is written in Java and runs on a laptop equipped with a Apple M2 Pro processor and 16GB of RAM. Figure 3 shows WRM-RS searching for a route at different steps of the search process. The first row on the left shows all the routes discovered during phase 1. A wide variety of routes emerged, which correspond to various possible paths through the islands with different dates of passage. The colored route is the least costly route of the selection, the *best route*. When the first phase terminates the cost of the best route is 419050.0. It passes to the south of Sardinia, Sicily and Crete. The colors indicate the power level of the engine on each

²National Oceanic and Atmospheric Administration, <https://nomads.ncep.noaa.gov>

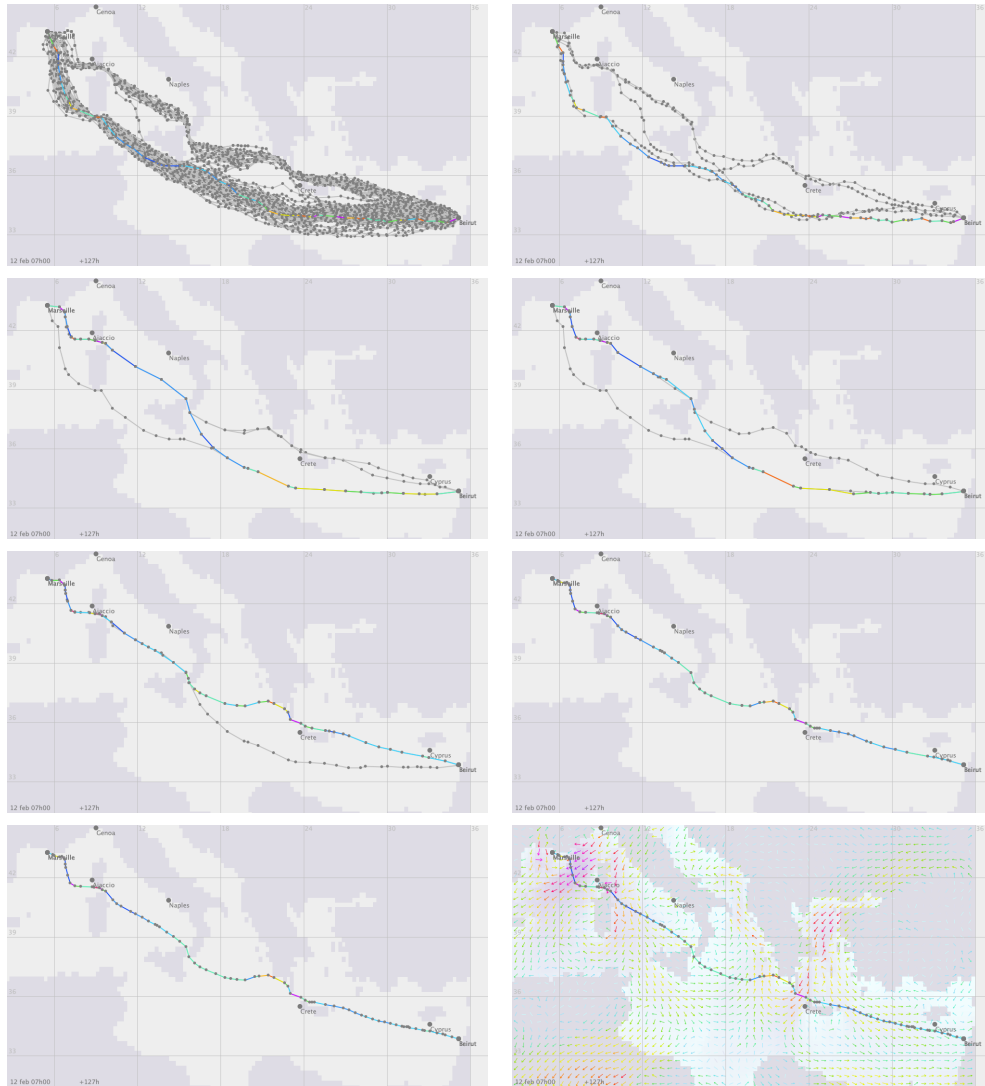


Fig. 3: The selection of routes at different steps during the search process

leg. From all the routes discovered in phase 1, five are selected for phase 2, which are shown on the first row on the right (figure 4 shows a 3-dimensional representation of the routes discovered in phase 1 and of the five routes selected for phase 2, in which the z -axis represents time). The selections of routes at the beginning of phases 3 to 6 are displayed on the next two rows of figure 3. As the search progresses the routes of the selection become better and better. At the beginning of phase 3, the itinerary of the best route changes. Then, the best route passes between Sardinia and Corsica, and to the north of Sicily, with a cost of 391585.7. At the beginning of phase 4, the best route still passes to the south of Crete with a cost of 389119.3. This is no longer

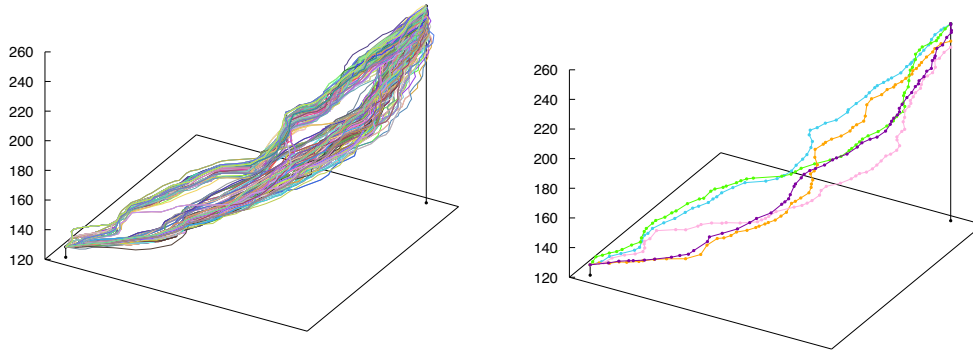


Fig. 4: 3D representation of the selection of routes at the end of phase 1

the case at the beginning of phase 5 (third row on the left), as at this point the best route passes between Crete and Greece with a cost of 377079.5. All along the runs of phases 3 and 4, the different options corresponding to the routes of the selection were taken into account, but some of them have been improved much more than others. And finally, the itinerary that passes to the north of Crete has become better than the others. The 6th phase begins with a selection reduced to a single route whose cost is 374138.2 (third row on the right).

The program stops after 36.1 seconds. The final best route returned by **WRM-RS** has a cost of 373736.5, and is composed of 78 legs. It leaves Marseille at 07:00 am on February 12 and reaches Beirut at 0:59 pm on February 17. The route is displayed on the last row of figure 3, with and without weather forecasts. The weather conditions represented at each point are the conditions expected when a ship following the best route is at that same distance (orthodromic distance) from departure. The color of the arrows indicates the wind force, the color of the background indicates the waves height. A video of **WRM-RS** in action can be found at <https://youtu.be/PNhIilBw6m8>. Note that the final route contains changes in direction or in power level that a conventional container ship could not make. It is possible to remedy this problem, by constraining the propagation of the costs in the function `search_routes`. It suffices to discard the costs which are too far from the generating cost in terms of direction and power level. Naturally it is very likely that **WRM-RS** will then not be able to deliver routes as good as if there were no constraints. Another solution should be to smooth the final route afterwards. The objective here is to show the efficiency of **WRM-RS**'s strategy, we have therefore not taken these constraints into account so as not to interfere with the search process.

Figure 5 shows graphs generated during phases 1, 3, 4 and 5. In phase 1, the graph generation is special. There is no restriction on the positions of the waypoints, apart from the fact that for each waypoint there must be a route passing through it whose length does not exceed the length of the shortest route plus 40 per cent. In the other phases, the area within a certain perimeter around the routes of the selection

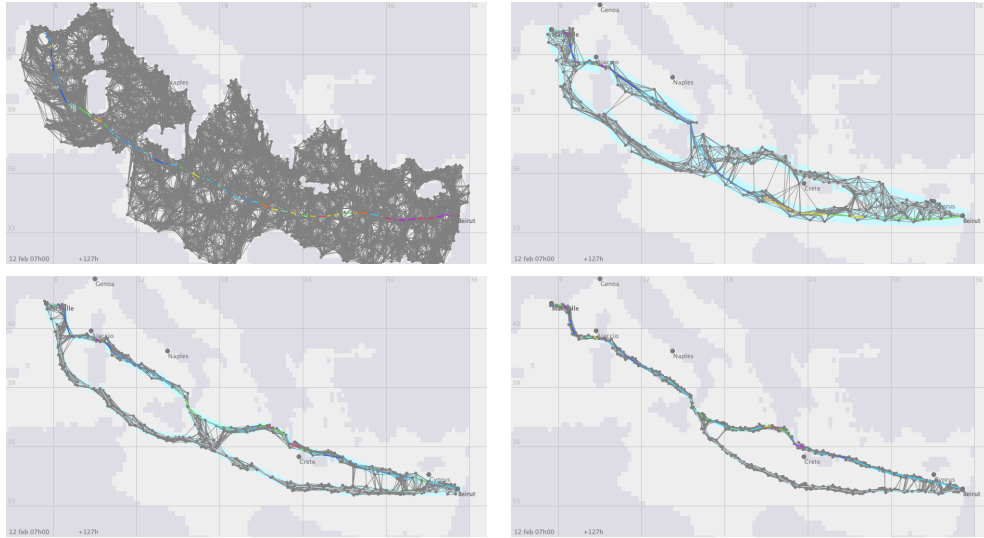


Fig. 5: Simplified versions of the problem generated in phases 1, 3, 4 and 5

is marked. It appears in light blue in the drawings. At each new phase the perimeter decreases and the marking becomes tighter around the routes of the selection. At the same time the number of potential waypoints is increased, and the ranges within which engine power levels are taken are reduced and readjusted, according to the region. The positions of the potential waypoints are chosen at random in the marked area, then connected to each other.

4.3 Shortest route

The cost of the journey, following the shortest route in terms of distance, can be estimated using *WRM-RS*. The shortest route passes between Corsica and Sardinia, then takes the Strait of Messina, and finally passes to the north of Crete and to the south of Cyprus. Figure 6 (drawing on the left) displays the itinerary that we have built joining the key passages with orthodromic routes. It is 1549.5 nautic miles long, whereas the orthodromic distance between Marseille and Beirut is 1496.3 nautic miles. We have evaluated the cost of the journey following the shortest route in different situations. Firstly ignoring the environmental factors, that is by taking into account only the resistance in calm water. Then, taking into account the effects of wind and waves, with a constant engine power level. Finally, adjusting the engine power level all along the journey. The best route discovered in this case is shown in figure 6 on the right. We used *WRM-RS*, simply positioning the potential waypoints on the shortest route. In the first case it appears, given the cost function we have used, that it is better to maintain a constant power level, as low as possible, 2200 kw in this case. The speed over ground of the ship is then also constant, and the journey takes place over the entire time window. In the second case we have determined the power level at which the voyage can be completed which gives the lowest cost. However, it is not always

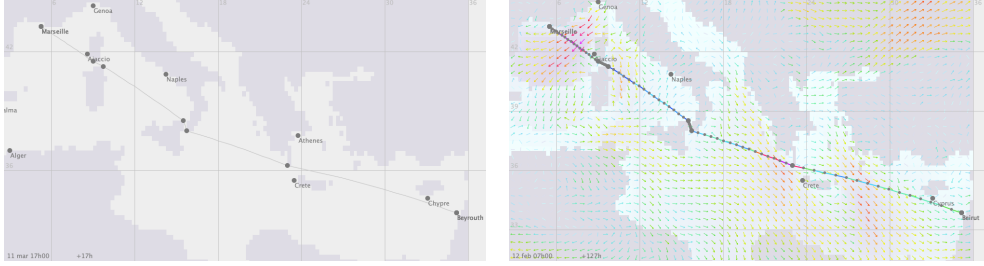


Fig. 6: The shortest route from Marseille to Beirut

possible to maintain a constant power level throughout the journey, as unfavorable weather conditions could prevent the ship from reaching its minimum speed, set to 6 knots. When this happens the engine power level is temporarily increased, by just what is needed. We obtained the best result with a power level set at 5100 kw and a departure from Marseille on February 12th at 10:19 pm.

<i>best cost ignoring environmental factors at constant power level</i>	274134.6
<i>best cost at constant power level</i>	629148.3
<i>best cost adjusting power level along the route</i>	484998.9

Fig. 7: Evaluation of the shortest route on the instance Marseille-Beirut

The results obtained in the different situations can be seen in figure 7. The first thing to note is that environmental factors play a very important role in our simulations. The cost is increased by a factor of at least 1.7 when these factors are taken into account. Secondly, the savings obtained by adjusting the engine power level are significant, around 22.9 percent if compared with a voyage at constant engine power level. Indeed, by modulating the speed, it is possible to escape the most unfavorable sailing conditions, and to take advantage of conditions that help the progression. The gains are very significant because wind and waves effects are heavily weighted in the *cost* and *duration* functions that we have used, as already mentioned.

4.4 Evaluation of WRM-RS

The aim here is to determine to what extent WRM-RS makes the right choice when there are obstacles on the way and the choice of the itinerary is not straightforward. The journey from Marseille to Beirut in the period from February 12, 2022 at 7:00 am to February 17, 2022 at 1:00 pm is particularly relevant from this point of view. It offers many possibilities, as there are several islands along the way, and different itineraries give high-quality routes. We have identified four places where a choice has to be made. For Corsica and Sardinia three options can be considered, the north route, the middle route which goes between Corsica and Sardinia, and the south route. For Sicilia, Crete and Cyprus there are two possibilities, passing to the north

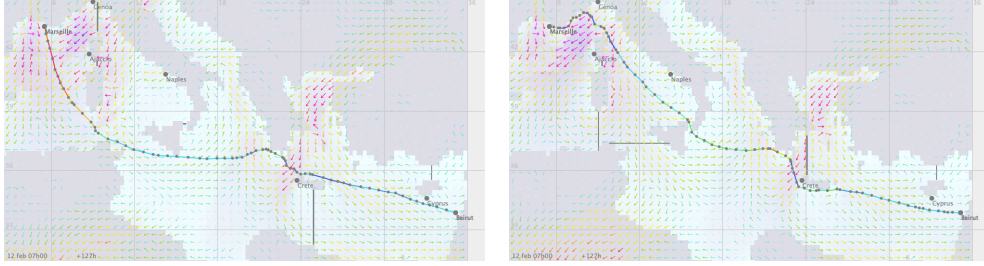


Fig. 8: Two routes with different itineraries but similar costs

or passing to the south. By forbidding the navigation in certain areas, the ship can be constrained to follow a well-defined itinerary. In doing so, we were able to evaluate the 24 possible itineraries between Marseille and Beirut. Itineraries that are very different can give routes with similar costs. For example figure 8 shows two routes discovered by WRM-RS corresponding to SSNS and NNSS itineraries. Barriers have been added to block certain passages. Although they correspond to very different itineraries, these routes have very similar costs, respectively 398156.6 and 398511.9. The average costs obtained by running WRM-RS 50 times for each of the 24 itineraries are reported in figure 9, ordered by increasing cost. The best results are achieved with the MNNS itinerary with an average cost of 370057.9. There are 8 other itineraries whose average costs exceed this cost by less than 8 percent. The fact that different itineraries give fairly similar results makes it difficult to find the best routes.

<i>CS</i>	<i>Si</i>	<i>Cr</i>	<i>Ch</i>	<i>avg</i>	<i>CS</i>	<i>Si</i>	<i>Cr</i>	<i>Ch</i>	<i>avg</i>
M	N	N	S	370057.9	S	N	S	S	417442.7
M	N	S	S	374377.8	N	N	N	N	421660.3
M	S	S	S	382229.9	M	S	N	N	421828.8
S	S	S	S	390718.8	M	S	S	N	426220.7
M	S	N	S	392801.6	S	S	N	N	426394.7
N	N	N	S	394744.7	N	S	N	S	427883.4
M	N	N	N	398087.7	S	S	S	N	429741.6
S	S	N	S	399027.1	N	N	S	N	430078.4
N	N	S	S	399564.5	S	N	N	N	441484.9
M	N	S	N	405178.8	S	N	S	N	449316.5
N	S	S	S	413852.8	N	S	N	N	454653.8
S	N	N	S	414246.2	N	S	S	N	45821.0

Fig. 9: Average costs obtained with WRM-RS for various forced paths

We have compared WRM-RS with WRM on the journey Marseille-Beirut leaving the choice of itinerary free. Implementing WRM from WRM-RS is quite easy, simply restricting the selection of routes to a single route in each phase. This can be done by setting

<i>phase</i>	1	2	3	4	5	6
<i>number of runs</i>	12	41	27	27	27	16
<i>routes</i>	–	1	1	1	1	1
<i>waypoints</i>	3000	150	225	300	500	600
<i>perimeter</i>	–	40	20	10	5	2.5
<i>dated costs for each point</i>	40	48	60	72	72	72
<i>power levels per leg (mean values)</i>	7	6.1	7.6	11.5	14.2	17.7

Fig. 10: Parameters used for WRM

the value of the parameter k to 1 in the function `search_phase`. In the first phase, the same parameters as for WRM-RS are used. So, for a given random seed, WRM and WRM-RS discover exactly the same routes in the initial phase. In the other phases, the routes selection contains only the best route discovered so far. The numbers of runs in the different phases have been adjusted to obtain the same computation times as with WRM-RS (figure 10).

	WRM	WRM-RS
<i>average cost</i>	386031.9	372551.1
<i>best cost</i>	366914.4	366532.4

Fig. 11: WRM-RS compared to WRM on the instance Marseille-Beirut

WRM and WRM-RS were run 1000 times each, with the same random seeds. The results are summarized in figure 11. It appears clearly that WRM-RS outperforms WRM. In average WRM-RS returns routes whose costs are 3.49 percent better than those discovered by WRM. This trend is confirmed using Student’s paired t-test ($P < .001$ with hypothesis $WRM > WRM-RS$). The reason is that for this instance, most of the times, the best route discovered during the first phase does not correspond to the itinerary which gives the best results. This can be due to the narrowness of the Messina Canal and of the passage between Corsica and Sardinia, or simply to chance, as the routes discovered in the first phase are not optimized, and between two itineraries of similar quality it is not necessarily the best one that will generate the best routes during this phase. WRM-RS strategy is very useful in this case. It makes it possible to reconsider itineraries that seemed irrelevant at the end of the first phase or later, but which in the end give the best routes, as we saw when running WRM-RS on the journey from Marseille to Beirut in section 4.2. From phase 2, WRM explores uniquely the search space around the best route discovered so far. Then it is unlikely that it will discover other itineraries. If the itinerary that gives the best results (SNNS) is forced, we observed that WRM-RS finds slightly better routes than if the choice of the itinerary is completely free. However, the gain is very low (0.65 percent better in average, compared over 1000 runs with the same random seeds), which means that WRM-RS terminates with the best itinerary most of the time. Finally, running WRM and WRM-RS 50 times each with the

same random seeds on each of the 24 possible forced itineraries, we found very little difference between the two approaches (on average a difference of 0.3 percent in favor of WRM-RS).

Obstacles are not necessarily land masses or reefs or shallow waters, that should be avoided. They can also be *weather obstacles*, such as storms, strong swells, or simply adverse weather conditions. By maintaining several possible itineraries, WRM-RS has every chance of avoiding the obstacle in the best possible way, even if it is moving. In situations where completely different itineraries can lead to quite similar results, the gains can be significant. Figure 12 shows WRM-RS at two different times while searching for a route in the North Atlantic, from the strait of Gibraltar to St-Pierre et Miquelon in the period from March 3, 2022 at 0:00 am to March 15, 2022 at 12:00 pm. The photo on the left shows all the routes discovered in the first phase. Two very different options are clearly visible, one passing to the north and the other to the south. Indeed, at the time the vessel is due to make the voyage, strong westerly winds are blowing over the North Atlantic. At this stage, the best route (in color) is to the south at a cost of 818074.5. The photo on the right was taken during phase 4. The three routes of the selection are clearly visible. The best route now passes to the north. In the end, the best route returned by WRM-RS passes to the north at a cost of 701293.2. With the same initial route selection, WRM finds a southern route whose cost is 740394.9. On this instance, the routes discovered with WRM-RS have a cost 1.78 percent better than those discovered with WRM in average (over 500 runs with same random seeds and similar computation times for WRM and WRM-RS).

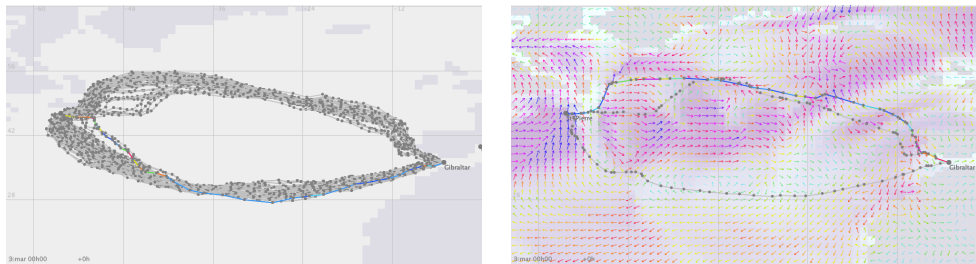


Fig. 12: Options North and South to go from Gibraltar to St-Pierre et Miquelon

5 Conclusion

In this paper we have described WRM-RS, a metaheuristic approach for weather routing based on WRM [4]. WRM-RS implements a specific strategy to find good quality routes when there are obstacles such as land masses or reefs, but also moving obstacles such as storms or areas which are best avoided due to weather conditions. In the presence of obstacles, choices have to be made about the itinerary. An approach like WRM, which continuously converges towards a region of the search space centered on the best route discovered at this point, can get stuck on an itinerary that does not give the best solutions. WRM-RS maintains a diversified selection of high-quality routes, with the

aim of considering different possibilities for routing for as long as possible. We have compared WRM-RS to WRM on the journey from Marseille to Beirut in the period from February 12, 2022 at 7:00 am to February 17, 2022 at 1:00 pm. Several itineraries are possible for this journey, with fairly similar costs, which makes the choice all the more difficult. WRM-RS shows an average cost saving of around 3.49 percent compared to WRM. It should be noted that the additional cost of maintaining a selection of routes representing different itineraries is almost negligible: on our example, we have found an average gain of only 0.65 percent with WRM-RS, if all the itineraries, except the one which produces the best results, are forbidden. This also means that WRM-RS makes the right choice most of the time.

Although significant advances have been made regarding the accuracy of the weather forecasts, there may still be discrepancies between predictions and actual conditions, in terms of timing, location, or intensity, especially over the long term. The degree of confidence in forecasts and the variability of the predictions depending on location and time, are aspects that need to be taken into account when evaluating a route. A slightly more costly route is thus preferable if the chances of the weather conditions changing during the journey are low. It seems essential to introduce a reliability criterion into routing systems in order to generate good quality routes offering a low risk of change. This will be the subject of future developments based on WRM-RS.

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